NBS

Technical Note 232

BIBLIOGRAPHY ON THE MEASUREMENT OF BULK RESISTIVITY OF SEMICONDUCTOR MATERIALS FOR ELECTRON DEVICES

JUDSON C. FRENCH

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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NATIONAL BUREAU OF STANDARDS

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BIBLIOGRAPHY ON THE MEASUREMENT OF BULK RESISTIVITY OF SEMICONDUCTOR MATERIALS FOR ELECTRON DEVICES

Judson C. French

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C., 20402 - Price 60 cents

Contents

Bibliography on the Measurement of Bulk Resistivity of Semiconductor Materials for Electron Devices

Judson C. French

In support of a study of accurate measurements of the bulk resistivity of semiconductor materials such as germanium and silicon which are used in electron devices, a literature search has led to the development of a rather large collection of references. The file cards making up the bibliography are reproduced in this Technical Note for the assistance of others who are concerned with the improvement and standardization of these measurements.

1. Introduction

In the course of a study of accurate measurements of the bulk resistivity of semiconductor materials for use in electron devices, for example, germanium and silicon, a search of the literature has been conducted.[1] The result has been the accumulation of quite a number of references which appear to offer promise of being helpful to the study. The subject matter includes topics which are obviously pertinent, such as measurement procedures and correction factors, as well as topics of a more indirectly applicable nature, such as sample preparation techniques and dimensional measurements, surface and pressure effects, uniformity, and so on. In regard to the former category, the collection is believed to be quite complete through 1963; a number of entries in the period to about mid-1964 are also included. The entries in the latter category are only those which have been selected as being of present or anticipated application to some of the specific problems of this study.

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[1]This work has been supported in part by the Advanced Research Projects Agency under Order No. 373-62 and the Air Force Cambridge Research Laboratories under PRO 61-560 and 62-200.

Nevertheless, others who are concerned with semiconductor resistivity measurements have expressed interest in having the collection made available for their use. For this reason, the file cards which form the working bibliography have been reproduced in this Technical Note with the hope that they will indeed be helpful in this field.

Because of the overlapping nature of the topics in many of the articles, no attempt has been made to group the cards by subject matter. Instead, they are arranged alphabetically on the basis of the author's name. An abstract is included as a guide to the article's content. This is frequently the author's abstract. To provide a brief index to the material covered by the references, a breakdown of the bibliography into thirteen categories of especial interest to the present study has been made. This has been based in many instances only on the statement in the abstract. It is recommended that this index be considered only to be a means of quickly finding the major references in these categories. It provides a starting point in seeking a complete set of references on a given topic. The identification numbers of the cards, which are used in the index, are to be found typed near the upper right hand corners of the cards.

Although the cards have been reproduced on both sides of a page, they may be cut out and attached to suitable file cards using two copies of the Technical Note if this should be desirable to provide a working file.

2. Index to Subject Matter

The subject matter of the collected references has been divided into the thirteen categories listed on page 3 in Section 2a. In Section 2b on pages 4 to 6, the identification numbers of appropriate cards are listed below the numbers corresponding to these categories.

2a. Index Categories

1. Bulk resistivity measurement: dc methods requiring probes or other contacts.

2. Bulk resistivity measurement: ac methods requiring probes or other contacts. (See also Category 1 for applicable techniques.)

3. Bulk resistivity measurement: ac contactless methods, excluding microwave frequencies, but including measurements of related properties such as dielectric constant and carrier lifetimes.

4. Bulk resistivity measurement: microwave methods, including microwave measurements of related properties such as dielectric constant and carrier lifetimes.

5. Bulk resistivity measurement: other methods than in Categories 1 to 4.

6. Layer resistivity measurement, including epitaxial and diffused layers. (See also Categories 1 to 5 for bulk measurement methods applicable to thin samples.)

7. Resistivity measurements at resistivities of 100 ohm-cm or greater.

8. Material properties, excluding inhomogeneities and anisotropies, but including surface and contact phenomena (see also Category 10), probe wear effects, mobility and lifetime measurements not included elsewhere, the dependence of resistivity on pressure, temperature and nuclear radiation, etc.

9. Sample inhomogeneities and anisotropies, including growth methods and defect determination.

10. Sample preparation and associated techniques, including crystal orientation, sawing, lapping, polishing, dimensional measurement, plating, application of leads, surface evaluation, etc. (See also Category 8, especially for contact phenomena.)

11. Miscellaneous equipment and techniques.

12. Correction factors, mathematical principles, and error analysis. (See also references on the specific method of measurement of interest. This category generally excludes papers with a theoretical introduction to a described method of measurement unless extensive correction factors are tabulated also.)

13. Survey articles.

2b. Index Tabulation

Categories 1 - 6

1			2	3	4		5	6
A4	L7	V3	A6	B25	A8	K27	A3	A6
A5	L13	V4	A7	C2	A9	L1	A6	A12
A7	M2	V5	B11	C10	A10	L8	B9	B1
A9	M6	V6	C6	D9	A11	L10	B14	B18
A10	M9	V8	D9	D14	A15	L11	B30	B30
A11	M11	V10	D16	D16	B5	L12	D14	B34
A12	N7	W1	F9	G7	B9	M21	D16	C13
A13	O3	W3	L13	G13	B10	N1	E2	D7
B2	O5	W7	P3	H12	B13	N2	F3	D16
B6	P3	W9	P16	I3	B17	N3	F6	F11
B15	P6	W13	P17	K28	B28	N4	G3	G1
B22	P12	W14	R19	K29	B29	N5	G7	G6
B26	P13	W16	R20	M6	C5	N11	G11	G11
B30	P16		V12	M20	C7	R1	H3	H9
C4	R7			N10	C8	R2	K8	H23
C11	R9			N13	C9	R4	K9	I4
C16	R12			O1	C10	R16	K15	K1
C20	R18			O4	C13	S2	K26	K7
D6	R19			P15	D9	S21	L14	K19
D7	R20			P16	D16	S29	M12	K23
D11	S9			P17	F1	S30	O1	K25
D13	S10			P19	F11	S39	O6	K26
D14	S11			R19	F15	T1	O7	K28
D16	S20			S26	G13	T2	O8	L3
E7	S22			T1	G17	T24	P2	M6
F2	S24			T24	G18	Z3	P8	M12
F6	S27			W6	H11		R5	N5
F8	S28			Y1	H20		R6	N7
G3	S33			Z2	H21		R20	P1
G11	S35				H22		S22	P15
H4	S40				H25		S40	P21
H5	S42				H27		S41	R6
H6	S46				H28		S50	R18
H7	S47				I3		T8	S9
H15	S48				J1		W16	S10
H19	S49				J2			S11
H23	S50				J3			S16
H26	T5				J4			S33
I3	T6				J5			S35
K5	T19				K2			S42
K6	T20				K17			S47
K7	U1				K18			S49
K14	V1				K19			T8
K25	V2				K24			T18
								T19

2b. Index Tabulation

Categories 7 - 9

7	8				9		
A7	A1	F12	N8	V9	A1	H8	S19
B22	A2	F13	N10	V11	A4	H10	S23
C5	A14	F14	O2	V12	A5	H13	S24
F9	A16	F16	P1	W2	A12	H14	S25
H19	B2	G2	P4	W5	A15	H17	S27
I3	B5	G4	P5	W7	A16	H24	S28
J3	B7	G7	P7	W8	B6	H26	S31
J5	B8	G9	P10	W10	B7	J9	S32
K8	B10	G13	P14	W15	B8	K1	S49
K29	B15	G15	P16	W17	B12	K3	S50
N10	B19	G16	P18	Y1	B14	K11	T3
P12	B20	H2	P20	Z1	B15	K20	T4
R16	B21	H6	P21	Z3	B16	K21	T7
R19	B24	H15	R8		B23	K26	T10
T6	B27	I2	R9		B26	L2	T11
	B29	I4	R10		B29	L4	T12
	B33	I5	R11		B30	L5	T13
	C2	J6	R12		C1	L6	T15
	C6	J7	R13		C3	L9	T16
	C9	J8	R14		C5	M1	T17
	C12	J9	R15		C10	M11	T20
	C14	K1	R18		C14	M14	T22
	C15	K4	R21		C15	M15	T23
	C17	K11	S1		D2	M16	V6
	C18	K13	S5		D6	M19	V13
	C20	K16	S6		D8	N9	W3
	C22	K22	S7		D15	O2	W5
	D1	K24	S8		D16	O6	W7
	D2	L5	S18		E1	O7	W11
	D4	L14	S24		E2	O8	W14
	D5	L15	S25		E5	P9	W16
	D9	L16	S28		E7	P21	
	D15	M3	S29		F10	R3	
	D16	M4	S35		G3	R8	
	D17	M5	S40		G4	R14	
	D18	M7	S41		G5	R17	
	D19	M13	T1		G8	R19	
	E1	M17	T2		G9	S4	
	E5	M19	T3		G12	S11	
	E6	M21	T4		G14	S14	
	E7	M22	T7		G15	S15	
	F4	M23	T10		H1	S16	
	F5	N1	T11		H4	S17	
	F9	N6	T14		H7	S18	
			V7				

2b. Index Tabulation

Categories 10 - 13

10		11	12	13
A1	S36	A14	A4	B33
A6	S37	D3	A5	C17
A13	S38	D13	B1	C18
B3	S43	H10	B34	D16
B4	S44	H18	C4	I3
B15	S45	P3	C11	K14
B20	T21	S3	C16	K29
B24	W7	S30	C21	N10
B31	W12	T9	D16	P5
B32	W17	V5	F2	P13
C6		V10	H4	R9
C19		W11	H5	R10
D10			J6	R19
D12			K5	S5
D16			K7	S6
E3			L7	S7
E4			L13	S8
E6			L16	S40
F2			M18	W16
F7			N12	
G14			P14	
G16			R7	
H6			S20	
H9			S28	
H15			S33	
H16			S34	
I1			S46	
K10			S47	
K12			S48	
L2			S49	
L15			U1	
M7			V2	
M8			V3	
M10			V8	
O9			W4	
P3				
P11				
P20				
P22				
P23				
R19				
S12				
S13				
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3. Index to Authors

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4. Bibliography

The bibliography is presented on the following pages.

The assistance provided by members of the Electron Devices Section, especially Barbara Averitt, Frank H. Brewer and Lydon J. Swartzendruber, in the preparation of the material for this Technical Note is gratefully acknowledged.

M. S. Ablova A1

Anisotropy of the Microhardness of Germanium

Soviet Physics - Solid State, vol. 3, p. 1320, December, 1961

Measured values of microhardness of single crystal germanium are found to vary by an amount of the order of ten percent depending on crystal orientation for a single value of load (200 gm). Surface treatment of a (111) surface, such as polishing or etching by different etchants, lead to a variation of a similar magnitude. References are given to measurements of microhardness on other semiconductor materials, including silicon-germanium alloys.

M. S. Ablova and A. R. Regel A2

Microhardness of Germanium of Various Conductivities

Soviet Physics - Solid State, vol. 4, p. 775, October, 1962

It is known that the addition of even small amounts of impurities (less than 1%) to a pure material may considerably alter its yield point. The change in mechanical properties on introduction of an impurity may be due to the following causes: elastic stresses in the lattice, due to the different dimensions of the impurity and the matrix atoms; interaction of the impurity atoms with one another and with dislocations (Cottrell interaction); interaction of gradients of impurity and dislocation concentrations; vacancies, interstitial atoms and dislocations produced on introduction of the impurity. Experimental work has shown that both an increase and a decrease of the yield point can be produced by an impurity.

E. Acs A3

A New Method for Measuring the Conductivity of Semiconductors (In German)

Proceedings of the Second International Measurements Conference, Budapest, 1961
Hungarian Scientific Society of Measurement and Automation, Budapest, 1961

The new method is measuring the specific resistance of the sample in a very low-frequency circuit, and there is not any need for galvanic contact between the sample and the measuring circuit.

The sample is suspended like a pendulum on a very thin yarn between the poles of an energized electromagnet. The attenuation of the pendulum is measured both in switched-in and switched-out magnetic fields.

S. V. Airapetyants and M. S. Bresler A4

Measurement of the Anistropy of Electrical Conductivity of Semiconductors by the Four Probe Method

Soviet Physics - Solid State, vol. 1, p. 134, January, 1959

A formula for calculating the anisotropy of the electrical conductivity of semiconductors from measurements made by the four-probe method is derived, and corrections to the electrical conductivity for the case of anisotropic substances are also calculated.

M. P. Albert and J. F. Combs A5

Correction Factors for Radial Resistivity Gradient Evaluation of Semiconductor Slices

Transactions of the Institute of Electrical and Electronics Engineers, vol. ED-11, April, 1964

Accurate determinations of radial resistivity gradients on semiconductor slices, using the four-point probe, can be made only if correction factors for the finite boundary conditions are applied to the measurements. The off-center correction is different from the center correction. Both are necessary for gradient evaluation. These corrections were derived assuming homogeneous material but are useful approximations for nonhomogeneous materials.

The corrections are given as generalized formulas and are graphed for the 62- and 25-mil probes, for the center, and 1/8 inch from the edge positions.

C. C. Allen and E. G. Bylander A6

Evaluation Techniques for the Electrical Properties of Silicon Epitaxial Films

Metallurgy of Semiconductor Materials, vol. 15, J. B. Schroeder, ed., conference, Los Angeles, 1961, p. 113, John Wiley and Sons, Inc., New York, N. Y., 1962

Techniques for thickness and electrical measurements of epitaxial silicon films are described. The application of these techniques to device manufacture is discussed.

C. C. Allen and W. R. Runyan A7

An AC Silicon Resistivity Meter

Review of Scientific Instruments, vol. 32, p. 824, July, 1961

A versatile, all transistor four-point probe resistivity meter incorporating a dc probe bias supply in conjunction with an ac measuring circuit is described. It is direct reading and covers a resistivity range of 0.01 ohm-cm full-scale to 300 ohm-cm full-scale. With minor changes the range can be increased to 1000 ohm-cm.

G. L. Allerton and J. R. Seifert A8

Resistivity Measurements of Semiconductors at 9000 Mc

Transactions of the Institute of Radio Engineers, vol. I-9, p. 175, September, 1960

A very important measurement in the manufacture of semiconductor material is the volume resistivity of material. Presently, this is measured by sending a direct current through a sample of the material and measuring the voltage drop across two points on the surface of the material. A new approach has been made by conducting this measurement with a high-frequency test signal, and using test samples to load the transmission system. The resistivity of limited areas and depths of material is determined.

G. L. Allerton and J. R. Seifert A9

A New Method for Measuring the Volume Resistivity of Semiconductor Material

Semiconductor Products, vol. 4, p. 43, June, 1961

In the manufacture of transistors and other solid-state devices, silicon and germanium material is manufactured to have a volume resistivity required for the device being manufactured. A very accurate measurement of resistivity is required to determine device parameters and processing methods. The four-point probe method now universally used for these measurements can be replaced with a microwave measurement at certain ranges of resistivity and slice thickness of material with an increase in accuracy and speed of measurement.

G. L. Allerton and J. R. Seifert A10

Resistivity Measurements for Semiconductors

Western Electric Engineer, vol. 5, p. 43, July, 1961

Resistivity is not a property that is measured often in production work. But with semiconductors, resistivity measurements are made often and at several stages in manufacture. Several techniques for measuring resistivity (two- and four-probe direct-current methods) were developed in the early days of the evolution of transistor technology. The microwave methods disclosed here are distinctly different from those commonly-used methods and offer significant advantages in accuracy and labor effort. The present state of development of the microwave methods and some estimates of the direction expected of further refinements are presented.

G. L. Allerton and J. R. Seifert A11

Resistivity Measurements at Microwave Frequencies

Journal of the Electrochemical Society, vol. 108, p. 179C (A), August, 1961

Resistivity measurements can be made at microwave frequencies with less damage to material than obtained by a conventional four-point probe and in a faster and more accurate manner. A high Q resonant circuit has been developed for low resistivity ranges of 0.002 to 1.0 ohm-cm. A second method of measuring the transmission loss through thin slices is used to cover the resistivity range from 0.1 to 40 ohm-cm.

S. Amer A12

Van der Pauw's Method of Measuring Resistivities on Lamellae of Non-Uniform Resistivity

Solid-State Electronics, vol. 6, p. 141, March-April, 1963

When the resistivity of a lamella of non-uniform resistivity is measured by van der Pauw's method, an average value for the resistivity is found. It is shown here that, for circular lamellae and a simple resistivity distribution

$$\rho = \rho o + Mr^2 \qquad (Mr^2 << \rho o),$$

the result obtained by van der Pauw's method is, in a first-order approximation, the same as that obtained by an actual integration of the resistivity over the surface of the lamella. It is also essential, for the above result to be true, that the four contacts are not too close to each other.

This result is probably true for lamellae of other shapes and resistivity distributions, if the perimeter is a line of constant resistivity.

American Society for Testing and Materials A13

Tentative Methods of Test for Resistivity of Semiconductor Materials

ASTM Designation: F43 - 64T, American Society for Testing and Materials, 1917 Race St., Philadelphia, Pennsylvania, 1964

This is a standardization of bulk resistivity measurement with two-point and four-point probes.

M. Antler, L. V. Auletta and J. Conley A14

Automated Contact Resistance Probe

Review of Scientific Instruments, vol. 34, p. 1317, December, 1963

A probe is described that will determine (a) contact resistance with continuously increasing pressure from 0-1000 g, (b) contact resistance as a function of wipe distance at fixed normal load, and (c) the current-voltage properties of films from 0-200 V. In pressure and voltage modes, specimen positioning is entirely automatic and programmable. The probe locates the test surface on an X-Y plane, goes through the selected mode, and then automatically repositions and repeats the measurement according to test schedule. The wipe mode is performed manually. Resistance current, voltage, load, wipe distance, and location of the specimen are read out on an oscillographic recorder. Contact resistance is measured by the four-point technique from 10^{-4} to $10^{3}\Omega$. The resistance span is divided into six ranges which change automatically, from high to low, when the resistance decreases to a preset percentage of the scale. The open circuit dc voltage of the resistance measuring circuit is 10^{-2} or 5×10^{-2} V, depending on resistance range.

C. P. Aron A15

Detection of Sample Inhomogeneities by Their Effect on Dielectric Measurements at Microwave Frequencies

Proceedings of the Institution of Electrical Engineers, vol. 111, p. 310, February, 1964

Inhomogeneities in solid dielectrics may be detected by mounting the sample (of 3-5 mm thickness) in the end of a cavity excited in the H_{01n} mode by a source that can be swept in frequency. RF output from the cavity is detected, amplified, and displayed on a c.r.o. against energizing frequency. the H_{01n} mode is degenerate with the E_{11n} mode and the degeneracy is resolved by the presence in the cavity of irregularities. For homogeneous samples the locus of cavity response with frequency is smooth, but for inhomogeneous samples it is irregular. The technique is useful for predicting the behaviour of the sample at high electric field strengths.

J. B. Arthur, A. F. Gibson, J. W. Granville and E. G. S. Paige A16

The Diffusion Constant, Mobility and Lifetime of Minority Carriers in Germanium Containing Parallel Arrays of Dislocations

Philosophical Magazine, ser. 8, vol. 3, p. 940, September, 1958

The presence of a high density of parallel edge dislocations in n-type germanium is found to enhance significantly the diffusion of holes in a direction parallel to the dislocations. The apparent diffusion constant is therefore anisotropic. In p-type germanium, on the other hand, the diffusion constant is isotropic and the carrier lifetime anisotropic.

At high electric fields the drift mobility of holes in n-type germanium is found to be anisotropic with respect to the dislocation array, no comparable effect occurring in p-type material.

These results can be explained by a model which assumes that dislocations introduce an additional acceptor level approximately intermediate in energy between the conduction and valence energy bands.

G. Backenstoss B1

Evaluation of the Surface Concentration of Diffused Layers in Silicon

Bell System Technical Journal, vol. 37, p. 699, May, 1958

A method for determining the surface concentration of diffused impurity layers in semiconductors is described. It is shown that the surface concentration may be evaluated if the sheet resistivity of the layer, junction depth, impurity distribution across the layer, background resistivity, and the carrier mobility are known. The calculations have been made for several typical impurity distributions in silicon.

G. C. Bailey and C. M. Williams B2

In-Pile Hall Coefficient and Conductivity Measurements on Zone-Refined P-Type Silicon

Journal of Applied Physics, vol. 34, p. 1935, July, 1963

The Hall coefficient and conductivity have been measured during pile-irradiation for a number of zone-refined, p-type silicon crystals with initial resistivities of 1, 8, and 100 ohm-cm. The conductivity of zone-refined silicon shows much faster changes with irradiation than pulled silicon samples of equivalent resistivity. The 100 ohm-cm samples exhibit a monotonic nonlinear decrease of $\ln\sigma$, conductivity, vs ϕ_s, integrated fast flux, whereas the other samples with initial Fermi levels closer to the valence band have one or two regions of linear decrease in $\ln\sigma$ vs ϕ_s before the nonlinear decrease region is observed. The Hall mobility for the 100 ohm-cm samples decreases and becomes negative as a result of the carrier density decreasing with irradiation. In the case of the 8 ohm-cm sample, the Hall mobility decreases with irradiation whereas the 1 ohm-cm sample shows no change in Hall mobility with irradiation up to the maximum integrated flux used in the present experiment. The origins of the dependence of $\ln\sigma$ on ϕ_s as well as the behavior of the Hall coefficient and Hall mobility with irradiation are discussed.

D. Baker B3

A Gauge for the Precision Measurement of the Thickness of Germanium and Silicon Wafers

Proceedings of the Institution of Electrical Engineers, vol. 106B, supplement No. 17, p. 1168, May, 1959 (Discussion, loc. cit., p. 1181)

Some of the difficulties associated with the precision measurement of the thickness of thin germanium and silicon wafers, together with several possible methods of measurement, are briefly discussed. A gauge which employs the optical-lever principle is described in which frictional restraint of the moving parts is reduced to that of a knife edge alone, thus ensuring good repeatability of reading with probe pressures of less than 3-g. The gauge covers the range 0 to 270μ with an over-all accuracy of $\pm$0.5μ.

D. Baker and J. R. Tillman B4

The Preparation of Very Flat Surfaces of Silicon by Electropolishing

Solid-State Electronics, vol. 6, p. 589, November-December, 1963

Slices of silicon can be very successfully polished by anodic dissolution in a cell using a horizontal rotating disk as cathode, a viscous electrolyte, and a very small anode-cathode spacing (e.g. 150 μ). The surfaces of n-type material of resistivity >0.05 Ω-cm must be illuminated during polishing, necessitating perforation of the disk to admit a beam of light to them. The optimum cell voltage is always above that for which the differential conductance of the cell is negative, and is usually about 10 v. The dissolution of 50 μ from a surface initially lapped or mechanically polished leaves it very flat and free of all work damage; electron micrographs show the residual local departures from flatness to be <0.01 μ. Material so prepared offers advantages in planar technology and as substrate for epitaxial growth. A full quantitative understanding of the mechanisms involved is still lacking, however.

T. Ya. Banis, A. I. Verbra, M. V. Denene and Yu. K. Pozhela B5

Measurement of Semiconductor Electrical Conductivity in High Microwave Fields (In Russian)

Lietuvos Fizikos Rinkinys. Litovskii Fizicheskii Sbornik. vol. 1, no. 3-4, p. 361, 1961

It is shown that the microwave electric field in a semiconductor is in square root proportion to the power falling on the sample in present methods of determining conductivity from experimental data.

P. I. Baranskii B6

Volume-Gradient Phenomena and Limits of Applicability of the Potentiometric Probe Method of Measuring the Electrical Conductivity of Semiconductors

Soviet Physics - Solid State, vol. 3, p. 643, September, 1961

Limits are investigated of the applicability of the potentiometric probe method of measuring the electrical conductivity of semiconductors, as it is used in experiments with real crystals which, in principle, are never free of resistivity gradients. These gradients invariably result in various volume-gradient phenomena, whose effect on results of accurate measurements has to be taken into account.

P. I. Baranskii, G. M. Dzyubenko and N. S. Konoplyasova B7

Experimental Study of the Nature of the Volume-Gradient EMF Produced in Germanium in the Presence of Current

Soviet Physics - Solid State, vol. 3, p. 638, September, 1961

A detailed description is given of experiments performed on n-type Ge with the aim of investigating the nature of volume-gradient emf δ_p which is produced along resistivity gradients in Ge in the presence of current. On the basis of our investigation of the effect of various factors on δ_p we concluded that the formation of the emf is due to distributed injection (exclusion) of minority carriers which are produced in germanium along resistivity gradients during the passage of current.

P. I. Baranskii and P. M. Kurilo B8

Dependence of the Volume Peltier Effect on Resistivity Gradients

Soviet Physics - Solid State, vol. 2, p. 424, September, 1960

The dependence of the volume Peltier effect, Ep, on the value of the resistivity gradients in single crystals of germanium was studied at room temperature; it was shown that $E_p\big|_{I=const} = (1/\rho)(d\rho/dx)$.

H. M. Barlow and J. Brown B9

Microwave Methods of Measuring Mobility in Semiconductors

Solid State Physics in Electronics and Telecommunications, vol. 1, p. 199, Academic Press Inc., New York, N.Y., 1960

The microwave region of the frequency spectrum is of great interest in that both optical techniques and the techniques of low-frequency circuitry can be used for measurements. The mobility of a charge carrier in a semiconductor and the number of such carriers per unit volume are essential parameters in determining the magnitudes of any effects involving current flow. The simplest method of determining the density of charge carriers at low frequencies is to use the Hall effect, while at optical frequencies it would be possible to make use of radiation pressure. Each of these effects can be demonstrated at microwave frequencies and in fact they are simply different manifestations of the same basic phenomenon. Some of the possible ways in which these effects may be used for mobility measurements are being investigated at University College, London, and are described in this paper.

H. E. M. Barlow and K. V. G. Krishna B10

A Hall-Effect Microwave Mixer

Proceedings of the Institution of Electrical Engineers, vol. 109, p. 131, March, 1962

The paper describes the theory and performance of a new microwave mixer based on the fact that the Hall electric field produced at any point in a semiconductor is dependent on the vector product of the current density and the magnetic field applied at that point. This mixer stage behaves differently from the more conventional forms in that the output contains only components of the local-oscillator and signal frequencies.

Besides being a linear device, the Hall-effect mixer has a power-handling capacity which is much larger than that of the ordinary crystal mixer. Moreover, the technique used offers a useful method for measuring the Hall mobilities of carriers in semiconductors at microwave frequencies.

New information is also given about a technique for the preparation of evaporated indium-antimonide films which proved to have a Hall mobility as high as one-fifth of the material in bulk.

A. L. Barry and W. D. Edwards B11

Circuit to Facilitate the Measurement by the Four-Probe Method of the Resistivity of Silicon in the Range 0.002 to 10,000 Ohm-Cm

Journal of Scientific Instruments, vol. 39, p. 119, March, 1962

A simple ac operated four-probe device and associated circuit for the measurement of semiconductor conductivity is described. The 400 cps measuring current can be varied from 0.12 μa to 2.5 ma, which enables resistivities in the range 0.01 to 500 ohm-cm to be measured with accuracy to ±4%. By taking suitable precautions this range can be extended to 0.002 to 10,000 ohm-cm. The waveform of the signal at the voltage probes is monitored as an indication of the correct operation of circuit and probe unit. The limitations of the circuit and the four-probe method are discussed.

R. T. Bate and A. C. Beer B12

Influence of Conductivity Gradients on Galvanomagnetic Effects in Semiconductors

Journal of Applied Physics, vol. 32, p. 800, May, 1961

An approximate solution is found of a boundary-value problem arising from the continuity equation in an inhomogeneous semiconductor, leading to rotational current vectors. Results are used to predict the effect of carrier-concentration gradients on magnetoresistance. The predicted weak-field effects are especially significant in degenerate semiconductors and n-type III-V intermetallics where the "intrinsic" magnetoresistance is small. In strong fields, even small gradients in carrier concentration can completely alter the field dependence of the magnetoresistance. Experimental results indicate that transverse currents, which do not occur in the simple case discussed, do appear in general, and further perturb the magnetoresistance. The influence of inhomogeneous magnetic fields is discussed briefly.

A. C. Baynham, J. W. Granville and A. F. Gibson B13

On the Dielectric Constant of Germanium at Microwave Frequencies

Proceedings of the Physical Society, vol. 75, p. 306, February, 1960

It is generally believed that the dielectric constant of intrinsic germanium at room temperature is about 16.0 and independent of frequency throughout the long wavelength infra-red, microwave and radio frequency spectrum. During measurements on certain electrical properties of germanium at 34.75 Gc/s it was desirable to check the dielectric constant and we were surprised to obtain a value of 14.94. Further detailed examination around this frequency showed up a small but significant dispersion region and it is the purpose of this note to describe the results obtained.

C. P. Bean, R. W. DeBlois and L. B. Nesbitt B14

Eddy-Current Method for Measuring the Resistivity of Metals

Journal of Applied Physics, vol. 30, p. 1976, December, 1959

A method for measuring the resistivity of metallic specimens is described. The measurement is made by noting the rate of decay of flux from a bar situated in an external magnetic field that has been rapidly reduced to zero. The method is suitable for specimens greater than 5×10^{-3} cm in diameter. For a specimen 1 cm in diameter, resistivities from 10^{-11} to 10^{-3} ohm-cm may be measured with an error of less than three percent. The method requires no contact to the specimen, and local values of resistivity may be measured. Several applications are described.

A. C. Beer and Associates B15

Investigations and Measurements of Properties of Single-Crystal Silicon (Final Report)

U. S. Government Research Reports, vol. 30, p. 261 (A), October, 1958 (AD133736)

Investigations were made of methods for determining minority carrier lifetime, resistivity, and charge carrier density and mobility in silicon crystals. Four methods of measuring minority carrier lifetime in silicon were investigated and are compared on the basis of suitability as a standard method. The photoconductivity decay method was found to be the most promising as regards all-around suitability. A study of the details of this method disclosed several precautions which must be observed to obtain reproducible and meaningful values of the lifetime. Special attention is given to the variation of lifetime with injection level in p-type silicon. For measurements of resistivity, either electroforming or plating procedures were perfected for overcoming difficulties from rectifying contacts and surface oxide films. The profiling of the Hall mobility along a crystal is accomplished with four potential probes arranged in a diamond array.

D. C. Bennett and B. Sawyer B16

Single Crystals of Exceptional Perfection and Uniformity by Zone Leveling

Bell System Technical Journal, vol. 35, p. 637, May, 1956

The zone-leveling process has been developed into a simple and effective tool, capable of growing large single crystals having high lattice perfection and containing an essentially uniform distribution of one or more desired impurities. Experimental work with germanium is discussed, and the possibility of broad application of the principles involved is indicated.

J. N. Bhar B17

Microwave Techniques in the Study of Semiconductors

Proceedings of the Institute of Electrical and Electronics Engineers, vol. 51, p. 1623, November, 1963

This paper describes some microwave methods for the measurement of semiconductor parameters developed at the Institute of Radio Physics and Electronics, University of Calcutta, India. The theory of conduction in semiconductors at microwave frequencies is first reviewed briefly. A SWR method is then outlined and its application to the study of temperature variation of conductivity and dielectric constant is discussed. An experimental arrangement for the measurement of surface conductance utilizing the above method is also described.

A technique for the measurement of infrared absorption coefficient of a semiconductor is then presented and the experimental results obtained with a p-type silicon sample are given.

The paper concludes with a description of two different methods developed for measuring the minority carrier lifetime. The possibility of utilizing one of these methods for obtaining the diffusion length, diffusion constant and surface recombination velocity in addition to lifetime, is also indicated.

J. R. Biard and S. B. Watelski B18

Evaluation of Germanium Epitaxial Films

Journal of the Electrochemical Society, vol. 108, p. 177C (A), August, 1961

A method has been developed for rapid and accurate determination of the resistivity of p-type epitaxial germanium films deposited on p+ germanium substrates. Determination of the resistivity is not dependent on a knowledge of film thickness. Data are presented for films with resistivities of 0.05 - 7.0 ohm-cm, deposited on 0.002 ohm-cm substrates; film thicknesses range from 0.15 to 0.6 mil.

J. S. Blakemore B19

Design of Germanium for Thermometric Applications

Review of Scientific Instruments, vol. 33, p. 106, January, 1962

Germanium doped with certain impurities has a strongly temperature-dependent conductivity below the liquid air range, suitable for use in secondary thermometry. Two mechanisms are responsible for this behavior: (1) Down to about 10°K, the conduction is provided by free current carriers liberated from impurity atoms; (2) Control of the conductivity below approximately 10°K is exercised by the relatively feeble "impurity conduction" process. For both, conductivity depends on the primary doping atoms and on the density of compensating impurities; low temperature impurity conduction can be inhibited unless some compensating centers are present. So that germanium thermometers should have resistance-temperature characteristics which "scale" well from one unit to another, a number of compensators sufficient to suppress any influence of uninvited impurities should be incorporated. By control of the primary and compensating impurity densities, a resistance-temperature characteristic can be controlled to emphasize a desired range. The transistion between the conduction processes is sharp for some impurities but occurs over a wide temperature range for others, influencing the suitability for thermometry. Characteristics of wide range and narrow range thermometer materials are illustrated.

A. Boatright, W. A. Merkl and H. Mette B20

High PME Sensitivities by Optical Polishing of Germanium Surfaces

Review of Scientific Instruments, vol. 33, p. 1281, November, 1962

High sensitivities in photomagnetoelectric (PME) devices for fast-response light detection or magnetic field measurements depend primarily on the success of providing a semiconductor slab with recombination rates as low as possible at the illuminated surface and as high as possible at the opposite surface. While it is known that high carrier recombination always occurs at mechanically abraded surfaces and is, therefore, easily achieved by mechanical polishing or sandblasting, the attainment of low recombination surfaces is more difficult and has been successful so far only by carefully controlled etching with CP-4 or other etchants. We have now round, however, that sensitive cells with low recombination front surfaces may also be obtained by optical polishing of Ge with diamond paste and that these cells possess some advantages over chemically etched cells.

I. I. Boiko, E. I. Rashba and A. P. Trofimenko B21

Thermally Stimulated Conductivity in Semiconductors

Soviet Physics - Solid State, vol. 2, p. 99, July, 1960

A theory of thermally stimulated conductivity is constructed on the basis of a quite general model of a semiconductor. It is shown that an analysis of plots of thermally stimulated conductivity for various heating rates allows one to determine the depth of localized levels. A preliminary comparison of theory and experiment is made.

G. P. Bolognesi, A. Pierno and G. Redaelli B22

Resistivity Measurements on Highly Resistive Silicon

Energia Nucleare (Italy), vol. 11, p. 18, January, 1964

A four-point probe has been built for resistivity measurements on silicon with resistivity greater than 100 ohm-cm, which is especially useful for thin slices as used in radiation detectors.

F. Bourassa B23

Vacuum Float Zone Refining of Silicon

Semiconductor Products, vol. 4, p. 37, April, 1961

Float zone refining, once considered a hopeless commercial process, has become practical by virtue of the introduction of various innovations to the basic technique. Among these innovations have been the application of automation, the use of ultra-high vacuum, a method for controlling crystal diameters, and the development of doping during the refining process.

F. P. Bowden and J. B. P. Williamson B24

Electrical Conduction in Solids - I. Influence of the Passage of Current on the Contact Between Solids

Proceedings of the Royal Society, A, vol. 246, p. 1, July, 1958

The effect of passing an electric current through the interface between two contacting pieces of gold has been investigated, and it has been shown that the current can cause appreciable changes in the true area of contact between the surfaces. This phenomenon has been studied by measuring the associated alterations in the constriction resistance. (This is the resistance caused by the constriction produced in the current stream as it passes through the tiny areas of contact between the metals.) It is shown that the response of the region of contact may be explained as a result of the heat generated in this resistance by the current.

The response of the contact region to short-duration pulses of current has been studied. The results show that the behavior is independent of the length of the pulse in the range investigated (10μs to 10ms). They also indicate that when a short pulse of current passes between the pieces of metal mechanical collapse will occur only if the current is sufficiently large to cause melting of the metal near the interface.

J. C. Brice and P. Moore B25

Contactless Resistivity Meter for Semiconductors

Journal of Scientific Instruments, vol. 38, p. 307, July, 1961

Resistivity is determined as a function of the eddy currents induced in the specimen by a 10-Mc oscillator. Resultant amplitude changes in the oscillator output are measured with a valve voltmeter.

J. C. Brice and A. A. Stride B26

A Continuous-Reading Four-Point Resistivity Probe

Solid-State Electronics, vol. 1, p. 245, July, 1960

The apparatus uses ball-point probes and can be run along the surface of the specimen, providing a continuous signal from which a resistivity profile may be derived.

H. B. Briggs B27

Optical Effects in Bulk Silicon and Germanium

Physical Review, vol. 77, p. 287, January 15, 1950

Pure bulk silicon and germanium are highly transparent to infra-red energy of wave-lengths greater than their photoelectric long-wave limits, i.e., $1.2X10^{-4}$ cm for silicon and $2.2X10^{-4}$ cm for germanium. As examples of the transmission through thick samples it may be noted that a germanium slab of thickness 6.0 mm, part of a standard high back-voltage melt, showed very little absorption in the wavelength range from 2 to 6.5μ. A sample of high-purity silicon, of thickness 5.2μ, showed little absorption in the wavelength range from 1.2μ to 6μ.

M. E. Brodwin and R. J. Vernon B28

Instrument for Measuring the Magnetomicrowave Kerr Effect in Semiconductors

The Review of Scientific Instruments, vol. 34, p. 1129, October, 1963

An instrument is described which measures the transport properties of high-conductivity semiconductors. It employs a microwave turnstile junction to determine the complex orthogonal amplitudes of the reflected waves from a magnetized sample. The data are obtained by a double-bridge technique of high sensitivity. Some experimental results on germanium at room temperature are presented.

M. A. C. S. Brown B29

Deviations from Ohm's Law in Germanium and Silicon

Journal of the Physics and Chemistry of Solids, vol. 19, p. 218, May, 1961

The deviation from Ohm's law in germanium and silicon at high electric fields has been measured by a microwave method at room temperature. It has been found that this deviation depends on the type and resistivity of the material, and also on the orientation of the electric field with respect to the crystallographic axis. Small deviations from the well-known quadratic variation with electric field have been observed. The quantity measured has been related to the steady-state deviation from Ohm's law by an expression involving the energy relaxation time of the carriers and the period of the microwave frequency used. Agreement with the experimental values for the steady-state deviation from Ohm's law has been obtained by using a theory which considers scattering by both acoustical and optical modes, combined with a postulated increase in the effective masses of the free carriers.

J. Brownson B30

A Three-Point Probe Method for Electrical Characterization of Epitaxial Films

Journal of the Electrochemical Society, vol. 111, p. 919, August, 1964

A three-point probe has been devised which makes possible simple, rapid measurements of resistivity and conductivity type of epitaxial silicon films. The probe in contact with a silicon crystal is effectively a point-contact diode with ohmic base termination. The external circuitry measures this "diode's" V-I characteristics. Its peak inverse voltage is a predictable function of resistivity and hence resistivity is determined from this parameter. The advantage of the probe is that special preparation of rectifying and nonrectifying contacts is not necessary. The design, calibration, and operation of the probe are discussed in addition to some experimental results such as resistivity as a function of location within the reactor and a relatively simple method for measurement of resistivity gradient in the film. Finally, the method's limitations in measuring thin, high resistivity films are described and capability limits defined.

T. M. Buck B31

Discussion of "Etching of Abraded Germanium with CP-4 Reagent," E. N. Pugh and L. E. Samuels, J. Electrochem. Soc., vol. 109, p. 409, May, 1962, and "A Metallographic Investigation of the Damaged Layer in Abraded Germanium Surfaces," E. N. Pugh and L. E. Samuels, J. Electrochem. Soc., vol. 108, p. 1043, Nov., 1961

Journal of the Electrochemical Society, vol. 109, p. 1220, December, 1962

There is agreement that the metallographic method of determining the depth of abrasion damage is convenient and useful, but the conclusion that this microscopic method is the most reliable method is disputed. Results of several methods are presented with references to the original work and it is concluded that the differences in sensitivity between the metallographic method and the lifetime method are small and probably insignificant, but that if a comparison is made, most published data appear to favor the lifetime method.

T. M. Buck and F. S. McKim B32

Depth of Surface Damage Due to Abrasion on Germanium

Journal of the Electrochemical Society, vol. 103, p. 593, November, 1956

The approximate depth of surface damage on Ge as it influences surface recombination velocity has been measured for a variety of abrasive treatments by etching, weighing, and making two types of photomagnetoelectric measurements. Values range from 1μ or less for fine polishes to 35μ for heavy sandblasting. Close correlation is found with changes in reverse characteristics of grown junction p-n diodes treated in the same manner.

E. Burstein and P. H. Egli B33

The Physics of Semiconductor Materials

Advances in Electronics and Electron Physics, vol. 7, p. 1, Ed. by L. Marton, Academic Press, Inc., New York, N. Y., 1955

This is a presentation of data, concepts and references showing the status and trends of semiconductor physics. Subject headings are:

I Introduction
II Nature of Semiconductors - Chemical Binding, Energy Band Structures
III Trends in Fundamental Properties - Energy Gap, Mobility
IV Impurity and Lattice Defect Centers - Character of Levels in the Forbidden Band, Homopolar Semiconductors, Polar Semiconductors
V Lifetime of Electron-Hole Pairs
VI Procedures for Determining Characteristic Properties of Semiconductors - Carrier Concentration and Mobility, Forbidden Energy Gap, Energy Levels within the Forbidden Band, Effective Mass
VII Current Information on Familiar Semiconductor Materials - Elemental Semiconductors, Compound Semiconductors

References

K. M. Busen and G. A. Shirn B34

The Average Conductivity of Diffused Layers in Semiconductors

Solid-State Electronics, vol. 7, p. 49, January, 1964

For the determination of the average conductivity σ of diffused layers in semiconductors one must evaluate an expression where the mobility, μ, as a complicated function of the concentration, C, stands under the integral sign. Because the determination of σ this way is rather inconvenient, simplified relations have been derived under the assumption that the mobility is equal to the value of μ for the concentration $C = C_o$ and is constant over the whole concentration profile of the layer. It can be shown by numerical evaluations that the error introduced thereby amounts, even in extreme cases, to less than a factor of 1.5 for average conductivities of diffused layers in silicon and germanium. For general considerations an expression has been derived which gives an upper limit for the error in σ which arises by keeping μ = constant = μ_o. The simplified relations can be employed for a quick determination of surface concentrations from only a four-point probe measurement, omitting the junction delineation which normally is required in addition, or for quick estimates of the average resistivity of a diffused layer from diffusion parameters. Evaluations for a variable mobility can be obtained by the application of correction factors. For Ge and Si these factors have been determined.

P. R. Camp C1

Resistivity Striations in Germanium Crystals

Journal of Applied Physics, vol. 25, p. 459, April, 1954

Germanium metal, both single crystalline and polycrystalline, is frequently found to contain sharp fluctuations in impurity concentration. These are superimposed on the gradual variations expected as the result of ordinary segregation processes.

A rather simple technique for detecting fluctuations of this kind has been developed. It is more sensitive than resistivity scanning and does not involve the use of radioactive tracers. This technique has been applied to a number of samples. The origin, value, and elimination of these fluctuations are discussed briefly.

The method involves a copper-decoration technique.

M. Cardona, W. Paul and H. Brooks C2

Dielectric Constant Measurements in Germanium and Silicon at Radio Frequencies as a Function of Temperature and Pressure

Solid State Physics in Electronics and Telecommunications, vol. 1, p. 206, Academic Press Inc., New York, N.Y., 1960

This paper reports the results of experimental work on the dependence of the dielectric constant on pressure and temperature, conducted partly to clarify the dependence of the electron wave-vector on these parameters and partly to interpret experiments on the pressure variation of the ionization energy of impurity levels, of the ionized impurity scattering and the optical transmission.

J. R. Carruthers and K. E. Benson C3

Solute Striations in Czochralski-Grown Silicon Crystals: Effect of Crystal Rotation and Growth Rates

Applied Physics Letters, vol. 3, p. 100, September 15, 1963

The location, spacing, and magnitude of solute inhomogeneities produced parallel to the solid-liquid interface of silicon crystals by transient growth effects were investigated through measurement of resistivity variations as a function of crystal seed rotation, growth rate, and solute concentration. Such concentration gradients in the crystal are known to affect the local breakdown voltage characteristics in semiconductor devices. In addition, such solute inhomogeneities cause differences in the rate of chemical etching, electromechanical polishing, electroplating and alloying.

S. B. Catalano C4

Correction Factor Curves for Square-Array and Rectangular-Array Four-Point Probes near Conducting or Nonconducting Boundaries

Transactions of the Institute of Electrical and Electronic Engineers, vol. ED-10, p. 185, May, 1963

Resistivity measurements made with a four-point probe on a sample having at least one of its dimensions small (i.e., of the order of the spacing between the points of the probe or smaller) require a correction factor to compensate for this condition. Correction factors for various four-point probe arrangements near a conducting or a nonconducting boundary have been derived and plotted for cases where: 1) the four-point probe array is rectangular and of various proportions rather than square, 2) the current points of the square- or rectangular-array probe are perpendicular to the boundary, and 3) the current points of the square- or rectangular-array probe are parallel to the boundary.

L. Cerny, J. Cihelka and V. Husa C5

Contact-Free Measurement of Conductivity of Silicon and Its Type Determination (In German)

Elektrotechnik und Maschinenbau (Austria), vol. 80, p. 184, April 15, 1963

The method described is suitable for feeding silicon ingots (as available in zone-melting techniques) through a resonator cavity. The p and n border regions are rapidly determined as well as the type of conductivity.

S. W. Chaikin, J. R. Anderson and G. J. Santos, Jr. C6

Improved Probe Apparatus for Measuring Contact Resistance

Review of Scientific Instruments, vol. 32, p. 1294, December, 1961

An apparatus, employing a fine-wire probe, for the detection of insulating surface films on metal surfaces is described. A chemical cleaning procedure to prepare reliably clean palladium and gold surfaces is reported, and examples of the reproducibility of the method are given. Examples of the use of this apparatus include: the detection of high-resistance areas on relay contacts taken from sealed relays, and a study of insulating base metal oxide impurities in commercial relay contacts. In the latter work, a sensitized paper test showed areas of iron and copper deposits on the contacts which could be correlated with areas of high resistance as indicated by the probe.

K. S. Champlin and D. B. Armstrong C7

Explicit Forms for the Conductivity and Permittivity of Bulk Semiconductors in Waveguides

Proceedings of the Institute of Radio Engineers, vol. 50, p. 232, February, 1962

Recent interest in the analysis of waveguides containing bulk semiconductors has been motivated by two different possible applications: 1) microwave measurement of electron transport phenomena, and 2) development of bulk semiconductor microwave devices. In the first application, one desires to find the conductivity and/or permittivity (or changes in these quantities caused by carrier injection, dc electric and magnetic fields, etc.) from measurement of the transmission or reflection coefficient of a waveguide containing the semiconductor. For the second application, the inverse problem is generally of interest. The discussion in this note is confined to the first application, the measurement problem.

K. S. Champlin and D. B. Armstrong C8

Waveguide Perturbation Techniques in Microwave Semiconductor Diagnostics

Transactions of the Institute of Electrical and Electronics Engineers, vol. MTT-11 p. 73, January, 1963

Scattering processes in semiconductors are often studied by observing scattering averages with measurements of various dc transport phenomena. With microwaves, the observation frequency can be of the order of the scattering frequency, so that the corresponding microwave transport property may be complex. Thus in studying detailed scattering mechanisms, a microwave transport experiment contains potentially more information than the analogous dc experiment. This paper discusses perturbation techniques which are useful in determining the microwave conductivity and low-field Hall effect of a bulk semiconductor contained in a waveguide from measurement of the properties of the transmitted wave.

K. S. Champlin, D. B. Armstrong and P. D. Gunderson C9

Charge Carrier Inertia in Semiconductors

Proceedings of the Institute of Electrical and Electronics Engineers, vol. 52 p. 677, June, 1964

The conduction process in semiconductors exhibits effects associated with inertia of the carriers when the observation frequency is comparable to the reciprocal of the relaxation time for randomization of momenta. These effects can cause significant changes in the conductivity and permittivity of germanium and silicon measured at ordinary microwave frequencies and should become increasingly important as semiconductor devices are developed for ultra-microwave applications. The present paper derives equivalent circuits which illustrate inertial effects and discusses their temperature dependence. A highly accurate reflection bridge technique for measuring microwave conductivity and permittivity is then described. Finally, measurements of conductivity and permittivity of n-type silicon and p-type germanium at 24 Gc and at temperatures between 77° and 300° Kelvin are presented and compared with theory. At 77°, the inertial effects are found to be largest for the p-type germanium and cause the microwave conductivity to be less than the dc conductivity by a factor of one-half.

K. S. Champlin and R. R. Krongard C10

The Measurement of Conductivity and Permittivity of Semiconductor Spheres by an Extension of the Cavity Perturbation Method

Transactions of the Institute of Radio Engineers, vol. MTT-9, p. 545, November, 1961

A technique based on cavity perturbation theory is described with which one can determine the microwave conductivity and dielectric permittivity of a small sphere of completely arbitrary conductivity. These properties follow from the measured frequency shift and change in Q occurring when the sample is inserted into a region of maximum electric field in a cavity resonator. The range of validity of the quasi-static internal field approximation is discussed, and curves are provided for extending the measuring technique beyond this range. The extended theory is valid for the entire conductivity range from zero to infinity. Measurements on several samples of known conductivity and permittivity in which the approximation is not satisfied are seen to agree with the theory. For highly conductive materials the present method is closely related to the "eddy current loss" measuring technique discussed by others. The two methods are compared. Because the measuring technique employs a spherical sample, it may be applied to materials with nonisotropic carrier mobilities and to semiconducting materials for which contact fabrication techniques are poorly known.

S. Ch'ang-hou C11

Correction Functions for the Measurement of Specific Resistance by the Four-Probe Method on Semiconductor Specimens of Rectangular Form (In Chinese)

Acta Physica Sinica, vol. 19, p. 370, June, 1963

On the basis of a theoretical analysis, a general expression is derived for the correction functions of specific resistance of semiconductors by the four-probe method on specimens of rectangular form. These expressions, which simultaneously allow for the influence of three limiting dimensions on the measured results, serve as formulae for the calculation of correction coefficients. Tables of values of different correction functions are given. It is noted that in order to decrease the errors of measurement, it is necessary not only to improve the apparatus and technique of the method, but also to choose the correction factor properly.

P. W. Chapman, O. N. Tufte, J. D. Zook and D. Long C12

Electrical Properties of Heavily Doped Silicon

Journal of Applied Physics, vol. 34, p. 3291, November, 1963

Measurements have been made of the temperature dependences of the electrical resistivity and Hall coefficient in samples of n- and p-type silicon having impurity concentrations in the 10^{18} to 10^{20} cm^{-3} range. The resistivity data extend from 4° to 900°K, and the Hall data from 4° to 300°K. The results exhibit two noteworthy features: viz., (1) a hump or maximum in the resistivity vs. temperature curves at or slightly below the degeneracy temperature in each sample, which is most pronounced in the least heavily doped samples and gradually fades out as the impurity concentration increases, and (2) an extension of the positive dependence of resistivity on temperature below the hump or degeneracy temperature to surprisingly low temperatures in each sample.

C. K. Chatterji, S. K. Roy and B. R. Nag C13

Microwave Measurement of Surface Conductance of Semiconductors

Proceedings of the Institute of Electrical and Electronics Engineers, vol. 52, p. 873, July, 1964

It is expected that the measurement of surface conductance at microwave frequencies will help in extending the knowledge of the nature of this scattering mechanism, though no microwave measurement of surface conductance has been reported so far. The authors have been trying a microwave method for the measurement of surface conductance of Si and have obtained results which appear to be promising. The object of the present communication is to present this method.

M. V. Chukichev and V. S. Vavilov C14

Generation of Lattice Defects in Silicon Crystals as a Result of Thermal Neutron Irradiation in a Nuclear Reactor

Soviet Physics - Solid State, vol. 3, p. 1103, November, 1961

Changes in the properties of a crystal exposed to neutrons can be attributed to the following: 1) elastic scattering of fast neutrons, 2) nuclear transmutations and 3) recoil of excited nuclei associated with the emission of γ-rays. The number of atoms displaced by each of these mechanisms has been calculated for silicon. The results of this calculation are compared to experimental data.

J. W. Cleland and J. H. Crawford, Jr. C15

Radiation-Induced Disorder in Semiconductors

Proceedings of the International Conference on Semiconductor Physics, Prague, 1960, p. 299, Academic Press, Inc., New York, N.Y., 1961

The variation of σ and μ_H of n-type Ge with neutron bombardment has been treated on the basis of a disordered-region model of lattice damage. It is found that the bulk of the initial change in these properties can be accounted for in terms of disordered regions approximately 100 Å in radius for the neutron spectrum employed.

J. F. Combs and M. P. Albert C16

Diameter Correction Factors for the Resistivity Measurement of Semiconductor Slices

Semiconductor Products, vol. 6, p. 26, February, 1963

The accurate measurement of the resistivity of semiconductor slices with the four-point probe requires the use of a correction factor for the slice diameter. Neglecting this factor will cause errors from +5% for 20 mm diameter slices to +18% for 10 mm diameter slices in measurements made at the center of the slice with a 62.5 mil point-spacing four-point probe. Measurements made at off-center locations will be in error by an even greater amount. The derivation of the diameter correction factor and a table which combines both thickness and diameter corrections is described in this article.

E. M. Conwell C17

Properties of Silicon and Germanium

Proceedings of the Institute of Radio Engineers, vol. 40, p. 1327, November, 1952

This article provides the latest experimental information on those fundamental properties of germanium and silicon which are of device interest, currently or potentially. Electrical properties, especially carrier density and mobility, have been treated in greatest detail. Descriptive material has been provided to the extent necessary to give physical background.

E. M. Conwell C18

Properties of Silicon and Germanium: II

Proceedings of the Institute of Radio Engineers, vol. 46, p. 1281, June, 1958

This paper attempts to bring up to date the information on fundamental properties of silicon and germanium. Much the same topics are covered as in the author's earlier article "Properties of Silicon and Germanium", which appeared in the 1952 Transistor Issue of PROCEEDINGS. Also included is some of the detailed knowledge on the band structure which has been obtained since 1952. This is essential to the understanding of many of the properties of these materials.

B. J. Coughlin, G. L. Davis and R. L. Kingsnorth C19

Orientation Control for Germanium Wafers

Journal of Scientific Instruments, vol. 36, p. 144, March, 1959

In the manufacture of semiconducting devices employing wafers of germanium single crystals, it is usually important that the orientation of the wafers be controlled to within a degree or so. In most cases the surface of the wafer should coincide as nearly as possible with a (111) plane -- usually that normal to the [111] direction of growth of the ingot; this note describes a method for accurately mounting ingots for cutting slices and a method for determining the orientation of small wafers.

R. H. Creamer C20

The Measurement of the Electrical Resistivity of Silicon

British Journal of Applied Physics, vol. 7, p. 149, April, 1956

A modified four-probe method is described which employs probes made from wires containing a donor or acceptor type impurity for n- or p-type silicon respectively. By discharging a condenser between the probes, low resistance stable contacts are obtained which allow a steady current to flow in the specimen and permit the potential to be measured with a standard potentiometer. Resistivity measurements by the normal method and by the four-probe method are compared; the latter measurements give an accuracy of about $\pm$ 7% for resistivities up to several hundred ohm centimeters.

E. L. Crow C21

An Analysis of the Accumulated Error in a Hierarchy of Calibrations

Transactions of the Institute of Radio Engineers, vol. I-9, p. 105, September, 1960

Calibrations of many types are performed in a hierarchy of calibration laboratories fanning out from a national standard. Often the statement is made that the accuracy of each echelon of the hierarchy should be 10 times the accuracy of the immediately following echelon. The validity of such statements is examined by deriving formulas for the total error accumulated over the entire sequence when systematic and random errors may occur in each echelon, and by determining how a given total error may be achieved at minimum total cost under reasonable assumptions for the form of the cost-error functions.

P. Csavinszky C22

Low-Temperature Impurity Conduction and Magnetoresistivity in N-Type Germanium

Physical Review, vol. 119, p. 1605, September 1, 1960

The resistivity of several lightly doped (Sb) n-type germanium samples has been calculated and compared with values measured at 2.5°K. An order of magnitude agreement has been obtained for a span of five orders of magnitude in the resistivities. It has been assumed that the mechanism of conductivity consists of jumping of electrons from occupied to empty donors. The number of charge carriers has been determined by calculating the number of "free" donor ions. The "trapped" donor ions, due to the presence of charged compensating acceptors, have been assumed not to participate in the conduction process. The effect of a constant magnetic field on impurity conduction has also been investigated and a simple theory of magnetoresistivity is presented. The calculated magnetoresistive ratio is in order of magnitude agreement with the measured value.

W. C. Dash D1

Mechanical Properties of Dislocation-Free Silicon Crystals

Bulletin of the American Physical Society, series II, vol. 4, p. 47, (A), January, 1959

At 900°C, single crystals of silicon deform readily at stresses of about 1 kg/mm^2 when dislocations are present. Plastic deformation does not occur in dislocation-free crystals at stresses over 20 kg/mm^2 if care is exercised in etching and handling the samples. If superficial damage produced during preparation of the samples is not completely removed, deformation occurs at much lower stresses in dislocation-free crystals at 900°C. Samples with cross-sectional areas of 0.25 mm^2 have been bent elastically at room temperature to strains of 2% before fracture. The presence of dislocations does not affect these results. Elastic strains of this magnitude have been reported previously only for whiskers and for bulk specimens with 100 times smaller cross-sectional areas. Two conclusions can be drawn: Silicon crystals in which no dislocations can be detected by decoration and etch pit techniques are much stronger at high temperatures than those in which dislocations are present. The mechanical strength at all temperatures is very sensitive to the condition of the surface.

W. C. Dash D2

Growth of Silicon Crystals Free From Dislocations

Journal of Applied Physics, vol. 30, p. 459, April, 1959

The dislocations which occur in silicon crystals grown by the Czochralski method with and without a crucible are studied by etching and copper decoration techniques. A representative crystal with about 500 dislocations per cm^2 is examined in detail to provide general information about their distribution. Sources of dislocations which are improtant at particular stages of growth are isolated and means are found to minimize or eliminate them. Plastic generation is the only source found in the bulk of a crystal. For certain crystallographic directions it is possible to eliminate residual dislocations and thenceforth grow a dislocation-free crystal. This is interpreted in terms of climb. In a supersaturation of vacancies, an edge dislocation can be forced completely out of a crystal; a screw will remain straight or may be distorted into a coaxial helix. When the dislocations are eliminated, the growing crystal can withstand large temperature fluctuations without further generation of dislocations. A procedure is outlined for the growth of dislocation-free silicon germanium crystals. It is believed that the conclusions reached during the course of this investigation may be applied to the development of methods for growing dislocation-free crystals of other substances.

T. M. Dauphinee D3

An Isolating Potential Comparator

Canadian Journal of Physics, vol. 31, p. 577, May, 1953

A circuit is described by which electromotive forces can be compared accurately without making any direct electrical connection between them. A double-pole, double-throw chopper, having a capacitor connected between the vibrating contacts, is used with a galvanometer or electronic amplifier to indicate any inequality between the emf's without allowing any net flow of current between the circuits. Polystyrene condensers and mechanically driven choppers are used to minimize leakage and pickup problems.

Potentiometric measurements may be made through this "isolating potential comparator" to ± 0.1 μv. The error due to potential difference between the circuits is about 10^{-6} of the difference for 100-ohm circuits. An analysis of the method is given and optimum capacitor and galvanometer characteristics determined. Magnitude and elimination of errors are discussed.

The comparator is suitable for measurement or control of emf differences between thermocouples which are electrically connected through the tips. It also has many applications in resistance measurement and resistance thermometry.

E. A. Davies and D. S. Gosling D4

Non-Ohmic Behavior in Silicon

Journal of the Physics and Chemistry of Solids, vol. 23, p. 413, April, 1962

The non-ohmic behaviour of covalent semiconductors in an intense electric field is a well-known phenomenon. A number of experimental and theoretical studies, mainly on germanium, have been published. The experiments reported here were carried out on high resistivity (70 Ω-cm) n-type silicon to which fields of up to 60 kV/cm were applied. The results are given in the form of a field-current density characteristic and a curve showing the variation of mobility with field. These measurements were taken in the course of an investigation into other hot-electron effects and so the apparatus and specimens were not designed primarily for measuring high field mobilities. Consequently, the high accuracies which can be obtained in such experiments are not claimed.

P. P. Debye and E. M. Conwell D5

Electrical Properties of N-Type Germanium

The Physical Review, vol. 93, p. 693, February 15, 1954

Measurements of conductivity and Hall effect from 11°K to 300°K on a set of n-type germanium samples covering the range from intrinsic to degenerate are reported. The theory of mobility is reviewed briefly. The treatment of impurity scattering by Brooks and Herring is presented, and their formula for the impurity mobility is used throughout. An analytical formula for obtaining the mobility from lattice and impurity mobilities is included, and it is noted that both lattice and impurity mobility vary with temperature raised to a power different from theoretical predictions. The effect of electron-electron collisions on the mobility is considered in a qualitative manner.

In fitting the concentration data, the parameters involved are activation energy, acceptor concentration, and effective mass. The variation of activation energy with concentration does not agree with that observed by Pearson and Bardeen for p-type silicon. The ratio of Hall to drift mobility is shown to agree with the theoretically predicated value within about 10 percent in the range 78°K to 300°K.

P. Dew-Hughes, A. H. Jones and G. E. Brock D6

Improved Automatic Four-Point Resistivity Probe

Review of Scientific Instruments, vol. 30, p. 920, October, 1959

A continuously recording automatic four-point resistivity probe is described. This instrument is the most rapid and convenient means for determining the resistivity profile, and hence the distribution of net extrinsic conduction centers along the length of a polycrystalline bar or single crystal of semiconductor material. It is the only method available for determining the quality of such material within a very short time of its preparation, and thus is important as a quality-control tool in any semiconductor crystal-growing operation. It is severely limited by three factors: (1) it is only a surface measurement, (2) it gives no information about the degree of compensation existing in the material, and (3) it cannot detect the presence of electrically inactive impurities. When combined with more complete characterization of samples cut from a few discrete points along the crystal, it is invaluable as a means of interpolation between these discrete points.

D. H. Dickey D7

Diffusion Profile Studies Using a Spreading Resistance Probe

The Electrochemical Society Meeting, Pittsburgh, April, 1963, Extended Abstracts of Electronics Division, vol. 12, no. 1, p. 151

Measurement of the spreading resistance from a pair of small-area pressure contacts has been used to determine resistivity profiles in diffused silicon structures. The technique is used on an angle-lapped specimen and depends on the small sampling volume of the spreading resistance measurement to obtain local resistivity. The method can be used to determine diffusion coefficients and surface concentrations with great ease and rapidity, even on multiply-diffused structures.

J. A. M. Dickhoff D8

Cross-Sectional Resistivity Variations in Germanium Single Crystals

Solid-State Electronics, vol. 1, p. 202, July, 1960

Germanium single crystals frequently show considerable cross-sectional resistivity variations. The dependence of these variations upon crystal orientation as well as upon the shape of the solid-liquid interface during crystal growth has been investigated. It appears that a direct relationship exists between the crystal orientation, the shape of the growth interface and the occurrence of persistent cross-sectional resistivity variations. The origin of these variations is closely related to the presence of a flat facet on the otherwise curved growth interface, which facet coincides with a [111] plane. The segregation constants of several impurities appear to be different for the flat part and for the curved part of the growth interface, thus causing cross-sectional variations of the impurity concentration. Methods for preventing these variations are discussed.

B. Donovan and N. H. March D9

High Frequency Conductivity in Semiconductors

The Proceedings of the Physical Society, vol. 69, sec. B, p. 528, May, 1956

The theory of the electrical conductivity in alternating fields is developed for non-degenerate semiconductors with spherical energy surfaces. As in the Drude-Zener theory, the conductivity is a complex quantity and the real and imaginary parts are derived as functions of frequency and of temperature.

The cases of lattice scattering and impurity scattering are investigated separately for single-band models and the results are applied to intrinsic semiconductors by combining the scattering mechanisms. The loss tangent is also calculated and a comparison is made with the available experimental data.

T. M. Donovan and B. O. Seraphin D10

Undamaged Germanium Surfaces of High Optical Quality

Journal of the Electrochemical Society, vol. 109, p. 877, September, 1962

A modification of Sullivan's technique is described which yields surfaces of about 0.1 μ/in. flatness and a rms roughness of only 10-13 Å, approaching the finish of the best fused quartz optical flats. At the same time it shows by means of electron diffraction, surface recombination velocity, and field-effect measurements that these surfaces approach structurally and electrically surfaces that had been etched in CP-4.

V. A. Dorin and M. M. Kozlov D11

Probe of Silicon Carbide for Testing Semiconductor Materials (In Russian)

Zavodskaya Laboratoriya, vol. 30, p. 206, February, 1964

Silicon carbide is claimed to be more effective than tungsten or steel as a probe for measurement of p-type and n-type semiconductors. The probe has a specific resistance of 10 ohm centimeters and leaves a track of approximately 1.5 microns in width. Contact resistance is 10^9ohms. In measuring with an automatic autorecording electrometer with an input resistance of 10^{13}ohms, no distortions of magnitude have been observed in the difference of potentials.

R. Dreiner and R. Garnache D12

Precision Orientation of Germanium Crystals in the [111] Direction Using Alloy Pits

Journal of Applied Physics, vol. 33, p. 888, March, 1962

A method is described for orienting germanium crystals in the [111] direction with an accuracy within six minutes of arc. N-type germanium is alloyed by liquid indium. The indium is then etched off and the resulting alloy pits are inspected by means of interference fringes. The information obtained from these pictures is used to determine the orientation with the accuracy noted above. An alternate method is described using information obtained from delineated p-n junctions on two angle-lapped bevels.

J. J. Duga, J. J. Freundlich and R. T. Bate D13

Automatic Data Recording System for Semiconductor Research

Review of Scientific Instruments, vol. 33, p. 365, March, 1962

A completely programmable automatic data recording system has been constructed and is described in detail. Being originally designed for the measurement of the resistivity and Hall coefficient of semiconductors as functions of temperature, the system features: (1) a 100-step temperature detector to initiate a measurement cycle at a preselected temperature; (2) a 100-step input selector which can choose from up to 17 different voltages in a preprogrammed sequence and, in addition, can control environmental conditions; (3) a high-precision voltage amplifying and measuring system; and (4) an output selector containing appropriate binary-code translation circuitry and a combination typewriter-tape punch. The data are typed and simultaneously punched on tape in a desired format, and the tape information is converted to cards for data processing by a digital computer. The operation of each sub-system is described, and the over-all versatility is demonstrated by several different types of applications.

J. J. Duga, R. K. Willardson and A. C. Beer D14

Resistivity, Mobility and Carrier Concentration Determinations

Battelle Memorial Institute, Scientific Report No. 1, Contract No. AF 19(604)-1852, April, 1957 (AD 117071)

Studies of the more common methods of measuring the electrical properties (ρ, μ_H, and R_H) of semiconductors were carried out, and appropriate modifications were made on those which appeared to be most feasible and applicable for obtaining profile measurements along single-scrystal specimens of silicon.

For the measurement of resistivity, electroforming and plating techniques were used in conjunction with standard two- and four-probe methods to overcome difficulties arising from rectifying contacts and surface oxides. The profiling of the Hall mobility was accomplished by the use of four probes arranged in a diamond array, using methods similar to those adopted for the resistivity probes to eliminate contacting difficulties. Other methods of determining resistivity are evaluated. Performance graphs indicate the degree of reliability of the methods and numerous drawings and photographs provide details of the design and construction of the apparatus.

G. Dumas and C. Georges D15

Phenomena of Compensation in Silicon Single Crystals (In French)

Solid State Physics in Electronics and Telecommunications, vol. 1, p. 251, Academic Press, Inc., New York, N.Y., 1960

The metallurgists who have developed the fabrication of single crystal silicon drawn from a melt by the Czochralski method are familiar with the phenomena of impurity compensation. The purest commercially available silicon commonly used thus far contains several residual impurities. The electrically active impurities detectible through resistivity measurements at ordinary temperatures are mainly: a p-type impurity, boron, removed only with great difficulty and reintroduced during pulling by contamination from the crucible; and n-type impurities usually in very small amounts, principally phosphorous. Boron-antimony compensation is discussed. Resistivity and lifetime measurements on compensated crystals are presented.

W. C. Dunlap, Jr. D16

Conductivity Measurements on Solids

Methods of Experimental Physics - Solid State Physics, K. Lark-Horovitz and V. A. Johnson, eds., vol. 6, pt. B, p. 32, ch. 7.2, Academic Press, Inc., New York, N.Y., 1959

Methods of obtaining conductivity data on metals, semiconductors, and insulators are described. Factors affecting the suitability of various methods and the precision attainable include contact resistance and form of sample, i.e., whether in the form of single crystal, film, powder, or small crystallite. Effects of such factors as surface conducting or insulating layers, various atmospheres, and other perturbing factors are also discussed.

I. M. Dykman and P. M. Tomchuk D17

Effect of Electric Field on the Temperature of Electrons, Electrical Conductivity, and Thermionic Emission of Semiconductors.1- Atomic Semiconductors, Development of the Method

Soviet Physics - Solid State, vol. 2, p. 1988, March, 1961

By solving the kinetic equation, the distribution function of electrons in atomic semiconductors in the presence of electric field has been found. The interaction between the electrons, acoustic phonons, and impurity centers has been taken into account, as well as the interaction between electrons due to Coulomb forces. It was shown that under certain conditions the interactions between electrons approximately follows the Maxwell distribution, with an effective temperature T, different from the temperature T_o of the lattice, the values of conduction current and T have been calculated as functions of the intensity of the electric field and of the parameters of the semiconductor. Since T can be considerably higher than T_o, this difference has a particularly strong effect on the intensity of thermionic emission. The solution obtained is also applied to the determination of the distribution function and electronic current in plasma.

I. M. Dykman and P. M. Tomchuk D18

Influence of an Electric Field on Electron Temperature, Electrical Conductivity and Thermionic Emission in Semiconductors. III - Thermionic Emission

Soviet Physics - Solid State, vol. 3, p. 464, July, 1961

We have determined the spherically symmetrical part of the fast conduction electron distribution function in a semiconductor in the presence of an electric field. We have established criteria for the field which causes perceptible electron gas heating and calculated the thermionic current,I. Two limiting cases are considered: 1) when the impact ionization has practically no influence on I, and 2) when the impact ionization is essential. In the first case the distribution function of fast electrons (essential for thermionic emission) appears to be approximately Maxwellian with respect to electron temperature equal to the lattice temperature T_0. In this case the dependence of I on T_0, and the energy distribution of thermal electrons is similar to the corresponding characteristic of the equilibrium thermionic emission, but the magnitude of I may exceed the equilibrium thermionic emission current by several orders of magnitude. In the second case the fast electron distribution function is, generally speaking, different from Maxwellian. Under certain definite conditions however, this distribution function can approach the Maxwellian type with electron temperature greater than T_0 but less than T.

I. M. Dykman and P. M. Tomchuk D19

Influence of Electric Field on Electron Temperature, Electrical Conductivity, and Thermionic Emission of Semiconductors. IV - Low Lattice Temperatures

Soviet Physics - Solid State, vol. 3, p. 1393, January, 1962

The method developed in [I] is extended to the case of low lattice temperatures. It is shown that in the region of impurity scattering the electron-electron interactions substantially influence not only the symmetric but also the asymmetric part of the scattering function. More general formulas are obtained for the determination of electron temperature and conduction current by taking into account the above mentioned variation of the asymmetric part of the distribution function.

G. Eckhardt and S. R. Lederhandler E1

Determination of Dislocation Densities in Silicon Crystals by an Optical Method

Solid State Design, vol. 3, p. 27, May, 1962

If a crystalline material plastically deforms because of an external force, upon removal of that force, a frozen-in stress will exist in the interior of the material. Stresses of this type have been studied principally by x-ray diffraction techniques. Another method for the investigation of stress utilizing the photoelastic patterns gives a direct picture of the magnitude, direction, and distribution of internal stress.

D. F. Edwards and P. D. Maker E2

Qualitative Measurement of Semiconductor Homogeneity from Plasma Edge

Journal of Applied Physics, vol. 33, p. 2466, August, 1962

The carrier concentration homogeneity in a semiconductor can be quantitatively measured from the position of the plasma edge. This has been demonstrated for an InAs sample for which changes of homogeneity of about 0.5% have been measured. This plasma edge method for measuring carrier concentration inhomogeneities is at least an order of magnitude more sensitive than other methods reported to date and can be applied for any semiconductor that has a well-defined plasma edge.

J. W. Edwards E3

The Orientation of Cubic Semiconductor Crystals by X-Ray and Optical Means - Pt. 1 X-Ray Method for Orienting Semiconductor Crystals of Cubic Habit

Semiconductor Products, vol. 6, p. 30, May, 1963

This method covers the back-reflection Laue procedure for orienting silicon, germanium, gallium phosphide, gallium arsenide, indium antimonide, indium arsenide, cadmium selenide, or other cubic crystals in the various crystallographic directions, for the purpose of preparing slices or specimens of known orientation. The method is applicable to monocrystalline grains of unknown orientation situated in a matrix or to single crystal ingots from boat, Czochralski, float zone, or other processes.

J. W. Edwards E4

The Orientation of Cubic Semiconductor Crystals by X-Ray and Optical Means - pt. 2 Optical Method for Orienting III-V Compound Crystals

Semiconductor Products, vol. 6, p. 34, June, 1963

This method is used for determining the orientation of III-V crystals and orienting crystals in various <hkl> directions for slicing. As described herein, the method is generally applicable to cubic crystals which cleave on {110} class of planes and can be used for single crystals grown with known or random orientation, and for monocrystalline grains about one-eighth inch across, or greater, at the surface of a polycrystalline matrix.

Gallium arsenide and other III-V compounds have {110} cleavage planes. Roughening the surface of crystals of these compounds exposes numerous {110} facets which are symmetrically disposed around certain crystallographic directions. Reflection of a parallel beam of light from the roughened surface and adjustment of the crystal position to give certain symmetrical light patterns locate the crystal axes.

W. D. Edwards E5

Interactions between Oxygen and Aluminum in Germanium

Journal of Applied Physics, vol. 34, p. 2497, August, 1963

This note discusses the reaction of oxygen with aluminum in germanium and the resulting effects on the electrical properties of the germanium. Addition of oxygen to the ambient atmosphere during crystal growth was observed to neutralize the acceptor action of aluminum, or to provide donor action depending on oxygen concentration. Reactions of aluminum and oxygen in the host germanium melt form electrically inactive complexes. Preliminary experiments show no significant reactions of this type involving oxygen with antimony, indium, boron or bismuth. In silicon, oxygen apparently does not react significantly in the melt or in the solid during growth, but subsequent heat treatment of silicon crystals containing aluminum and oxygen produce complexes with donor properties, unlike the case for germanium.

R. L. Eisner E6

The Contact Resistance of Electroless Nickel Plating on Phosphorus-Doped Silicon

The Electrochemical Society, Inc., Fall Meeting - New York, N.Y., Extended Abstracts of Electronics Division, vol. 12, p. 114, September-October, 1963

Although there is extensive literature available on plating of metals onto silicon, there is very little information available on the contact resistance between the plating and the substrate. It is quite conceivable that this resistance might not be zero because of the likelihood of various components of the plating solution remaining on the interface between the silicon and the plated metal. The results of electroless nickel plating on silicon wafers with very thin highly doped surface layers, where the contact resistance was measured by successively lapping and plating, show that the contact resistance can be as high as 30 milliohms. Thus the present process can not be recommended for high current devices.

A. Ertel E7

Method of Evaluating Silicon Monocrystals for the Fabrication of Diffused Junction Devices

Journal of the Electrochemical Society, vol. 107, p. 190C(A), August, 1960

During the manufacture of silicon-diffused junction devices, such as rectifiers and zener voltage regulators, changes in resistivity during high-temperature diffusion operations along with initial crystal imperfections may result in devices having reverse voltage characteristics other than those desired. A method of predetermining the quality of devices which may be expected from a given monocrystal is described. Characterization is made immediately after diffusion and prior to device fabrication. Some typical evaluations are described and discussed in detail.

I. Falkvik F1

Method of Measuring the Dielectric Constant at Microwave Frequencies by Means of the Perturbation Method

Proceedings of the Institute of Electrical and Electronics Engineers, vol. 52, p. 203, February, 1964

This communication describes a possibility of measuring the dielectric constant and the corresponding losses of a material. The formulas give expressions for the frequency shift and the change of the Q-factor, which are both easily determined by measurements. The shape treated is the sphere, but if rods are used, the formulas are quite similar. The sample is put in a position where the magnetic fields are zero.

E. Fischer F2

An Instrument for Determining the Conductivity and the Type of Conduction in Semiconductors

Proceedings of the Second International Measurement Conference, Budapest, 1961 Hungarian Scientific Society of Measurement and Automation, Budapest, 1961

A two-point thermoelectric probe system is used for determining conductivity type. The specific conductivity is measured by a four-point probe system. Various forms of construction are considered, in each of which two of the points are rigidly joined while the other two are free to move with respect to the first pair. The effect of the construction on probe spacing errors is discussed, and an automatic system for probe measurements along the length of a semiconductor rod is described.

G. Fischer, D. Greig and E. Mooser F3

Apparatus for the Measurement of Galvanomagnetic Effects in High-Resistance Semiconductors

Review of Scientific Instruments, vol. 32, p. 842, July, 1961

An apparatus for the measurement of galvanomagnetic effects in high-resistance semiconductors is described. The apparatus allows the resistivities of samples to be measured whose resistances fall within the range 10^1 to $10^{12}\Omega$. The Hall coefficients of these samples can also be determined with the apparatus as long as the charge carrier mobilities of the samples exceed 1 cm^2/v sec. A discussion is given of the fundamental limitations of Hall coefficient measuring equipment.

V. I. Fistul' and A. Ya. Gubenko F4

The Specific Resistance of High-Alloy Germanium

Soviet Physics - Solid State, vol. 3, p. 1173, November, 1961

An analysis of Hall measurements to determine the dependence of specific resistance on impurity concentration n leads to the following empirical formula for monocrystalline germanium doped with arsenic (n-type):

$$\rho_n = 4.3 \times 10^8 n^{-0.6} .$$

Data are presented for

$$10^{18} cm^{-3} < n < 5 \times 10^{19} cm^{-3} .$$

From other work, an expression for p-type germanium is found:

$$\rho_p = 8.15 \times 10^9 n^{-0.66}$$

These are in disagreement with Johnson and Lark-Horowitz (1947). The formulas are stated to be applicable for $n \geq 4 \times 10^{16} cm^{-3}$.

V. I. Fistul' and E. M. Omel'yanovskii F5

Electrical Conductivity of Germanium Heavily Alloyed with Phosphorus

Soviet Physics-Solid State, vol. 4, p. 1007, November, 1962

In heavily alloyed germanium the relation between electrical conductivity and electron concentration depends substantially on the nature of the alloying admixture. Thus a difference in conductivity was observed between crystals of germanium alloyed with arsenic and antimony, respectively. This result was confirmed. The dependence of conductivity on electron concentration, n, in germanium alloyed with phosphorus, proved to coincide with the same dependence for germanium with arsenic. On the other hand, a difference in conductivity between germanium alloyed with arsenic and phosphorus, respectively, at $n > 10^{19}$ cm^{-3} was observed.

This contradiction impelled us to conduct a thorough investigation of the conductivity of germanium with phosphorus admixture and to compare the results obtained with the conductivity of germanium containing arsenic, which we studied earlier.

R. Fivaz F6

Universal Instrument for the Measurement of the Galvanomagnetic Effects in Semiconductors (In French)

Helvetica Physica Acta, vol. 36, p. 1052, December, 1963

The apparatus can be used for the determination of the electrical conductivity and Hall coefficient on samples having a very wide range of resistance. Resistances as low as 10^{-3} ohm and as high as 10^{12} ohm can be measured. The sensitivity of the Hall measurement is such that mobilities of the order of 0.1 cm^2/V sec can be estimated using a magnetic field of no more than 10^4Oe. For low-resistance measurements a direct-current chopper is employed. For high-resistance samples a double electrometer, which acts as an impedance-matching device, is also incorporated. Results obtained from experiments on the temperature variation of the resistivity and Hall coefficient of GaSe are given.

J. M. Flores F7

Simple Technique for Making an Electric Contact on Silicon

Review of Scientific Instruments, vol. 35, p. 112, January, 1964

A method is described for making ohmic contacts on high resistivity silicon which does not require heating the whole crystal to be studied. By sparking on the silicon surface with two electrodes of Al (for p-type silicon) or Au-Sb (for n-type silicon), contacts have been obtained which were useful at temperatures as low as liquid nitrogen.

H. Frank F8

A Four-Electrode Probe with Mercury Contacts for Determining the Resistivity of Silicon (In Russian)

Czechoslovak Journal of Physics, vol. 9, p. 524, April, 1959

A description is given of the measuring equipment for determining the resistivity of silicon plates by the four-electrode method. A novelty is the use of a measuring probe with mercury contacts which have linear characteristics and a low resistance after previous formation by a capacitor discharge. The equipment is also suitable for measuring other semiconductors, such as germanium, etc.

H. Frank F9

Determination of Resistivity of Very Pure Polycrystalline Silicon (In Czeckoslavakian)

Czechoslovak Journal of Physics (Czech. Ed.) vol. 9, p. 263, September, 1959

The frequency dependence of the real component of the impedance was measured on a sample of compact polycrystalline silicon, prepared by thermal decomposition of silanes. A physical model of polycrystalline silicon was proposed and an equivalent circuit was found which corresponds to the measured frequency dependence. Measurement of the temperature dependence of the conductivity at 30 MHz confirmed the intrinsic character of the material. Since the effective mobility of the current carriers in polycrystalline material was not known the lower limit for the resistivity could only be estimated, the value of which is very probably over 1000 ohm-cm.

R. C. Frank F10

Gases in Solids

International Science and Technology, vol. 1, p. 53, September, 1962

The most well-known effect is that of oxygen on the resistivity of silicon. It was found that when silicon single crystals were grown from the melt in fused silica crucibles, the crystals became contaminated with oxygen from the fused silica. The oxygen-contaminated crystals were largely p-type but upon heat treatment between 300°C and 700°C often became converted to n-type. The resistivity of the very pure silicon crystals grown by the crucibleless floating-zone method is often of the order of 100 ohm-cm, while the oxygen-contaminated silicon varies from a few ohm-cm to 300 ohm-cm.

A. H. Frei and M. J. O. Strutt F11

Skin Effect in Semiconductors

Proceedings of the Institute of Radio Engineers, vol. 48, p. 1272, July, 1960

The theory of skin effect in semiconductor materials including the effect of displacement currents is discussed. In the case of flat plates, formulas are derived for the field distribution, the impedance and the eddy-current power losses, considering symmetrical electric as well as magnetic fields. Impedance as a function of frequency is measured for germanium in the microwave cm-range. The measured values agree with the theoretical results. The equivalent depth of penetration is calculated and compared with the skin depth for metals. All theoretical results are represented in graphs for different values of the ratio Y, i.e., the displacement current divided by the conduction current. The formulas are extended to the case of complex permeability, corresponding to hysteresis.

H. Fritzsche F12

Effect of Uniaxial Compression on Impurity Conduction in N-Type Germanium

Physical Review, vol. 125, p. 1552, March 1, 1962

Results are given of resistivity measurements on Sb-, As-, or P-doped Ge at temperatures between 1.3°K and 300°K under stresses ranging from 2×10^7 to 2×10^9 dynes/cm^2.

H. Fritzsche and M. Cuevas F13

Impurity Conduction in Transmutation-Doped P-Type Germanium

Physical Review, vol. 119, p. 1238, August 15, 1960

The Hall coefficient and resistivity of germanium single crystals bombarded with slow neutrons were measured between 1.2°K and 300°K. Slow neutron capture and subsequent nuclear transmutation produce majority impurities, gallium atoms, and compensating impurities, arsenic and selenium atoms. P-type samples with gallium concentration ranging from 8×10^{14} to 5×10^7 per cc with a fixed compensation ratio of 0.40 were thus prepared and the impurity conduction was studied as a function of the average distance between the majority impurities. The effective radius a of the acceptor ground-state wave function is 90.1 Å according to Miller's theory of impurity conduction, whereas a = 40 Å according to Twose's theory. The latter value agrees well with the effective radius of the Kohn-Schecter acceptor wave function. The activation energy of impurity conduction changes slowly with impurity concentration from 3.5×10^{-4} to 5.9×10^{-4} ev and agrees well with the predictions of Miller's theory for gallium concentration below 5×10^{15} per cc. Measurements on samples which contain different dislocation densities but identical impurity concentrations show that up to 10^4 dislocations per cm^2 do not affect impurity conduction.

C. S. Fuller and R. A. Logan F14

Effect of Heat Treatment upon the Electrical Properties of Silicon Crystals

Journal of Applied Physics, vol. 28, p. 1427, December, 1957

Studies have been made of the process in which donors are introduced into silicon by heating in the temperature range 300°C - 500°C and are caused to disappear on heating at higher temperature. This phenomenon is shown to depend on the conditions of growth and the heat-treatment history of the crystal. Evidence is summarized which shows that oxygen is the impurity from which the donors are formed. The characteristics of the processes involved are described and possible mechanisms are discussed.

J. K. Furdyna and S. Broersma F15

Microwave Faraday Effect in Silicon and Germanium

Physical Review, vol. 120, p. 1995, December 15, 1960

The Faraday rotation and ellipticity in a system of quasifree carriers is discussed and applied to microwave measurements on semiconductors. The theoretical expressions for these effects are analyzed with a digital computer for various ranges of the magnetic field B, the mobility μ, the conductivity σ, the frequency ω, the collision time τ and the dielectric constant of the host material ϵ_{st}. It is possible to simplify these expressions in certain limiting cases. For μB smaller than unity, the rotation and ellipticity are proportional to B. For μB larger than both unity and $\omega\tau$, they decrease as B^{-1} and B^{-3}, respectively. A maximum occurs near $\mu B = 1$ when $\omega\tau$ is small.

Rotation measurements on n- and p-type single crystals of silicon at room temperature, with resistivities from 0.5 to 40 ohm-cm, utilizing 9.6- and 35-kMc/sec radiation, are compared with the theory. Results for n-type germanium at 78°K, with μB varied up to about 6, agree with the calculated low- and high-field behavior. Faraday ellipticity measurements on n-type germanium crystals at 78°K are in qualitative agreement with the theory. In the case of small losses, the sign of the ellipticity is determined by the sign of the quantity $(4\omega\tau-\sigma/\omega\epsilon_{st})$.

Y. Furukawa F16

Electrical Properties of Heavily Doped N-Type Germanium

Journal of the Physical Society of Japan, vol. 16, p. 687, April, 1961

Experimental studies were made on electrical resistivity, Hall coefficient and magnetoresistance of As- Sb- and (AS + Sb)-doped germanium in the electron concentration range of $(10^{18}\sim3\times10^{19}cm^{-3})$. The mobility difference between As- and Sb-doped germanium has been observed at room temperature. The difference seems to be related with the difference in the ionization energy of group V elements. From the present experiment, it has been concluded that in heavily doped germanium, interaction between electron and ionized impurity should be treated as short range force instead of Coulomb force owing to the fairly large screening effect, and as the result the nature of the core of impurity influences directly upon the impurity scattering.

E. E. Gardner, J. F. Hallenback, Jr. and P. A. Schumann, Jr. G1

Comparison of Resistivity Measurement Techniques on Epitaxial Silicon

Solid-State Electronics, vol. 6, p. 311, May-June, 1963

Two methods, a three-point breakdown method and a two-point constriction-resistance method, have recently been proposed for direct measurements on epitaxial silicon. The advantages and disadvantages of each method are presented here.

W. W. Gärtner G2

Temperature Dependence of Carrier Densities, Mobilities, Diffusion Constants and Conductivities in Germanium and Silicon

Semiconductor Products, vol. 3, p. 29, July, 1960

Carrier densities, mobilities, diffusion constants and conductivities are important design parameters in all semiconductor devices of the conventional and the micro-electronic type. The temperature dependences of the material properties determine the temperature sensitivity of the final devices. The computation of these dependences is therefore necessary in most design work to minimize the temperature variations in the electrical characteristics. As an aid in these time-consuming computations and for rapid estimates the seven graphs in this article show the above-mentioned properties for impurity concentrations usually encountered in semiconductor devices and over the temperature range usually encountered in device operation.

Gy. Gergely and O. Hantay G3

On the Measurement of Cross-Sectional Resistivity Variation on Semiconductor Crystals

Solid-State Electronics, vol. 5, p. 416, November-December, 1962

In this paper a simple, accurate method is described for determining the radial distribution of resistivity on slices of rotation symmetrical crystals, layers and diffused sheets. Two ohmic contacts are prepared on a thin round slice of silicon or germanium crystal. A small area contact (<0.5 mm) is applied in the center and the periphery surface of the crystal is plated with some suitable metal using masking techniques. Direct current is passed through the contacts. Using this arrangement, the distributions of current and potential are rotation-symmetrical and the radial variation of potential can be precisely determined by moving the point probes.

W. E. K. Gibbs G4

Anisotropy in the Conductivity of Hot Holes in Germanium

Journal of Applied Physics, vol. 33, p. 3369, November, 1962

The anisotropy in the conductivity of p-type germanium at fields of up to 3 kV/cm has been measured at lattice temperatures of 77°K and 21°K for specimens with impurity concentrations from $3.0 \times 10^{14} cm^{-3}$ to $3.2 \times 10^{15} cm^{-3}$. The electric field vector was found to deviate from the current vector toward the [111] direction for specimens in the (111) plane, and this behavior is opposite to that previously published by Sasaki et al. The anisotropy decreased with increased impurity concentration and the reduction of temperature from 77°K to 21°K shifted the anisotropy-electric field curve to lower fields.

A. F. Gibson and E. G. S. Paige G5

An Interpretation of Certain Transport Properties in Germanium Containing Parallel Arrays of Edge Dislocations

Philosophical Magazine, ser. 8, vol. 3, p. 950, September, 1958

An interpretation is given of the anisotropic effects observed by Arthur et al. (1958) in germanium containing parallel arrays of edge dislocations. The anisotropy of the diffusion constant and high field mobility in n-type crystals is considered quantitatively. The diameter of the space-charge cylinder surrounding the dislocations (1.6×10^{-4} cm) and the fraction of time an injected hole spends within the space-charge region (1/2) is deduced from the analysis.

R. Glang and W. B. Easton G6

Donor Concentration at the Surface of a Diffused N-Type Layer of P-Type Germanium

Journal of the Electrochemical Society, vol. 107, p. 758, September, 1960

Four methods of evaluating the donor concentration at the surface of a diffused n-type layer on p-type germanium have been investigated. All methods assumed a complementary error function (erfc) distribution in the diffused layer. The methods required the use of experimental data for junction depth and sheet resistivity, and of various published data for germanium. The methods were applied to calculate the donor concentrations at the surfaces of diffused samples. Under conditions which were expected to result in an erfc impurity distribution, the actual concentration profile in the vicinity of the junction deviated from the erfc law. Due to this deviation, one of the methods of calculating the surface concentration was ruled out. With the other three methods, calculated surface concentrations agreed within a factor of 2 or 3. The disagreement is mainly caused by lack of precise information with respect to the electron mobilities in the diffused layer. Therefore, all the methods represent approximations only.

V. M. Glazov and S. N. Chizhevskaya G7

Investigation of the Electrical Conductivity of Germanium and A^{III} Sb Compounds in the Melting Region and the Liquid State

Soviet Physics - Solid State, vol. 3, p. 1964, March, 1962

In this work the temperature dependence of electrical conductivity of Ge, AlSb, GaSb, and InSb was investigated in the melting region and the liquid state. An increase in the electrical conductivity of these substances was noted in a narrow temperature interval after melting, which was due to the gradual dissolution of rigid directed bonds.

The investigated compounds and Ge display qualitative similarity in the change of their properties on melting and may be included in a single group within which complete analogy is observed in the structure and character of the chemical bond both in the solid and liquid states.

A. Goetzberger, B. McDonald, R. H. Haitz and R. M. Scarlett G8

Avalanche Effects in Silicon P-N Junctions. II. Structurally Perfect Junctions

Journal of Applied Physics, vol. 34, p. 1591, June, 1963

The fabrication of a planar guard ring diode which exhibits uniform microplasma-free breakdown is described. Discrepancies are discussed between the behavior of these junctions and those reported by Batdorf et al. and Chynoweth, including results showing extremely hard V-I characteristics associated with uniform avalanche breakdown. Experimental evidence is presented which confirms Shockley's theory in which the breakdown behavior is predicted from the Poisson distribution of impurities within the space-charge layer. The photomultiplication technique as described in Paper I (Haitz, et al.) is applied to uniform p-n junctions. The linearity of 1/M vs. V, as predicted by theory, was verified for values of M between 1.6 and 500. For higher values, the multiplication curves deviate from a straight line. In this higher range they are in good agreement with the pulse-multiplication model developed in Paper I. Light emission patterns from these junctions are shown and a correlation between these patterns and crystal properties is discussed. The effects of resistivity striations in the silicon single crystals is shown to have a strong effect on breakdown areas and no effects of dislocations and oxygen on uniformity are found.

J. Goorissen, F. Karstensen and B. Okkerse G9

Growing Single Crystals with Constant Resistivity by Floating Crucible Technique.

Solid State Physics in Electronics and Telecommunications, vol. 1, pt. 1, p. 23, Academic Press, Inc., New York, N.Y., 1960

A method is described which makes it possible to grow single crystals of germanium with a constant impurity concentration along the crystal axis. The equipment consists of an ordinary vertical crystal puller. The graphite crucible has a special shape.

N. Ya. Gorid'ko, P. P. Kuz'menko, and N. N. Novikov G10

The Change of Mechanical Properties of Germanium with Changing Concentration of Current Carriers

Soviet Physics - Solid State, vol. 3, p. 2652, June, 1962

In this work, the change in microhardness of a surface layer of germanium was studied as the concentration of free current carriers was varied. The concentration of current carriers was changed by varying the illumination of the germanium surface and by introducing minority carriers by injection from a point contact. On the basis of data available in the literature, a possible explanation is given for the mechanism of the change in toughness properties of germanium with change of the number of free carriers.

An effect also detected was a change of the surface properties of germanium which has been exposed to light for a long time. This is probably caused by a regrouping of dislocations in the specimen during the time of illumination.

Yu. I. Gorkun G11

Concerning the Effect of Current Electrodes on the Resistivity Change in a Magnetic Field

Soviet Physics - Solid State, vol. 3, p. 173, July, 1961

The dependence of the resistivity change in a magnetic field on the geometrical size of a specimen and the arrangement of probes is discussed, taking into account the short-circuiting effect of current electrodes.

A. J. Goss and R. E. Adlington G12

The Effect of Seed Rotation on Silicon Crystals

Solid State Physics in Electronics and Telecommunications, vol. 1, pt. 1, p. 28, Academic Press Inc., New York, N.Y., 1960

The rotation of the seed and crystal, which is normally employed during crystal pulling, is dealt with in detail in this paper.

B. R. Gossick G13

The Dipole Mode of Minority Carrier Diffusion, with Reference to Disordered Regions Induced in Semiconductors by Pile Irradiation

Proceedings of the International Conference on Semiconductor Physics, Prague, Czechoslovakia, 1960, p. 302, Publishing House of the Czechoslovak Academy of Sciences, Prague, Czechoslovakia, 1961; distributed in the Western Hemisphere by Academic Press, Inc., New York, N. Y.

This paper deals with electrical conductivity by minority carriers, including field and frequency dependence, as well as current density and Hall coefficient for both carriers, in semiconductors containing disordered regions.

H. G. Gould G14

Determining P- and N-Type Conduction in Very Small Crystals

Review of Scientific Instruments, vol. 33, p. 1471, December, 1962

The hot-point probe has long been used to permit the rapid identification of the majority carrier in semiconducting elements and compounds. In the usual arrangement, two tungsten needles, one of which is heated, touch the semiconductor and are connected to a galvanometer. The semiconductor surface thus forms both hot and cold thermocouple junctions. Interpretation of the conductivity type rests upon the sign of the thermal emf generated. If the cold junction becomes negative, the material is n-type. P-type material will be negative at the hot junction. The usefulness of hot-point probing is limited when applied to large bandgap, high-resistivity crystals because of the tendency of the probes to form point-contact rectifiers.

By using liquid gallium or liquid mercury, ohmic contacts can be made to a crystal. Two pools of gallium are bridged by the crystal and the probe is put into the liquid metal.

C. Grandjean G15

Study of Germanium by Transparency in Infrared Light; Double Refraction of Silicon and Germanium

Philips Research Reports, vol. 16, p. 343, August, 1961

This paper begins with the description of the apparatus used, which is essentially a Nipkov disk and a lead-sulphide cell, capable of low-definition examination of silicon and germanium in linearly or circularly polarized light. Subsequently, some results obtained with this apparatus on silicon and germanium are given. Finally, the principle and the results of measurements of the photo-elestic constant of silicon ($k = 1.97 \pm 0.05$) in [111] direction and germanium ($k = 0.026 \pm 0.04$) in [100] direction are defined; knowledge of these constants makes it possible to state the minimum stresses which can be detected in silicon and germanium.

J. A. Greenwood and J. B. P. Williamson G16

Electrical Conduction in Solids. II. Theory of Temperature-Dependent Conductors

Proceedings of the Royal Society of London, series A, vol. 246, p. 13, July, 1958

The experiments in part I by Bowden and Williamson on the behavior of the contact between metals when large currents pass the interface have yielded results which cannot be explained by the classical theory of constriction resistances. To provide an account of this anomalous behaviour a new mathematical treatment of the general problem of the electrical heating of conductors has been developed. This treatment gives, under the appropriate conditions, a concise derivation of all the main results of the accepted theory and it leads to three new conclusions.

The new treatment is applied to the calculation of the spatial distribution of current for a particular shape of conductor, one which is relevant to many resistance welding processes. The predictions agree accurately with experimental data obtained from the examination of a series of welds.

The theory is then applied to the special case of the electrical contact between gold pieces and shown to offer an explanation of the anomalous behaviour mentioned above. Good agreement is demonstrated between the theoretical predictions and the experimental results.

M. W. Gunn G17

The Microwave Measurement of the Complex Permittivity of Semiconductors

Proceedings of the Institute of Electrical and Electronics Engineers, vol. 52, p. 185, February, 1964

The complex permittivity of semiconductors determined for an inhomogeneously filled waveguide using a single mode approximation is compared with that obtained using the solution of the transcendental equation which completely describes the H_{10} mode in the system. Some experimental problems are also discussed. Comment is made on the work on this subject by B. R. Nag, S. K. Roy and C. K. Chatterji, Proceedings of the Institute of Electrical and Electronics Engineers, vol. 51, p. 962, June, 1963

M. W. Gunn G18

The Microwave Conductivity of Germanium

Proceedings of the Institute of Electrical and Electronics Engineers, vol. 52, p.851, July, 1964

Measurements were made of the conductivity of a germanium sample, about 0.1 $(\text{ohm-cm})^{-1}$, subjected to voltage pulses producing electric field strengths up to 3 kv/cm, using a low field microwave probing signal at 9.392 GHz. Measurements were made under two conditions: with the probing field and the pulsed field parallel and with them perpendicular. In the former case, the differential carrier mobility for the applied field controlled the conductivity, while in the latter case, the dc mobility was more applicable. This dependence on angle offers the possibility of rotating the plane of polarization of a propagating microwave field in germanium by an applied dc field.

R. H. Haitz, A. Goetzberger, R. M. Scarlett and W. Shockley H1

Avalanche Effects in Silicon P-N Junctions. I. Localized Photomultiplication Studies on Microplasmas

Journal of Applied Physics, vol. 34, p. 1581, June, 1963

An improved experimental technique is described for the investigation of carrier multiplication in very small areas, particularly microplasmas. A light spot of a few microns diameter is positioned to cover a microplasma of comparable or smaller size and the multiplied photocurrent is measured as a function of reverse voltage.

Diameters of the microplasma regions varied from less than one to more than 5μ. Multiplication factors as high at 10^6 were measured. At high multiplication ($M > 100$), a deviation from the theoretically expected linear dependence of $1/M$ vs. V is observed. This deviation, preventing accurate determination of microplasma diameters of less than 1μ, can be described by (1) the influence of the space charge of the multiplied carriers, and (2) the pulsing mechanism of the microplasma.

The pulsing effect apparently caused negative resistance in the V-I characteristic of a diode containing a microplasma. Dependence of this negative resistance on lead resistance, shunting capacity, and light intensity was investigated, and can be explained with the pulse model.

G. L. Hall H2

Ionized Impurity Scattering in Semiconductors

Journal of the Physics and Chemistry of Solids, vol. 23, p. 1147, August, 1962

Takimoto's treatment of the mobility of conduction electrons in semiconductors, of which the Conwell-Weisskopf and Brooks-Herring formulas are special cases, is extended by evaluation of a certain integral. Improved BH, CW, and Takimoto formulas are presented and the associated scattering potentials are derived. An incidental feature is that the cut-off inherent in the CW formulation is eliminated.

H. Hamer H3

A New Technique for Measuring Hall Effect Coefficient

Semiconductor Products, vol. 5, p. 35, June, 1962

A technique for measuring the Hall effect coefficient using an alternating magnetic field and constant current is described. Since the Hall voltage is alternating at the same frequency as the applied field and in phase with it, it is possible to obtain adequate rejection of stray signals. The field coil is excited directly from the ac line with a sample current obtained from a battery through a current control circuit. The sample holder contains a sense coil adjacent and parallel to the sample. The voltage induced in the sense coil is out of phase with the magnetic field and is put through a phase shifter to bring the voltage in phase with, and opposite in polarity to, the Hall voltage. An adder circuit combines the Hall voltage and a part of the sense voltage and the resultant signal is sensed by a transistorized null detector circuit. The Hall coefficient range is dependent upon the thickness of the sample and the sense coil used. An accuracy of ± 5 percent is obtainable.

E. B. Hansen H4

On the Influence of Shape and Variations in Conductivity of the Sample on Four-Point Measurements

Applied Scientific Research, Section B, vol. 8, no. 2, p. 93, 1960

The influence of the finite size of the sample and of variations in conductivity through the sample on the voltage-current ratio found by four-point measurements is investigated. Expressions for this ratio are found for samples of infinite length and with rectangular or semicircular cross section. In the first case the influence of a finite length and of an exponential variation of the conductivity along the axis of the sample is examined. A chart showing the correction factor for a bar of rectangular cross section is presented.

J. K. Hargreaves and D. Millard H5

The Accuracy of Four-Probe Resistivity Measurements on Silicon

British Journal of Applied Physics, vol. 13, p. 231, May, 1962

Causes of error in the technique are elucidated and precautions necessary for accurate results are considered.

G. G. Harman and T. Higier H6

Some Properties of Dirty Contacts on Semiconductors and Resistivity Measurements by a Two-Terminal Method

Journal of Applied Physics, vol. 33, p. 2198, July, 1962

The surface and bulk properties of semiconductors have been studied by a two-terminal method using dirty contacts. These contacts are defined as ones that are easily applied and removed and that are separated from the bulk by surface states, oxides, adhered gasses, and chemical films. The method essentially involves measuring the resistance-voltage (R-V) characteristics from the millivolt range up to about 100 V, and from these data the sample resistivity can be obtained directly. The effect of work damaging or etching the semiconductor surface can be readily evaluated. By observation of the shape of the R-V curves it is possible to separate the bulk from the surface effects, calculate the surface barrier height and thickness from tunneling equations, and determine whether the barrier is a surface film or due to metal-semiconductor contact potential difference. An application of the theory of electric field tunneling of Holm to the data of silicon carbide gives values of about 2.4 eV for the barrier height and 13 Å for the barrier width of the film on the surface. Efforts were concentrated on silicon carbide and silicon, but the techniques are applicable to all types of semiconductors.

T. C. Harman H7

Measurement of Thermoelectric Materials and Devices

Semiconductor Products, vol. 6, p. 13, September, 1963

The measurements of electrical resistivity, Seebeck coefficient, thermal conductivity and the thermoelectric figure of merit are discussed in detail. Emphasis is placed on the underlying principles rather than on a comprehensive discussion of the many experimental arrangements which are presently in use. Various experimental factors which may lead to significant measurement errors are mentioned in connection with some experimental methods which have been found useful.

N. J. Harrick H8

Semiconductor Type and Local Doping Determined Through the Use of Infrared Radiation

Solid-State Electronics, vol. 1, p. 234, July, 1960

The techniques outlined for germanium are generally most sensitive in doping ranges where standard techniques are insensitive. Semiconductor type is determined from the direction of drift of an added carrier packet, and thus the minority carrier is determined. Three methods are discussed for determination of semiconductor doping level and its homogeneity: (1) a measure of the infrared absorption of the sample gives the equilibrium carrier density from which the doping density can be computed; (2) a determination of the maximum extraction level can be used to calculate the local sample doping level and (3) since any inhomogeneities in a sample act like junctions, local injection-extraction effects occur if a current is passed through the sample, and from observation of these effects the nature of the local doping can be deduced. Approach (1) is more useful for heavily doped samples, while (2) and (3) are more useful for near-intrinsic samples. The advantages of these techniques are that sample preparation is simple, sample parameters are not masked by the surface, and information about the nature of the sample deep within the bulk can be obtained without dissecting the sample.

N. J. Harrick H9

Use of Frustrated Total Internal Reflection to Measure Film Thickness and Surface Reliefs

Journal of Applied Physics, vol. 33, p. 2774, September, 1962

When total internal reflection of light occurs, radiation penetrates beyond the reflecting surface into the rarer medium where the intensity decreases with distance from the interface in an exponential manner. Since the degree of coupling to this radiation can be controlled by adjusting the proximity of another object to this interface, it is possible to utilize this phenomenon in the measurement of film thickness and to obtain high-contrast images of surface reliefs.

W. E. Haupin H10

Electrical Analog of Multiresistivity Systems Using Single Resistivity Media and Amplifier Circuits

The Review of Scientific Instruments, vol. 35, p. 1050, August, 1964

A model is constructed from material of a single electrical conductivity. Current amplifiers, having a low insertion voltage loss, increase or decrease the current flow at boundaries representing changes in conductivity. By making the amplifier gain proportional to the required conductivity change at the boundary, the correct potential field is maintained throughout the model. This new technique overcomes the difficult chore of obtaining graded materials of accurate electrical conductivities.

P. Hedvall and J. Hägglund H11

Cavity Method for Measuring Dielectric Constants at Microwave Frequencies

Ericsson Technics (Sweden) vol. 19, no. 1, p. 89, 1963

A circularly cylindrical cavity with a dielectric sample as a central rod is used for measuring the relative dielectric constant (ε) and the dissipation factor ($tg\delta$) of the sample. Curves and tables for determining ε and $tg\delta$ from measurements of the resonant freqnency and the Q-value of the cavity are presented. These are based upon an exact calculation of the resonant frequency behaviour of the TM_{010} mode as a function of ε. The results are valid up to high ε-values in contrast to those which can be obtained from the frequently used perturbation methods.

H. K. Henisch and J. Zucker H12

Contactless Method for the Estimation of Resistivity and Lifetime of Semiconductors

Review of Scientific Instruments, vol. 27, p. 409, June, 1956

In the processing of semiconducting materials, it is often desirable to estimate the resistivity and bulk lifetime of charge carriers rapidly and without special shaping of the specimens. The device described in this note is designed to accomplish this. Resistivity is measured by determining the change in Q of a resonant circuit, the change being brought about by placing a specimen in close proximity to the test coil. Lifetime is measured by illuminating the specimen while it is near the coil and determining the losses introduced by the resulting photoconductivity.

C. Herring H13

Effect of Random Inhomogeneities on Electrical and Galvanomagnetic Measurements

Journal of Applied Physics, vol. 31, p. 1939, November, 1960

The effects of inhomogeneities on piezoelectric, galvanomagnetic, and thermoelectric measurements are treated. The scale of the inhomogeneities is supposed small compared with the dimensions of the specimen being measured, but large compared with mean free path, Debye length, etc. Formulas often roughly valid for quite sizable fluctuations, are derived for all the effects. For material which, if uniform, would show a high field saturation of transverse magnetoresistance, the presence of appreciable inhomogeneities in the Hall constant will cause the magnetoresistance to increase indefinitely with field, due to the current distortions arising from the large and fluctuating Hall fields. For an isolated inclusion, these distortions extend, at high fields, to distances in the direction of the magnetic field which are many times the diameter of the inclusion. Even the random distribution of impurities in a semiconductor can sometimes give rise to perceptible fluctuations on a scale large enough for concepts of macroscopic conduction to be applicable. The total effect of fluctuations cannot be properly treated by the present methods; however, when the macroscopic part of the fluctuations is large, conventional impurity-scattering theories must be inadequate. Applications to polycrystalline metals and semiconductors are discussed briefly.

W. Heywang and M. Zerbst H14

Properties of High-Purity Silicon

Siemens Review, vol. 25, p. 44, April, 1958

A new method has been evolved whereby heated silicon does not come into contact with any foreign material during the entire fabrication process. In this way it has been found possible to grow silicon crystals of the same high purity and lattice perfection as hitherto with germanium.

T. Higier and G.G. Harman H15

The Contact Properties of Thin Films on Semiconductors

Proceedings of the International Research Symposium on Electric Contact Phenomena, College of Technology, University of Maine, Orono, Maine, p. 31, November, 1961

It is an object of this talk to show that one can simultaneously study certain bulk and surface properties of semiconductors with dirty contacts using a simple two terminal measurement technique.

W. J. Hillegas, Jr. and G. L. Schnable H16

Plating of Metals on Semiconductors

Electrochemical Technology, vol. 1, p. 228, July-August, 1963

The science and technology of plating of metals on semiconductors are reviewed. The aspects in which plating on semiconductors differs from conventional plating technology and the mechanisms by which plating can be obtained are discussed. Reasons for plating on semiconductors, and typical applications, are summarized.

J. M. Hirshon H17

Industrial Preparedness Measure for High Purity Silicon - Final Report

Philco Corporation, Lansdale Division, Lansdale, Pennsylvania, Report No. R215.1F, Contract No. DA 36-039-SC-72768, October, 1960 (AD 256041)

A process was developed to produce ultra-high-purity single-crystal silicon having a resistivity greater than 500-ohm-cm and a minimum lifetime of 400 μsec. from silane. A summary of the electrical characteristics of the delivered material is presented.

G. Hitchcox H18

Extending the Limits of Resistance Measurement Using Electronic Techniques

Journal of the British Institution of Radio Engineers, vol. 16, p. 299, June, 1956

This paper is confined to a discussion of devices and techniques which are suitable for inclusion in commercial instruments, rather than of those which, by their complication, delicacy, or specialization, are restricted to the laboratory. It opens with a description of the basic ohm-meter in its two dual forms, refers to three low resistance systems, two using direct and one alternating test currents, and then goes on to describe what is thought to be a noval instrument which can measure very low resistance using pulsed test currents to reduce thermal dissipation in the test sample.

At the very high resistance end of the range where extension has been much greater, the three principal systems are discussed, together with the application of modern devices such as differential constant current generators, electronic stabilizers, dynamic capacitor modulators, and so on; and the paper ends with a detailed description of a widely-used general purpose commercial megohommeter.

A. Hoffmann, K. Reuschel and H. Rupprecht H19

Measurement of the Hall Effect and Conductivity of Super-Pure Silicon

Journal of the Physics and Chemistry of Solids, vol. 11, p. 284, October, 1959

With the floating-zone technique super-pure, uncompensated p-type silicon has been obtained with a resistivity above 100,000 ohm-cm. The intrinsic conductivity range of these samples is reached at temperatures as low as 40°C. The intrinsic density n_i obtained over a range from 50°C to 100°C agrees quite closely with the n_i-values determined by other investigators. The distribution coefficient k of boron is slightly below 0.9.

D. A. Holmes and D. L. Feucht H20

Microwave Measurement of Conductivity and Dielectric Constant of Semiconductors

Proceedings of the Institute of Electrical and Electronics Engineers, vol. 52, p. 100, January, 1964

Commenting on a publication of the same title by B. R. Nag, S. K. Roy and C. K. Chatterji in Proceedings of the Institute of Electrical and Electronics Engineers, vol. 51, p. 962, June, 1963 in which agreement between measurements and a theory based on dominant mode analysis is reported, the authors point out that an exact field theory solution for the reflection coefficient or VSWR would require the use of higher order modes. A variational method is presented which, applied to the situation described by Nag, et al., yields a different sign in the dominant mode propagation constant.

D. A. Holmes and D. L. Feucht H21

Excess Carrier Concentration in a Bulk Semiconductor Illuminated by a Pulse of Light

Proceedings of the Institute of Electrical and Electronics Engineers, vol. 52, p. 630, May, 1964

This paper extends the solution for transient behavior of the excess carrier density within a semiconductor due to illumination by a light pulse (presented by J. N. Bhar in "Microwave Techniques in the Study of Semiconductors", Proceedings of the Institute of Electrical and Electronics Engineers, vol. 51, p. 1623, November, 1963) to apply to three conditions not covered in the original presentation. First, the time, t, in the solution is extended to include all t from the onset of the light pulse. Second, it eliminates the assumption that the light pulse is long enough to establish a steady state excess carrier density. Finally, it considers penetration of light into the bulk of the semiconductor, with attendant carrier generation, instead of limiting the solution to surface effects.

D. A. Holmes, D. L. Feucht and H. Jacobs H22

Microwave Interaction with a Semiconductor Post

Solid-State Electronics, vol. 7, p. 267, April, 1964

A theoretical analysis and experimental results are presented for a new microwave electrodeless technique for measuring semiconductor conductivity using a circular or square semiconductor post mounted vertically in the center of a rectangular waveguide. The validity of microwave studies of recombination effects in semiconductors using this geometry is also established by showing that there is a linear relationship between transmitted microwave power and excess carrier density for small values of excess carrier density.

H. Hora H23

On the Measurement of Semiconducting and Other Electrical Properties by a Five-Probe Method (In German)

Zeitschrift für angewandte Physik (Germany), vol. 15, p. 491, June, 1963

The theory of a five-probe method for the measurement of electrical conductivity is given. Calculations of the various functions involved have been made using an IBM 1620 computer and are presented in graphical form. Comparisons are made with the standard four-probe calculations.

F. H. Horn H24

Melted-Layer Crystal Growth and Its Application to Germanium

Journal of the Electrochemical Society, vol. 105, p. 393, July, 1958

Single-crystal material of constant impurity distribution may be grown conveniently from a doped melted layer maintained above the solid retained in a crucible.

F. Horner, T. A. Taylor, R. Dunsmuir, J. Lamb and W. Jackson H25

Resonance Methods of Dielectric Measurement at Centimeter Wavelengths

Journal of the Institution of Electrical Engineers, vol. 93, part 3, p. 53, January, 1946

The paper deals with the theory and experimental development of resonator systems suitable for measurement of the permittivity and power factor of solid dielectric materials in the wavelength range below 50 cm (600 Mc/s). The relative suitability of three forms of resonator, namely a short-circuited length of coaxial transmission line operating in the principal mode, and hollow cylindrical cavity-resonators operating respectively in the E_{010} and H_{01n} modes, is discussed. The theory governing the resonant behaviour of these systems when wholly and partially filled with "lossy" dielectric is developed, leading to relations connecting the permittivity and power factor of the latter with the resonant wavelength and Q-factor respectively.

J. Hornstra and L. J. van der Pauw H26

Measurement of the Resistivity Constants of Anisotropic Conductors by Means of Plane-Parallel Discs of Arbitrary Shape

Journal of Electronics and Control, vol. 7, p. 169, August, 1959

It has been shown previously (1958) that the resistivity of an isotropic conductor can conveniently be measured by preparing a plane-parallel sample of arbitrary shape with four small contacts at arbitrary places A, B, C and D along the circumference. The resistivity follows from the values of the "resistances" $R_{AB,CD}$ and $R_{BC,DA}$ and the thickness h, using the relation previously derived. $R_{AB,CD}$ is defined as the voltage difference $u_D - u_C$ per unit current if the current enters the sample at A and leaves it at B and $R_{BC,DA}$ is similarly defined.

It is the purpose of this note to point out that the relation reported previously not only applies to isotropic conductors, but can also be used to determine the resistivity constants of anisotropic materials. Such an anisotropic material has in general, three resistivity constants ρ_1, ρ_2, ρ_3, corresponding to three orthogonal direction, the X-, Y-, and Z-axes of the resistivity tensor of the crystal.

H. Hsieh, J. M. Goldey and S. C. Brown H27

A Resonant Cavity Study of Semiconductors

Journal of Applied Physics, vol. 25, p. 302, March, 1954

A solution of Maxwell's equations is obtained in a resonant cavity with a center post of arbitrary electrical properties. The solution gives the dielectric coefficient and the conductivity of the center post in terms of the natural frequency and Q of the cavity. The theory is of particular use in the study of semiconductors where perturbation theories are of little value. It is shown that a transition from a cylindrical mode to a coaxial mode occurs as the conductivity of the center post is varied. This transition occurs for a relatively small change in conductivity. The present results are compared with those of perturbation theory, and it is shown that the latter are valid over a greater range than the conditions imposed in their derivation indicate.

V. Husa (Gusa) and B. Kvasil H28

Measurement of the Conductivity of Semiconductors in the Centimeter Wave Band (In Russian)

Radiotekhnika i Eletronika, vol. 5, p. 796, May, 1960

Theory and results for measurements of the conductivity of germanium and silicon needle shaped samples by determining Q-change of a cavity are presented.

I. Ida and Y. Arai I1

Comparison of Characteristics Between Optically and Metallographically Polished Surfaces of Semiconductor Crystals

Tokyo Electrical Communication Laboratory Review, vol. 10, p. 443, September-October, 1962

The characteristics of polished surfaces of semiconductor crystals produced by optical and metallographical polishing have been investigated by means of micro-etching, phase contrast microscopy and electron microscopy. It is concluded that micro-cutting introduces the aggregations of fine scratches on the metallographically polished surfaces. Thermal flow also plays an important part in the origination of optically polished surfaces. Moreover, the depth of the worked layers on polished surfaces including the additional depths of secondary flaws is estimated to have a value of 1-3 μ.

M. A. Il'ina and I. A. Kurova I2

The Effect of Unilateral Compression on the Electric Properties of P-Type Germanium at Low Temperatures

Journal of Experimental and Theoretical Physics (U.S.S.R), vol. 14, p. 61, January, 1962

The resistance, Hall constant, and variation of the resistance in a magnetic field were measured at temperatures from 4.2°K to 3.7°K in p-type Ge subjected to unilateral compression.

The change of the conductivity of hole type Ge caused by the pressure is due to variation of the number of carriers in the band as well as to variation of their mobility. The sign of the deformation potential has been determined from the ratio of the mobilities for various crystallographic directions.

A. F. Ioffe I3

Methods of Measuring the Basic Properties of Semiconductors

Physics of Semiconductors, Chapter 6, p. 328, Academic Press Inc., New York, N.Y., 1960

The resistances at the contacts form the main source of error in measuring the electrical conductivity σ; insufficient area of contact is mainly responsible with low-resistivity material, while barrier layers at the contacts, arising from contact potential differences, are the cause with high-resistivity material. The effect in either case may be to reduce the current flowing by a factor 10 or more, so all such contact phenomena must be eliminated. This can be done by using electrode-free methods (where the currents are induced by alternating or rotating magnetic fields) or by electrode techniques, such as the two-point probe technique.

J. C. Irvin I4

Resistivity of Bulk Silicon and of Diffused Layers in Silicon

The Bell System Technical Journal, vol. 41, p. 387, March, 1962

Measurements of resistivity and impurity concentration in heavily doped silicon are reported. These and previously published data are incorporated in a graph showing the resistivity (at T = 300°K) of n- and p-type silicon as a function of donor or acceptor concentration.

The relationship between surface concentration and average conductivity of diffused layers in silicon has been calculated for Gaussian and complementary error function distributions. The results are shown graphically. Similar calculations for subsurface layers, such as a transistor base region, are also given.

W. B. Ittner III and P. J. Magill I5

A Survey of Contact Resistance Theory for Nominally Clean Surfaces

International Business Machines Journal of Research and Development, vol. 1, p. 44, January, 1957

While the theory of electrical contact resistance is, for the most part, well known, it is difficult to apply directly to the prediction of experimental results since, in general, the theory involves microscopic parameters beyond the control of the investigator. Recent measurements of contact resistance as a function of the applied contact load, carried out under specified conditions, have yielded results which are in excellent agreement with the general theory. In contrast to a number of previous publications, however, the results indicate that the contact area is determined completely by the applied load and an effective plastic yield pressure. Under conditions where contact wipe and vibration are held to a practical minimum, the contact area can be specified in terms of a plastic yielding mechanism down to pressures as low as 0.1 gram. In this region the bulk of the contact resistance is seen to be attributable, for nominally clean contacts, to an absorbed gaseous monolayer approximately two angstroms thick.

H. Jacobs, F. A. Brand, J. Meindl, M. Benanti and R. Benjamin J1

Some Device Aspects of Multiple Microwave Reflections in Semiconductors

Institute of Radio Engineers WESCON Convention Record, vol. 4, part 3, p. 42, 1960

In considering the transmission of microwave energy through a semiconductor medium such as high-resistivity germanium, an analysis has been made of the effects of absorption and multiple reflections within the medium. The dependence of these properties on frequency, sample length and conductivity has been determined analytically and experimentally verified. Variation of the conductivity by injected carriers results in changes in power transmitted. New device possibilities appear feasible, such as amplitude modulator with little or no change in phase, a phase shifter with no change in amplitude, and other optical-electrical devices.

H. Jacobs, F. A. Brand, J. D. Meindl, M. Benanti and R. Benjamin J2

Electrodeless Measurement of Semiconductor Resistivity at Microwave Frequencies

Proceedings of the Institute of Radio Engineers, vol. 49, p. 928, May, 1961

A new microwave technique for the measurement of conductivity of semiconductors has been explored and provides agreement with more conventional methods. The proposed technique depends upon the absorption of the microwave power being propagated through a semiconductor medium. This eliminates the need for electrode attachment, making the experimental aspects of the measurement more simple. In addition, since the microwave method depends more on bulk properties, it may be less subject to error due to surface leakage or crystal imperfections in the semiconductor.

H. Jacobs, F. A. Brand, J. D. Meindl and R. Benjamin J3

Multiple Reflections of Microwaves Propagating through a Semiconductor Medium

Proceedings of the Institute of Radio Engineers, vol. 49, p. 1683, November, 1961

In considering the transmission of microwave energy through a semiconductor medium such as high-resistivity germanium or silicon, an analysis has been made of the role of absorption and multiple internal reflections in the medium. In this problem the microwave radiation is assumed to be propagated through three media: air, a semiconductor slab, and air.

H. Jacobs, F. A. Brand, J. D. Meindl and S. Weitz J4

The Interaction of Electromagnetic Radiation and Semiconductors

Proceedings of the 1962 Army Science Conference, United States Military Academy, West Point, New York, 20-22 June, 1962, vol. 1, p. 339, Army Research Office, Office of the Chief of Research and Development, Department of the Army, Washington 25, D.C., (AD 286638)

A general theory of microwave transmission and reflection in semiconductors has been formulated. New techniques for measurement of physical properties of materials have been described pertaining to resistivity, dielectric constant, lifetime, and surface recombination velocity. In addition, device possibilities from the microwave region to the far infrared regions of the frequency spectrum are suggested. A new family of devices consisting of amplitude modulators, phase modulators or combinations have been developed by controlling the geometry of the semiconductor block and injection of excess minority carriers into the medium to vary its conductivity.

H. Jacobs, F. A. Brand, J. D. Meindl, S. Weitz, R. Benjamin and D. A. Holmes J5

New Microwave Techniques in Surface Recombination and Lifetime Studies

Proceedings of the Institute of Electrical and Electronic Engineers, vol. 51, p. 581, April, 1963

A new method of measurement of recombination effects in semiconductors is described. Germanium and silicon slabs are prepared to fill the cross section of a waveguide and changes in microwave transmission as a function of conductivity of the semiconductor provide a direct measurement of lifetime. It is shown that under specific conditions of thickness of the sample a linear relationship exists between the transmitted power and the conductivity, even when the conductivity approaches the value of the product of angular frequency and permittivity. Furthermore, the new technique of lifetime measurement is simpler than previously described microwave and conventional dc methods and can be used to cover a broader range of conductivities. Experimental data are given to illustrate the principles.

A. H. Jacobson, Jr. J6

The Growing Pains of a Billion Dollar Infant

The Solid State Journal, vol. 2, p. 59, December, 1961

The semiconductor industry has grown in the last dozen years from a scientific phenomenon discovered in a laboratory to a billion dollar industry. The resulting new solid-state devices which have been developed during recent years have revolutionized electronics. Among other topics, it is pointed out that accurate and reliable methods of measuring the various characteristics of solid-state materials and devices must be developed concurrently with the extension of understanding of the theoretical, scientific principles underlying the observed performance of semiconductors. Ideally, test equipment in this industry would be calibrated to some standard in the custody of the National Bureau of Standards. Since such an ideal standard is not yet available, the industry, for the time being, ought to consider a cross calibration program using the solid-state materials and devices themselves as a standard. Certainly the semiconductor industry should recognize the importance of test standards and initiate steps immediately to agree upon mutually acceptable reference measurement methods and acceptable standards which would be acceptable in application even though they may not be absolute in value.

R. Jaggi J7

Potentials in a Conductor of Varying Cross-Section

Physical Review, vol. 122, p. 448, April 15, 1961

A Bernoulli voltage, V_B, proportional to the square of the current I, may be expected in a conductor of varying cross section. Previous experiments to detect V_B are discussed. It is pointed out that in such experiments a Hall voltage, $V_H \propto I^2$ due to the magnetic field of the current I ("eigen-Hall effect", EHE), is superposed on V_B. The ratio V_H/V_B is calculated. Experiments are performed on a bismuth sample of varying cross section. The dependence of the measured voltages upon temperature and cross-sectional area show that the EHE is dominant over the Bernoulli effect.

W. E. Johnson and K. Lark-Horovitz J8

Neutron Irradiation of Semiconductors

U. S. Government Research Reports, vol. 30, p. 566 (A), December, 1958

Neutron irradiation of Si, Ge, Se and Te is discussed in detail, showing its effect on electrical conductance. In the case of silicon, selenium and cuprous oxide, resistivity is increased by some orders of magnitude, depending on time of irradiation. In the case of germanium, it has been found that neutron irradiation produces a change from n-type to p-type, and that in the case of p-type germanium, the resistivity drops monotonously as a function of irradiation.

M. H. Jorgensen, N. I. Meyer and K. J. Schmidt-Tiedemann J9

Conductivity Anisotropy of Warm and Hot Electrons in Silicon and Germanium

Solid State Communications, vol. 1, no. 7, p. 226, December, 1963

Experimental results for the anisotropy angle in n-type silicon are given for medium and high electric fields, i.e., for the warm and hot electron regions. Theoretical expressions for the coefficients β and γ characterizing the quadratic departure from Ohm's law are presented for the case of dominating acoustical scattering.

D. Kahng, C. O. Thomas and R. C. Manz K1

Anomalous Impurity Diffusion in Epitaxial Silicon Near the Substrate

Journal of the Electrochemical Society, vol. 109, p. 1106, November, 1962

The interfacial region for epitaxial silicon films grown on heavily doped substrates appears to have unusual and undesirable characteristics as exhibited by characteristic etch patterns and anomalously high diffusion rates. For very thin films this interfacial region may occupy the major portion of the total film thickness and so cause serious problems in device fabrication in such very thin films on highly doped substrates. The diffusion rate of impurities in the main body of the film, however, is consistent with the rate in normal bulk material.

S. P. Kalvenas and Yu. K. Pozhela K2

Investigation of Transistion Processes in Semiconductors Using Microwave Techniques (In Russian)

Lietuvos Fizikos Rinkinys. Litovskii Fizicheskii Sbornik, vol. 1, no. 3-4, p. 365, 1961

Presents experimental problems connected with the measurement of transistion processes in semiconductors using microwave techniques and experimental data about the distribution of minority current carriers in a semiconductor and about the relaxation kinetics of these processes.

H. Kato, H. Muraoka and T. Abe K3

Impurities in Semiconductor Materials

Toshiba Review, no. 7, p. 24, Autumn, 1961

Many problems remain to be solved before industrial production of Ge and Si single crystals with a guaranteed uniformity of product quality can be assured. Several problems are described in the present paper. Many of the problems are common to Ge and Si, but for convenience's sake the paper is divided into sections on Ge and on Si. In the section on Ge, the uniformity of the concentration of obtained single crystals and the behavior of gaseous impurities is stressed. In the section on Si, a brief description will be made of the distribution of impurity concentrations.

J. B. Keller K4

Conductivity of a Medium Containing a Dense Array of Perfectly Conducting Spheres or Cylinders or Nonconducting Cylinders

Journal of Applied Physics, vol. 34, p. 991, April, 1963

The effective electrical conductivity σ is computed for a composite medium consisting of a dense cubic array of identical, perfectly conducting spheres imbedded in a medium of conductivity σ_o when f, the fractional volume occupied by the spheres, is near its maximum value $\pi/6$. The result exhibits a singularity of σ at $f = \pi/6$, when the spheres touch each other. The previous results of Maxwell, of Rayleigh and of Meredity and Tobias are not valid near the singularity and they fail to reveal it. For $f = 0.5161$ our result yields $\sigma/\sigma_o = 7.65$, while the measurement of Meredith and Tobias yielded $\sigma/\sigma_o = 7.6$. For a medium containing a square array of perfectly conducting circular cylinders we obtain a result which agrees well with the numerical result of H. B. Keller and D. Sachs. We also prove that for any value of f, σ/σ_o for a medium containing a square array of nonconducting cylinders is the reciprocal of σ/σ_o for the same array of perfectly conducting cylinders.

D. P. Kennedy K5

Spreading Resistance in Cylindrical Semiconductor Devices

Journal of Applied Physics, vol. 31, p. 1490, August, 1960

For cylindrical semiconductor components, computation of spreading resistance is considered a boundary value problem of the solid circular cylinder. Solutions of this problem may be used, for example, to characterize the thermal spreading resistance within the package of a semiconductor device, the electrical spreading resistance in a mesa type parametric diode, and the extrinsic collector resistance of a mesa transistor. Equations describing the thermal (or electrical) spreading resistance are presented in graphical form for a range of geometrical parameters applicable to many practical situations. Further, examples are given for the potential distribution within each cylindrical structure considered in this analysis.

J. K. Kennedy K6

Four-Point Probe for Measuring the Resistivity of Small Samples

Review of Scientific Instruments, vol. 33, p. 773, July, 1962

The measurement of resistivity is basic to the semiconductor industry. The most convenient and probably the most commonly used method for this measurement utilizes the "four-point probe."

In practice, however, most resistivity measurements are made on samples of limited size, and as has been shown, when the sample size decreases below a semi-infinite volume, the apparent resistivity value varies as a function of the proximity of the probes to the boundaries of the sample. The actual sample size required to approach semi-infinite volume is a function of the probe point spacing. This is illustrated in figures, which show the sample sizes required in order that all correction factors become 0.99 when the probe spacings are 0.062 in. and 0.010 in., respectively. In this case, all boundaries are nonconducting.

F. Keywell and G. Dorosheski K7

Measurement of the Sheet Resistivity of a Square Wafer with a Square Four-Point Probe

Review of Scientific Instruments, vol. 31, p. 833, August, 1960

The sheet resistivity of a thin sample of semiconductor may be measured by the placement of four probes on the surface of the sample. When current is passed between two of the probes, the potential difference between the other two probes is proportional to the current and the sheet resistivity of the sample. Sheet resistivity is then proportional to PD ÷ current, the proportionality or correction factor being dependent on the geometry of the sample and the probe. Calculations have been made for the correction factors in the case of a square probe array placed symmetricaly on a square wafer. The correction factors for conversion of PD ÷ current to sheet resistivity are given for square dimensions, in units of probe spacing, over the range one to 50. The data include the special case d/s = 1 wherein the probe points are on the corners of the square.

V. I. Khotkevich and M. Ya. Zabara K8

New Scheme for Measuring Electrical Conductivity by the Induction Method

Instruments and Experimental Techniques, 1962, no. 1, p. 193, September, 1962 (Russian original dated January-February, 1962)

A new scheme was developed for the measurement of electrical conductivity by the induction method in the range of 10^{-6} to 10^{3} $ohm^{-1}cm^{-1}$. It is shown that the use of magnetic suspension and of an electronic chronoscope increases the accuracy by an order of one, and permits applications of the procedure over a wider range. The device specifications and test results of electrical conductivity measurements of metals, using cylindrical samples, are presented.

V. I. Khotkevich and M. Ya. Zabara K9

A New Arrangement of the Induction Method of Measuring Electrical Conductivity

Cryogenics (GB), vol. 3, p. 33, March, 1963

This paper describes fully a method of determining electrical conductivity by measuring the damping of the cylinder rotating freely in a fixed magnetic field. The accuracy of measurement is approximately 0.1%. From the sensitivity of the system in measuring the moment (10^{-3}erg) and the steady magnetic field which can be attained (10^{4} oersteds), it is calculated that the lower limit of conductivity which can be measured is 10^{-6} $\Omega^{-1}cm^{-1}$. On the high conductivity side measurements of up to 10^{7}-10^{8} $\Omega^{-1}cm^{-1}$ can be made.

I. D. Kirvalidze and V. F. Zhukov K10

The Possibility of Creating Ohmic Contact with Silicon by Rubbing the Metal onto the Semiconductor Using Dry Friction

Soviet Physics - Solid State, vol. 1, p. 1446, April, 1960

This paper describes a method of producing ohmic recombination contacts with both n- and p-type silicon without the necessity of treating the silicon with abrasive materials prior to application of the metal contacts. The "disturbed layer," which is formed as a result of grinding or abrading treatment of the semiconductor, contains a large number of superfine cracks and mutually disoriented mosaic microblocks. The disturbed layer in contact with metal gives good ohmic contact since, due to the presence of structural defects, the number of recombination centers is greater than in the undisturbed region of the semiconductor.

It is possible, however, to produce a "disturbed layer" without the use of abrasive methods and materials, by means of a process of dry friction between the metal and the semiconductor. In this case, two processes occur simultaneously, namely, the production of the "disturbed layer" and the deposition of metal by rubbing.

I. D. Kirvalidze and V. F. Zhukov K11

Concerning the Effect of Heat Treatment on the Electrical Properties of P-Type Silicon

Soviet Physics - Solid State, vol. 2, p. 537, October, 1960

In this paper, experimental results are presented of a study of the effect of heat treatment on the specific resistance and carrier concentration in p-type monocrystalline silicon.

D. L. Klein and D. J. D'Stefan K12

Controlled Etching of Silicon in the HF-HNO_3 System

Journal of the Electrochemical Society, vol. 109, p. 37, January, 1962

Some of the important factors that affect the degree of reproducibility of desired dimensions, flatness, and surface finish of chemically etched silicon have been investigated. The etching rate of single crystal silicon in hydrofluroic and nitric acids was studied as a function of the ratio of the concentrated acids, temperature, and stirring rate. These variables were found to be related to the etching rates over the ranges studied. No difference in etch rate was observed for n, p and n-p junction silicon, ranging in resistivity from 0.05 to 78 ohm-cm. The etch rate appears to be dependent on the diffusion of the fluoride species to the silicon surface in the nitric acid-rich region. The controlled etching technique has been applied to the etch-cutting of wafers from selectively masked silicon slices. Preliminary investigation has shown that this method is applicable for the preparation of slices for diffusion processing.

M. I. Klinger K13

A Statistical Theory of the Electrical Conductivity of Semiconductors

Soviet Physics - Solid State, vol. 1, p. 782, December, 1959

A general expression for the electrical conductivity obtained by Kubo is used to deduce an electrical conductivity formula for the case of a weak electron-phonon interaction. The new formula is discussed and used in scattering of electrons on polarized phonons. The contribution of virtual transitions and the criterion which determines the smallness of this contribution are also dealt with.

G. Knight, Jr. K14

Measurement of Semiconductor Parameters

Handbook of Semiconductor Electronics, L. P. Hunter, ed., 1st ed., sec. 20, p. 2, McGraw-Hill Book Company, Inc., New York, N.Y., 1956

Single-probe potential-profile, double-probe, and four-probe methods of measuring resistivity are described.

W.-H. Ko K15

The Forward Transient Behavior of Semiconductor Junction Diodes

Solid-State Electronics, vol. 3, p. 59, July, 1961

The transient behavior of junction diodes in response to a step current in the forward direction is analyzed and the theoretical results verified experimentally. The forward transient of the diode is resolved into junction voltage and bulk resistance components. The former is due to the gradual building up of the excess carrier density near the junction and the latter due to the conductivity modulation.

The theory given yields satisfactory explanation of all the observed phenomena: the diode acts inductively for large forward current, capacitively for small current and oscillatory for certain intermediate current.

Several applications are suggested, for example, the design methods to minimize the forward transient and the measurements of lifetime and bulk resistance from the transient observation.

S. H. Koenig K16

On the Nature of Electrical Conduction in Germanium at Low Temperatures; Non-equilibrium Bulk and Contact Phenomena

Solid State Physics in Electronics and Telecommunications, vol. 1, p. 422, Academic Press, Inc., New York, N.Y., 1960

It has been known for some time that the electrical conductivity of Ge below 10°K is highly non-linear. The variation of current density with electric field is characterized by a linear region for fields less than approximately 200 mV/cm followed by a region of increasing conductivity until a critical "breakdown" field, typically of the order of 10 V/cm, is reached, at which point the current density may rise by a factor of 10^4 for a 5 percent increase in applied electric field. These characteristics, which are polarity-independent and uniform throughout the bulk of a sample, are associated with a "heating" of the electron distribution and the strong enhancement of impact ionization of neutral impurities by the "hot" electrons. These and other characteristics discussed suggest novel cryogenic devices. Processes determining the response time of devices utilizing the non-linear conduction, as switching in and out of breakdown, and the relation of switching time to adjustable parameters are considered in detail.

T. Kohane K17

The Measurement of Microwave Resistivity by Eddy Current Loss in Small Spheres

Transactions of the Institute of Radio Engineers, vol. I-9, p. 184, September, 1960

Described here is a cavity perturbation method for measuring resistivity which is applicable to small samples of relatively high conductivity materials.

T. Kohane and M. H. Sirvetz K18

Measurement of Microwave Resistivity by Eddy Current Loss in Spheres

Review of Scientific Instruments, vol. 30, p. 1059, November, 1959

For the measurement of the microwave resistivity of high-conductivity ferrites, such as those having compositions near that of magnetite (dc resistivity approximately 10^{-2} ohm-cm), the cavity perturbation method usually used to measure the complex dielectric constant of high-resistivity materials is not applicable. For samples of reasonable size the assumption that the electric field throughout the sample is uniform is not valid because of the skin effect. Another cavity perturbation is presented in which no assumption is made regarding the depth of penetration of fields. The sample is spherical in shape and is placed in the cavity at a point of maximum magnetic field and zero electric field. Results of measurements on silicon and germanium are given.

R. Koike and H. E. M. Barlow K19

Microwave Measurements on the Magneto-Resistance Effect in Semiconductors

The Proceedings of the Institution of Electrical Engineers, pt. B, vol. 109, p. 137, March, 1962

The paper discusses the results of an experimental investigation concerned with the transverse magneto-resistance effect in very thin semiconducting films situated in a microwave field at 10 Gc/s, with a superimposed steady magnetic field, of flux density up to 0.45 Wb/m^2, applied at right angles to the surface of the film. The film used was of indium antimonide with a thickness of the order of 10^3 Å, much less than the skin depth at the frequency employed. It was deposited by evaporation in a vacuum on a thin sheet of mica and placed longitudinally in a rectangular waveguide with the surface of the film parallel to the narrow wall of the guide, in much the same way as in the ordinary vane-type attenuator. The steady magnetic field, applied transversely to the film, produces a change in its conductivity and a corresponding effect on the microwave transmission properties. This magneto-resistance effect is related to the mobility of the carriers in the semiconductor, and consequently the technique enables this mobility to be determined without the use of electrodes attached to the specimen.

D. T. Kokorev and N. F. Kovtonyuk K20

Analysis of the Homogeneity of Semiconductor Materials by Using the Method of the Volume Photo-EMF

Instruments and Experimental Techniques, 1962, No. 2, p. 382, November, 1962 (Russian original dated March-April, 1962)

The present article explores the applicability of the method of the volume photo-emf for inspecting the homogeneity of semiconductor materials. It is shown that the emf in homogeneous semiconductors arises only due to the space charge, while, in inhomogeneous semiconductors, the emf connected with the nonuniformity of resistivity is added to the emf which is due to the space charge. Recommendations concerning the methods and schemes for plotting the inhomogeneity distribution curves are given. This method can be successfully used for inspecting thin semiconductor plates, for instance, plates of GELS-30/1.5 germanium.

E. D. Kolb and M. Tanenbaum K21

Uniform Resistivity P-Type Silicon by Zone Leveling

Journal of the Electrochemical Society, vol. 106, p. 597, July, 1959

Silicon single crystals nominally 1 cm in diameter and 16 cm long have been grown with aluminum doping in a floating-zone apparatus. Crystals have been prepared with nominal p-type resistivities of 0.3 and 5 ohm-cm with variations of 5% or less along the crystal length. Variations of resistivity with rotation rate, growth rate, ambient gas flow rate, and other growth variables have been studied. Zone volume variations were also measured.

R. A. Kramer and L. M. Foster K22

Residual Resistivity

Compound Semiconductors, vol. I, Preparation of III-V Compounds, eds.: R.K. Willardson and H. L. Goering, ch. 16, p. 146, Reinhold Publishing Corporation, New York, N.Y., 1962

Electrical resistivity can yield a great deal of information about a metal if certain features of the conduction process can be isolated and identified. The measurement itself is generally simple, precise, and reproducible. This chapter is concerned with the use of resistivity measurements to measure and, in favorable cases, identify the impurities in metals that are employed for the synthesis of compound semiconductors.

H. Kressel and M. A. Klein K23

Determination of Epitaxial-Layer Impurity Profiles by Means of Microwave-Diode Measurements

Solid-State Electronics, vol. 6, p. 309, May-June, 1963

This note describes a non-destructive technique for measuring epitaxial-layer impurity profiles, which is based on the resistance change in reverse-biased p^+-n-n^+ diodes.

H. Kroemer K24

Microwave Interactions in Bulk Semiconductors: A Survey

1960 International Solid-State Circuits Conference, Digest of Technical Papers, Lewis Winner, ed., 1st ed., p. 86, New York 36, N.Y., 1960

There are three characteristic frequencies for a semiconductor: its cyclotron frequency ($\omega_c = eB/m^*$), its plasma frequency ($\omega_p = (ne^2/EM^*)^{1/2}$), and its collision frequency ($\omega = 1/\tau$). Non-resonant effects, where the microwave frequency differs appreciably from all of these, and resonant effects involving these frequencies, are discussed from the standpoint of the possibility of their providing parametric or true negative resistances which might yield bulk effects permitting amplification or generation of microwaves.

G. Ksoll K25

On the Determination of the Concentration Profile of Diffusion Layers in Silicon from Layer Conductivity Measurements

Physica Status Solidi, vol. 1, p. 181, June, 1961

A method of evaluating measurements of sheet resistivity with a four-point probe is described. The determination of the concentration profile of diffused layers without special assumptions concerning the concentration distribution is possible.

Experimental examinations of diffused p-type layers on n-type silicon in the vicinity of the junction result in considerable deviations of the measured distributions from the exponential function and the complementary error function, respectively.

I. Kudman K26

A Nondestructive Measurement of Carrier Concentration in Heavily Doped Semiconducting Materials and Its Application to Thin Surface Layers

Journal of Applied Physics, vol. 34, p. 1826, June, 1963

The position of the plasma edge has been used in this investigation as a measure of the carrier concentration in thin surface layers. A calibration curve of the position of the edge as a junction N can be obtained by measuring the reflectivity spectrum of single-crystal samples having known carrier concentrations. The plasma edge of the unknown sample is determined and N found from the calibration curve.

While this technique was originally employed to overcome the lack of a suitable measurement in thin surface layers, it represents a simple measurement for single-crystal samples. Although the measurable carrier range is limited, the measurement, being nondestructive and requiring no contacts, may be useful for certain applications. With a four-point probe measurement, carrier concentration, resistivity, and mobility can be determined nondestructively.

This method is equally applicable to Ge and Si. The range can be extended to lower carrier concentrations by use of a suitable infrared instrument.

B. Kvasil and V. Husa K27

The Measurement of Semiconductor Conductivity in Microwave Range (In Czechoslovakian)

Slaboproudy Obzor, vol. 20, p. 667, November, 1959

The paper contains the description of a contactless method of measuring semiconductor conductivity. The relations derived serve for calculating the conductivity of small semiconductor samples in a cavity resonator. Furthermore the quality factor (the electrical losses within the sample as a function of the conductivity) is analyzed. The region of this dependence for ascertaining the electrical conductivity without respect for the sample form is determined according to a simple formula. The results of verifying the method experimentally, its accuracy and applications are stated.

St. Kynev, M. K. Sheinkman, I. B. Shul'ga and V. D. Fursenko K28

Contactless Method for Measuring the Parameters of Certain Semiconductors

Instruments and Experimental Techniques, vol. 2, p. 376, November, 1962

A high-frequency method for measuring semiconductor parameters (the dark conductivity and the photoconductivity, including its kinetics) without attaching electrodes to the semiconductors has been developed. High-frequency electrodes whose shape makes it possible to perform local measurements of the parameters of thin semiconductor films on small sections of the specimen are proposed. The possibility of solving various problems concerning the investigation of photoelectric phenomena in semiconductors by means of this method is demonstrated on the example of CdS monocrystals and thin PbS semiconductor films.

T. Kytöniemi K29

A Method for Determining the Resistivity of Semiconductors with Relatively High Resistivity (In Finnish)

The State Institute for Technical Research, Finland. Valtion Teknillinen Tulkimuslaitos, Tiedotus. Sarja II - Metalli. 9, 34 pp., 1961

A review is given of the methods used for measuring the resistivity of semiconductors. There follows a description of the method of determination of the resistivity based on the measurement of impedance over a wide frequency band (10 c/s to 500 Mc/s). Three samples of Si crystal were employed. The impedance can be presented in the form of a parallel connection of resistance component R_p and the reactance component $1/\omega C_p$. From the graph showing R_p and C_p as functions of frequency, it can be seen that at high frequencies R_p and C_p approach constant values R' and C' respectively. From these values the resistivity of the sample can be determined by means of the formula presented. The value obtained for the resistivity is the bulk resistivity of the material.

E. F. Labuda and R. C. LeCraw L1

New Techniques for Measurement of Microwave Dielectric Constants

Review of Scientific Instruments, vol. 32, p. 391, April, 1961

A new technique is described which overcomes several disadvantages of currently standard methods. Perturbation techniques are used with thin rod samples placed in a TM_{012} cylindrical cavity in such a manner that all undesirable effects of the ends of the rod are eliminated. A considerable increase in repeatability and ease of measurement is obtained.

T. J. LaChapelle L2

Research on Solid State Diffusion in Semiconductor Materials. Final Technical Report

Pacific Semiconductors, Inc., Research and Development Department, Culver City, California, report no. 3000:5-5-F, contract AF 18(603)-117, September, 1957 (AD 136 553)

Several new pit patterns produced by the Dash etch technique are reported and photographs of these are shown. Distribution of impurities appears to be much more structure-sensitive than do diffusion rates.

Silicon surface preparation and properties have been investigated in their relation to diffusion. Flat, damage-free surfaces have been produced by the use of garnet abrasives and special etches.

The effects of diffusion and heat treatment were studied as they relate to the resistivity, minority carrier lifetime, and structural perfection of silicon. Both p- and n-type silicon showed resistivity increases. Lifetime after diffusion at 1200°C was severely degraded. The structure of diffused silicon appears to be far more imperfect than either heat-treated silicon or virgin (as grown) silicon. Known impurity-dislocation interactions and preliminary experiments suggest that contaminants in raw silicon are still an unknown variable.

M. F. Lamorte L3

Calculation of Concentration Profiles and Surface Concentration from Sheet-Conductance Measurements of Diffused Layers

Solid-State Electronics, vol. 1, p. 164, July, 1960

A method for obtaining the sheet-conductance profile of a diffused layer by ohmic contacts to the layer is suggested. Equations are presented from which the concentration profile may be obtained from sheet-conductance measurements by either the four-probe or ohmic-contact method. For three impurity-concentration distributions, equations are presented for surface concentration which necessitate the measurements of sheet conductance, junction penetration and the background conductivity. If the sheet conductance is much greater than the product of the background conductivity and the junction penetration, only the sheet conductance need be measured in order to determine the surface concentration.

J. J. Lander, H. Schreiber, Jr., T. M. Buck and J. R. Mathews L4

Microscopy of Internal Crystal Imperfections in Si P-N Junction Diodes by Use of Electron Beams

Applied Physics Letters, vol. 3, p. 206, December 1, 1963

The technique described employs an electron beam which scans the diode in synchronism with a display cathode-ray tube upon whose grid the diode signal is impressed. The beam current is multiplied by generation of hole-electron pairs in or near the space-charge region. Surface topology and internal defects influence transmission of the beam and internal defects influence collection efficiency. Crystal imperfections near the space charge region of p-n junctions can thus be observed at high magnification. To illustrate the resolution achieved and the versatility of the method, examples are given of the results obtained with diodes prepared by 4μ phosphorus diffusion into the [111] and [110] planes of a silicon crystal.

G. Landwehr L5

On the Evaluation of Electrical Conductivity along Grain Boundaries in Germanium Bicrystals (In German)

Physica Status Solidi, vol. 3, p. 440, March, 1963

The low-temperature hole distribution adjacent to the grain boundary of germanium bi-crystals with a tilt angle of 20° has been computed using the Thomas-Fermi method. The average thickness of the conducting p-type layer was found to be of the order of 50 Å, with an average hole density of 4×10^{18} cm^{-3}.

A. R. Lang L6

Studies of Individual Dislocations in Crystals by X-Ray Diffraction Microradiography

Journal of Applied Physics, vol. 30, p. 1748, November, 1959.

The distribution of imperfections within the interior of crystals has been studied using "projection topographs", which are x-ray diffraction images showing a projection of a slice of crystal and the imperfections in it. Individual dislocations have been observed in single crystals of diamond, silicon, germanium, lithium fluoride, sodium chloride, silver chloride, magnesium oxide, calcite, quartz, and aluminum. From the variation of dislocation contrast with the orientation of the x-ray reflecting plane the direction of the Burgers vector can be found. Dislocations can be seen with good contrast when the product of linear absorption coefficient μ and slice thickness t is of the order of unity or less. If $\mu t >> 1$ the contrast is reversed through the Borrmann effect. Stereo pairs of projection topographs can be prepared from the pair of reflections hkl and $\bar{h}\bar{k}l$.

J. La Plume L7

Theoretical Bases for the Measurement of Resistivity and the Hall Constant by the Probe Method (In French)

L'onde Electrique, vol. 35, p. 113, February, 1955

This paper covers the four-point probe theory for a filament of infinite length. The measurement of the Hall voltage is determined.

R. D. Larrabee L8

Measurement of Semiconductor Properties through Microwave Absorption

Radio Corporation of America Review, vol. 21, p. 124, March, 1960

A technique for utilizing microwave absorption as a probe for measuring semiconductor properties is described. The complete isolation between the microwave measuring circuit and the sample circuit makes this technique useful for many applications. It is shown that this technique can be used to measure minority carrier lifetime (decay of conductivity) in a way which requires no physical electrical connection to the sample under test.

J. E. Lewis and L. M. Foster L9

Radioactivation Analysis

Compound Semiconductors, R. K. Willardson and H. L. Goering, eds., vol. I, Preparation of III-V Compounds, Chapter 15, Reinhold Publishing Corporation, New York, N.Y., 1962

Among other topics discussed is the inhomogeneity of the neutron flux in existing facilities.

J. Lindmayer and M. Kutsko L10

Reflection of Microwaves from Semiconductors

Solid-State Electronics, vol. 6, p. 377, July-August, 1963

Reflection of microwave energy from a semiconductor is calculated and measured. The wave guide is terminated by a semiconductor-metal sandwich. The standing-wave ratio is calculated as a function of semiconductor thickness, resistivity and dielectric constant. The resulting complicated expression for the standing-wave ratio is computed and plotted for 25 and 100 Gc/s. The measurements agree relatively well with the calculated values.

J. G. Linhart, I. M. Templeton and R. Dunsmuir L11

A Microwave Resonant Cavity Method for Measuring the Resistivity of Semiconducting Materials

British Journal of Applied Physics, vol. 7, p. 36, January, 1956

A method is described for measuring the resistivity of semiconductors at centimeter wavelengths. A small spherical or cubic specimen is placed in a cavity resonating in the H_{011} mode, and the reduction in Q due to eddy-current loss in the specimen is measured. The theory given enables the resistivity of the material to be calculated. It is shown that resistivities in the range 0.005 to 10 ohm-cm can be determined.

S. H. Liu, Y. Nishina and R. H. Good, Jr. L12

Microwave Measurement of Mobility: Analysis of Apparatus

Review of Scientific Instruments, vol. 32, p. 784, July, 1961

The microwave mobility in a semiconductor can be obtained by mounting a sample in a bimodal cavity with an applied static magnetic field and then measuring the power transfer which is produced by the Faraday rotation in the sample. This paper gives an analysis of the effect based on the field distributions in the cavity and the wave propagation in the sample. The dependence of the power transfer on the static applied magnetic field, on the mobility and conductivity of the sample, and on an effective sample size is obtained.

M. A. Logan L13

An AC Bridge for Semiconductor Resistivity Measurements Using a Four-Point Probe

Bell System Technical Journal, vol. 40, p. 855, May, 1961

A new direct-reading ac bridge circuit has been developed to measure semiconductor bulk and sheet resistivity, using a four-point (or other appropriate) probe. The range of resistivity which can be measured is from 0.001 to 10,000 ohm-cm. Resistivity is read directly from resistance decades and a ratio multiplier, eliminating voltmeter and ammeter errors. The final reading is the result of a bridge-balancing operation for each measurement. Stability and sensitivity provide better than 0.5 percent electrical accuracy, with mechanical point spacing being the controlling limitation on the over-all accuracy of the measurement.

The use of ac eliminates the influence of rectification, thermal, or contact potentials on the measurements, and also provides sensitivity more readily than dc. The four-point probe and test specimen are the only nongrounded elements.

An appendix compiles four-point probe conversion factors for thin circular and rectangular slices of material. New tables are presented for slices having a continuous diffused skin all over, and thus also conducting across the back.

D. Long, C. D. Motchenbacher and J. Myers L14

Impurity Compensation and Magnetoresistance in P-Type Silicon

Journal of Applied Physics, vol. 30, p. 353, March, 1959

A new method is proposed for determining the separate concentrations of acceptor and donor impurities in crystals of p-type silicon, and thereby the degree of compensation of acceptors by donors. The method involves finding the total concentration of impurities in a sample from a measurement of the weak-field transverse magnetoresistance at 77°K and combining this result with the excess of acceptors over donors determined from a room-temperature resistivity or Hall-effect measurement. An empirical "master curve" of magnetoresistance vs. impurity density has been constructed for this purpose. The impurity densities for the master curve were measured by the usual method of fitting a theoretical carrier concentration vs. temperature equation to an experimental curve obtained from Hall-effect data.

A. Lorinczy, T. Nemeth and P. Szebeni L15

Observations on Germanium-Metal Contacts Used as Probes for Injected Carriers (In German)

Physica Status Solidi, vol. 2, no. 7, p. K157, 1962

The note reports some experimental peculiarities obtained on measuring the diffusion length by the Morton-Haynes method in n-type, Sb-doped, Ge single crystals of 25 ohm-cm and 6 ohm-cm, covered with a stabilized oxide layer. Diffusion lengths were measured with W and Sn pointed probes. Results obtained with the Sn probe were about half of those obtained with the W probe. Also the potential of the Sn probe was negative, while that of the W probe was, as expected, positive. Voltage current characteristics obtained with the Sn probe show p character for low, and n character for higher, voltages. On measuring the rectifying characteristics with 4.5v 50 Hz ac the potential of the Sn point becomes positive after "formation" by the alternating voltage, its value decreasing to a positive saturation value after about 10 minutes. It is probable that before and after "formation" diffusion lengths of majority and minority carrier respectively are measured. Surface states seem to be involved in these phenomena.

E. R. Love L16

The Electrostatic Field of Two Equal Circular Co-Axial Conducting Disks

Quarterly Journal of Mechanics and Applied Mathematics, vol. 2, p. 428, October-December, 1949

In the earliest discussion of this problem Nicholson expressed the potential as a series of spheroidal harmonics with coefficients satisfying an infinite system of linear equations, and gave a formula for an explicit solution; but this formula appears to be meaningless and its derivation to contain serious errors.

In the present paper, a much simpler, though still implicit, specification of the potential is developed; this involves a Fredholm integral equation, the existence and uniqueness of whose solution are deducible from standard theory. The specification so obtained for the potential is shown rigorously to satisfy the differential equation and boundary conditions of the electrostatic problem.

The Neumann series of the integral equation is shown to converge to its solution, so that the potential, and other aspects of the field, can be explicitly formulated and thus computed.

A. L. MacDonald and W. J. Heinecke M1

Effects of Heat Treatment of Diffused Silicon Material

Semiconductor Products, vol. 4, p. 19, September, 1961

The effects of post diffusion cooling treatments on several n-type silicon single crystals were investigated. Decreases of electron concentration were noted with heat treatment. Several combinations of cooling, quenching and annealing which lead to similar bulk properties are described. The magnitude of concentration changes is shown to be dependent upon the particular crystal and upon the position within the crystal. The application of these results towards the selection or preparation of material for particular device requirements is discussed.

A. L. MacDonald, J. Soled and C. A. Stearns M2

Four-Probe Instrument for Resistivity Measurements of Germanium and Silicon

Review of Scientific Instruments, vol. 24, p. 884, September, 1953

It is very convenient to measure the resistivity of germanium and other semiconductors with a four-probe instrument. Because of the repeated need for making such measurements a four-probe instrument was designed with the view of both ease of making such measurement and reproducibility of the measuring equipment.

J. Maczuk M3

Research Investigations on Electronic Properties of Semiconductors - Quarterly Progress Report No. 3

University of Pennsylvania, Moore School of Electrical Engineering, Philadelphia, Pennsylvania, Research Division Report No. 55-11, Contract No. DA-36-039-SC56722, November, 1954 (AD 52078)

A list is presented of injection phenomena and facts which were observed during the investigations of lifetime characteristics using Many's bridge method and the pressure point contact injection technique of Fabricand and Gelles. Final results of studies of the reversed sense injection are presented. They show that minority carriers injected from the base junction produce reversed-sense injection phenomena. Measurements of lifetime at 220°C show that both the reversed and right sense injection still are observable at this elevated temperature. A general critical review is presented regarding the reported lifetime values in the previous two reports and in this present one. Larger lifetimes are obtained in those injection devices which had smaller backward resistances (reversed sense injection). Preliminary values of injection ratio are presented which were calculated equations from Many's theory. The ratio is field and injection current dependent being larger where E or I is larger.

J. Maczuk M4

Research Investigations on Electronic Properties of Semiconductors - Quarterly Progress Report No. 4

University of Pennsylvania, Moore School of Electrical Engineering, Philadelphia, Pennsylvania, Moore School Report No. 55-23, Contract No. DA-36-039-sc56722, February, 1955 (AD 64020)

The results of studies of temperature dependence of lifetime and injection ratio in a p-type silicon single crystal of 125 ohm-cm resistivity are presented. Because of previous difficulties, care was taken to insure that plated rhodium electrodes were ohmic over the entire temperature range. With the crystal provided with such contacts only the expected injection phenomena were observed. No broken transient characteristics were observed. In this sample the lifetime increased with increase of temperature, and an acceptor recombination center with an energy level of 0.1 eV above the valence band was calculated. Lifetime did not decrease with decrease of temperature. No shifting from injection to ejection was observed with decrease of temperature. At room temperature the injection ratio is about 29%. It decreases slightly in the temperature range above and decreases more rapidly in the range below room temperature.

J. Maczuk and B. P. Fabricand M5

Electronic Properties of Semiconductor Materials - Quarterly Progress Report No. 1

University of Pennsylvania, Moore School of Electrical Engineering, Philadelphia, Pennsylvania, Moore School Report No. 57-19, Contract No. DA-36-039-SC72406, June, 1957 (AD 142568)

The temperature dependences of lifetime, injection ratio, and resistivity in p-type silicon crystals were measured by the use of the pulse decay method. Also the lifetime dependence on the resistivity of silicon samples was measured at room temperature. At a constant high temperature the lifetime and the injection ratio dependence on emitter current and sweeping electric field also was investigated.

S. Martinuzzi M6

A Device to Determine the Electrical Conductivity and Hall Constant of Thin Metallic and Semiconducting Films in a Vacuum (In French)

Le Journal de Physique et le Radium, vol. 22, p. 247, April, 1961

An arrangement is described for the vacuum determination of the electric conductivity and Hall constant of thin metallic films and semiconductors. The thin films on which the studies of electrical properties are made are prepared by thermal evaporation in the chamber of the evaporator in which a vacuum of the order of 10^{-6} mm of mercury is maintained.

S. Maruyama and O. Okada M7

Crow Track Formed by Mechanical Force on Silicon Crystal Wafer

Japanese Journal of Applied Physics, vol. 3, p. 300, May, 1964

Crow track is a type of crystal defect which is observed sometimes during the wafering process of silicon single crystals. This crystal defect is detected by means of chemical etching, but the exact source for its formation has not yet been known.

This report describes the experimental finding that one of the causes of crow tracks is an effect of a point-shock given mechanically to silicon crystals during their lapping process. The pressure which caused crow tracks is calculated to be 2.99×10^{10} dynes/cm^2 from a force of 400 grams and the point contact area of 1.31×10^{-5}cm^2, calculated from the formula for contact area of a sphere on a flat plate.

L. V. Maslova, O. A. Matveev and V. F. Afanas'ev M8

The Electropolishing of n-Type Silicon

Soviet Physics - Solid State, vol. 3, p. 1968, March, 1962

The electroetching and electropolishing of silicon with n- and p-types of conductivity have been carried out in solutions of fluoric acid with varying concentration.

A determination has been made of the dependence of the current density for the electropolishing of n-type silicon on the fluoric acid concentration.

R. G. Mazur and D. H. Dickey M9

The Spreading Resistance Probe - A Semiconductor Resistivity Measurement Technique

The Electrochemical Society Meeting, Pittsburgh, April, 1963, Extended Abstracts of Electronics Division, vol. 12, no. 1, p. 148

This paper presents a technique developed for determining the local resistivity of germanium and silicon. The technique involves a measurement of the spreading resistance of a known-area, metal-to-semiconductor pressure contact, applied to the surface of a specimen. The measurement procedure is described. Examples of measurements made to date on bulk silicon and germanium, and on epitaxial silicon, are presented, indicating the range of application and the advantages and limitations of the technique. No attempt is made to describe completely the electrical or mechanical properties of the pressure contacts used here, since the underlying theories of such contacts are largely incomplete. However, the problems involved in making quantitative resistivity measurements by measuring the spreading resistance of a metal-to-semiconductor point contact have been summarized by H. K. Henish, Rectifying Semiconductor Contacts, Clarendon Press, Oxford, 1957.

W. Mehl, H. F. Gossenberger and E. Helpert M10

A Method for the Preparation of Low-Temperature Alloyed Gold Contacts to Silicon and Germanium

Journal of the Electrochemical Society, vol. 110, p. 239, March, 1963

A method of etching a silicon sample while plating it is discussed. The temperature used in converting the plate to alloy is less than 400°C.

G. Meltzer M11

Minute Resistivity Variations in Germanium Crystals and Their Effect on Devices

Journal of the Electrochemical Society, vol. 109, p. 947, October, 1962

Minute variations of resistivity in germanium crystals were studied by the use of two methods of detection: selective copper plating and micropotential scanning. Results show that horizontal zone-leveled crystals have, in general, much larger minute resistivity variations than vertically grown crystals. Furthermore, n-type crystals have much larger resistivity variations than p-type crystals. These results, when applied to study of breakdown voltage in semiconductor devices, show that the range of breakdown voltage in p-n-p alloyed-junction transistors is much wider than the range in n-p-n devices.

N. I. Meyer and T. Guldbrandsen M12

Method for Measuring Impurity Distributions in Semiconductor Crystals

Proceedings of the Institute of Electrical and Electronics Engineers, vol. 51, p. 1631, November, 1963

A method for measuring the doping profile and its gradient in thin layers of semiconductor crystals is described.

A sine-wave signal applied to an appropriate p-n junction on the surface of a crystal gives rise to second and third harmonics in the output signal due to the non-linear capacitance-voltage characteristic of the junction.

Expressions are derived which relate the second and third harmonic distortion factors to the impurity concentration and its gradient as a function of the distance into the crystal. Measurements of the impurity profile in the base layer of some silicon and germanium transistors have been made.

A. Michels, J. Van Eck, S. Machlup and C. A. Ten Seldam M13

Pressure Dependence of the Resistivity of Germanium

Journal of Physics and Chemistry of Solids, vol. 10, p. 12, April, 1959

The effect of hydrostatic pressure on the resistance of a p-type sample of germanium (specific resistivity about 80 ohm-cm at 293°K) has been investigated up to 2700 atm at temperatures between 125°C and -150°C. The results in the intrinsic range indicate an increase in the energy gap of 5.4×10^{-6} eV/atm, in agreement with earlier experimental determinations. In the extrinsic region the resistivity decreases slightly with pressure, indicating an increase in hole mobility of 9 ppm/atm.

M. G. Mil'vidskii and A. V. Berkova M14

Revealing Heterogeneities in the Distribution of Impurities in Silicon Monocrystals

Industrial Laboratory, vol. 27, p. 569, May, 1961

A method has been developed for revealing the heterogeneities in the distribution of impurities in silicon monocrystals by anodic etching. The anodic etching of monocrystals of silicon of the electron type of conductivity is carried out in an electrolyte of composition $HF:CH_3COOH$ = 1:1 at a current density of 10 ma/cm^2 for 2 to 5 minutes with subsequent treatment in a solution of $HF:HNO_3$ = 1:4 for 20 to 30 seconds. The anodic etching of silicon monocrystals of the hole type of conductivity is carried out in the same electrolyte with a current density of 45-50 ma/cm^2 for 4 to 6 minutes with subsequent treatment in a solution of $HF:HNO_3$ = 8:1.5 for 10 to 15 seconds.

M. G. Mil'vidskii and B. I. Golovin M15

The Form of the Crystallization Front in Semiconducting Single Crystals Grown from the Melt by the Czochralski Method

Soviet Physics - Solid State, vol. 3, p. 737, October, 1961

A method is described for controlling crystal pulling in accordance with a calculated growth velocity program.

H. T. Minden M16

The Technology of Pulling Single Crystals

Part 1 - Semiconductor Products, vol. 4, p. 25, November, 1961
Part 2 - Semiconductor Products, vol. 4, p. 28, December, 1961

This article is intended to give a practical feel for the technique of pulling semiconductor single crystals from the melt. The conditions for dipping the seed and increasing the diameter of the crystal are given. The nature of some of the difficulties which occur is discussed in terms of the thermal configuration of the puller. Some of the causes of imperfect growth are presented from a macroscopic empirical viewpoint. Finally, some of the special techniques required for compound semiconductors are presented.

S. Minomura and H. G. Drickamer M17

Pressure Induced Phase Transitions in Silicon, Germanium, and Some III-V Compounds

Journal of the Physics and Chemistry of Solids, vol. 23, p. 451, May, 1962

Pressure induced phase transitions to a conducting state have been found for Si (195-200 kbars), Ge (120-125 kbars), and GaAs (245-250 kbars, 275-280 kbars), GaSb (80-100 kbars), InAs (100 kbars), InP (125-130 kbars), and AlSb (115-125 kbars). No transition occurred in the GaP to 550 kbars. Although it cannot be definitely proven, it is believed that, with the exception of GaAs, all transitions are solid-solid transitions, apparently to a metallic state. For GaAs, it is postulated that the first transition involves melting to a metallic liquid, while the second transition constitutes the freezing of the liquid.

A. Mircea M18

The Geometric Factor in Semiconductor Four-Probe Resistivity Measurements

Solid-State Electronics, Vol. 6, p. 459, September-October 1963

The application of the Green-function method to the mathematical problem connected with four-probe semiconductor resistivity measurements has led to a quite general solution of this problem. In the particular case of a linear array of probes lying on parallelepiped samples, the solution can be reduced to a more compact form. The solution is further simplified for the case of thin samples, where a slight approximation leads to the possibility of presenting it in closed form.

H. C. Montgomery M19

Electrical Properties of Surface Layers on CdTe Crystals

Solid-State Electronics, vol. 7, p. 147, February, 1964

Etching single crystals of CdTe with nitric and hydrofluoric acids produces a conductive surface layer of amorphous tellurium, having a sheet resistivity of several hundred Ω-per square. Leakage conductance between this layer and the bulk varies from 0.01 to 1 mho/cm^2 depending on the direction of the current. The conductive layer facilitates probe measurements of electrical properties, but results in anomalies near current electrodes or at sharp changes in body conductivity.

B. L. Mordike and N. C. Balchin M20

Contactless Residual Resistivity Measurement on Zone-Refined Tantalum (In German)

Zeitschrift fur Metallkunde, vol. 54, p. 278, May, 1963

A method is described by which the electrical resistivity can be determined from the decay time of induced eddy currents. The method is particularly suited to measuring the resistivity of specimens with a short gauge length. The results of measurements on zone refined tantalum are given.

T. N. Morgan M21

The Mobility of Electrons Heated by Microwave Fields in N-Type Germanium

Journal of the Physics and Chemistry of Solids, vol. 8, p. 245, January, 1959

Measurements of weak-field conductivity changes in semiconductors, "warm electron effects," present several experimental problems. Among these are (1) the difficulty of introducing the disturbing electric field into the crystal without producing contact effects and (2) the inaccuracies in the measurement of the small resistivity changes produced.

In an attempt to circumvent these problems we have superimposed a constant dc field and a modulated microwave field along the axis of the sample. By this means the disturbing microwave field is introduced into the crystal without the use of contacts, and its presence produces a modulation of the dc resistance which can be measured independently of any other microwave effects.

F. J. Morin and J. P. Maita M22

Conductivity and Hall Effect in the Intrinsic Range of Germanium

Physical Review, vol. 94, p. 1525, June 15, 1954

Conductivity and Hall effect have been measured in the intrinsic range of germanium from 250°K to 1000°K. From lattice-scattering mobility and conductivity below 500°K, a new empirical expression for carrier concentration is determined: $np = 3.10 \times 10^{32} T^3 \exp(-0.785/kT)$. An estimate is made of the contribution of optical modes to the lattice-scattering mobility. Conductivity from 500°K to 1000°K and Hall effect from 250°K to 1000°K are computed and compared with experiment. Included in the computation are: the empirical expression for carrier concentration modified by the change in intrinsic ionization energy produced by electrostatic interaction of charge carriers, extrapolated empirical lattice-scattering mobility, scattering by electron-hole collisions, and an extrapolation of the ratio Hall mobility/conductivity mobility.

F. J. Morin and J. P. Maita M23

Electrical Properties of Silicon Containing Arsenic and Boron

Physical Review, vol. 96, p. 28, October 1, 1954

Electrical conductivity and Hall effect have been measured from 10°K to 1100°K in single-crystal silicon containing arsenic and boron. Extrinsic carrier concentration is computed from Hall coefficient. Analysis of extrinsic carrier concentration indicates the ionization energy of arsenic donor levels to be 0.049 ev and of boron acceptor levels to be 0.045 ev for low-impurity concentrations. Fermi degeneracy is found to occur in the range 10^{18} to 10^{19} cm^{-3} impurity concentration. Extrinsic Hall mobility is computed from Hall coefficient and conductivity. Curves of Hall mobility against resistivity at 300°K are computed from theory and compared with experiment. The temperature dependence of lattice-scattering mobility is found from conductivity to be $T^{-2.6}$ for electrons and $T^{-2.3}$ for holes. From conductivity mobility and intrinsic conductivity, it is found that carrier concentration at any temperature below 700°K is given by the expression $np = 1.5 \times 10^{33} T^3 \exp(-1.21/kT)$. The temperature dependence of the ratio Hall mobility/conductivity mobility is determined for holes and electrons.

B. R. Nag and P. Das N1

Microwave Conductivity of Semiconductors in the Presence of High Steady Electric Fields

The Physical Review, vol. 132, p. 2514, December 15, 1963

The distribution function of carriers in a semiconductor when subjected to a small microwave field and a high steady electric field is derived, considering both the acoustic and optical phonon scattering. Expressions for microwave conductivity and change in apparent dielectric constant are obtained from the distribution function. It is shown by numerical calculations that the conductivity evaluated from these expressions agrees closely with the experimental value. The calculated value of the change in apparent dielectric constant, however, is found to be of the same order as the experimental value, but the agreement is poorer than that for the conductivity.

B. R. Nag and S. K. Roy N2

Microwave Measurement of Conductivity and Dielectric Constant of Semiconductors

Proceedings of the Institute of Radio Engineers, vol. 50, p. 2515, December, 1962

Measurement of semiconductor parameters at microwaves have been reported by several authors. In some of the reported measurements, the samples were put inside a waveguide and the semiconductor parameters were obtained by measuring the attenuation and phase-shift of the transmitted signal. Essentially the same method has been described in detail recently by Jacobs, et al., for evaluating the conductivity of a semiconductor sample assuming the value of the dielectric constant. Other workers obtained the semiconductor parameters by putting a small sample inside a cavity and determining the resonant frequency and Q of the loaded cavity. In the present communication a microwave method is proposed for measuring both the conductivity and dielectric constant of semiconductor crystals having conductivities lower than 1 $mho\text{-}m^{-1}$. The method is similar to that used for low-loss dielectrics.

B. R. Nag, S. K. Roy and C. K. Chatterji N3

Microwave Measurement of Conductivity and Dielectric Constant of Semiconductors

Proceedings of the Institute of Electrical and Electronic Engineers, vol. 51, p. 962, June, 1963

Conductivity and dielectric constant of semiconductors have been determined at microwave frequencies by measuring the attenuation and phase shift produced by a measured length of the semiconductor sample placed in a waveguide, or determining the resonance frequency and Q of a cavity loaded with the semiconductor. In an earlier communication, a VSWR method suitable for low-conductivity semiconductors was discussed. In this note, a method suitable for semiconductors with medium values of conductivity (0.1 - 10 mho-m^{-1}) will be presented. The semiconductor sample is prepared in the form of a thin slab and fitted in the center of a shorted waveguide parallel to the narrow side. The measurements consist of determining the VSWR and the shift of the minimum when the terminating shorted waveguide section is loaded with the semiconductor. The conductivity and the dielectric constant of the semiconductor sample can be evaluated from these data.

B. R. Nag, S. K. Roy and C. K. Chatterji N4

Correction to "Microwave Measurement of Conductivity and Dielectric Constant of Semiconductors"

Proceedings of the Institute of Electrical and Electronics Engineers, vol. 52, p. 185, February, 1964

Several symbols were incorrectly defined in the previous publication by these authors in vol. 51, p. 962, June, 1963 of the same journal. Corrected definitions are given here.

B. R. Nag, S. K. Roy and P. Das N5

Surface Effects on Microwave Signals Propagating in Semiconductors

Proceedings of the Institution of Electrical Engineers, vol. 110, p. 1181, July, 1963

The effect of the variation of electrical properties at the surface on the propagation of a microwave signal through a semiconductor placed in a guide are analysed by a perturbation method. General expressions are obtained for the reflection and transmission coefficient of the semiconductor sample. The result of the analysis are discussed with reference to microwave measurement of the bulk and surface properties of semiconductors.

M. Nakamura and W. Sasaki N6

The Effect of Tensile Stress on Impurity Conduction in N-Type Germanium

Journal of the Physical Society of Japan, vol. 17, p. 1311, August, 1962

A discussion is presented of experimental results for the case of high and intermediate concentrations of impurities.

N. G. Nakhodkin and V. P. Nemtsev N7

An Instrument for Studying Dependence of Electrical Properties of Thin Condensation Films upon Their Thickness

Instruments and Experimental Techniques, 1961, no. 4, p. 735, February, 1962

An instrument which permits the measurement of the electrical conductivity and other parameters of thin films of metals and semiconductors is described. Wedge-shaped films are obtained by deposition under ultra-high vacuum, approximately 10^{-9}mm Hg, and the electrical conductivity is measured at 12 points of varying thickness. The measurements may be made at temperatures between the boiling of liquid hydrogen and approximately +300°C. Sample data on Be films are presented.

M. Neuberger N8

Silicon: Electrical Conductivity

Hughes Aircraft Company, Culver City, California, Report No. DS-126, Contract No. AF 33(616)-8438, June, 1963 (AD 413746)

The Electronic Properties Information Center has been established to collect, index and abstract the literature on the electrical and electronic properties of materials and to evaluate and compile the experimental data from that literature. A modified coordinate index to the literature is machine stored and printed for manual use. The Center publishes data sheets, summary reports, thesauri, glossaries, and similar publications as sufficient information is evaluated and compiled. This report consists of the compiled data sheets on Silicon: Electrical Conductivity.

J. B. Newkirk and J. H. Wernick, Eds. N9

Direct Observation of Imperfections in Crystals

Proceedings of Technical Conference, St. Louis, March, 1961, American Institute of Mining, Metallurgical, and Petroleum Engineers, The Metallurgical Society, Interscience Publishers, John Wiley & Sons, New York, N.Y., 1962

The proceedings of a technical conference are presented, including material on observation of imperfections by means of optical and electron microscopy, X-ray diffraction topography, and field ion microscopy. In particular, X-ray studies of silicon and germanium are included.

F. Nibler and O. Hellinger N10

Measurement of the Specific Resistance of Semiconductors, with Special Reference to Pure Silicon Crystals of Resistivities up to 5×10^5 Ωcm and for Alternating Currents of 0.3 to 300 Mc/s Frequency (In German)

Zeitschrift für angewandte Physik, vol. 16, p. 308, July, 1963

Following a brief review of methods of measurement over various frequency ranges the possibility of distinguishing the true bulk resistivity from contact effects etc. is discussed quantitatively. A method is described which can determine resistivities between 5×10^2 and 5×10^5 Ωcm with a maximum error of about 7.5%.

Y. Nishina and G. C. Danielson N11

Microwave Measurement of Hall Mobility: Experimental Method

Review of Scientific Instruments, vol. 32, p. 790, July, 1961

Hall mobilities of germanium single crystals have been measured at a frequency of 9000 Mc over the temperature range 30°K to 300°K. A rectangular sample occupied the central part of a wall of a rectangular cavity, which was doubly degenerate in the TE_{101} mode and in the TE_{011} mode at a single resonance microwave frequency. The external magnetic field and the microwave field associated with one of the two modes gave rise to the other mode of oscillation. The theoretical analysis by Liu, Nishina, and Good was verified by measurements on an n-type sample having a room temperature resistivity of 0.40 ohm-cm. The measured Hall mobility at microwave frequencies (with a size correction) was compared with the dc Hall mobility between 30°K and 300°K. The agreement was excellent.

Y. Nomura N12

The Electrostatic Problems of Two Equal Parallel Circular Plates

Proceedings of the Physico-Mathematical Society of Japan, vol. 23, p. 168, March, 1941

The potential due to two equal parallel circular plates when the potential is specified over them is expressed as a series of integrals involving Bessel functions. Equations for the coefficients are found in terms of the boundary values and the solutions of these are determined numerically by iteration. Tables of these constants are given in the case of conducting plates. The capacity of the circular plates capacitor and the forces between two charged plates are calculated and these are plotted in curves against the distance between two plates.

D. W. Nyberg and R. E. Burgess N13

Electrodeless Techniques for Semiconductor Measurements

Canadian Journal of Physics, vol. 40, p. 1174, September, 1962

Electrodeless methods, based on the inductive coupling of samples to coils, for determining the electrical conductivity, the Hall mobility, and the magneto-resistance of a semiconductor are described. The theory is developed for cylindrical and spherical geometry samples and design considerations and experimental techniques are discussed. These methods eliminate problems encountered with standard four-probe methods, such as obtaining non-rectifying and non-injecting contacts, and applying electrodes to liquid or chemically active samples.

T. Ogawa O1

Measurement of the Electrical Conductivity and Dielectric Constant without Contacting Electrodes

Journal of Applied Physics, vol. 32, p. 583, April, 1961

A method is developed whereby electrical conductivity and dielectric constant of semiconducting and dielectric materials without contacting electrodes can be measured. The principle of this method is that a specimen suspended in a rotating field with a fine fiber is rotated by the torque proportional to the electrical conductivity or the imaginary part of its complex dielectric constant, and the torque exerted on it by a linearly polarized field is proportional to the real part of its dielectric constant.

An analysis of the method and some preliminary measurements of conductivity, photoconductivity, the dielectric constant of cadmium sulphate crystals and the dielectric loss of the lamella containing CdS power are presented. The latter shows the photodielectric effect.

C. R. Oliver and J. Isaacs 02

Neutron Activation as a Method of Determining Copper Contamination in Germanium During Processing

Colloque International sur les Dispositifs á Semiconducteurs, Paris, February 20-25, 1961, vol. II - Emploi et Fiabilité des Éléments Semiconducteurs, p. 758, Editions Chiron, Paris, France, 1961

This paper describes a technique for the submicro determination of copper in small germanium samples of the form normally encountered at all stages of transistor manufacture; and, as they are processed, thereby establishing the principal sources of contamination.

Previous work which reported that indium, on being alloyed into germanium, could leach out copper has been followed using this technique, and results are given.

The method described depends on nuclear activation of the copper-contaminated germanium followed by chemical separation of copper and germanium and the subsequent counting of the residual radioactive copper isotope. Specifically, the copper contamination occuring during processing of drift field and mesa type germanium transisitors has been investigated.

P. J. Olshefski 03

Constant-Current Generator Measures Semiconductor Resistance

Electronics, vol. 34, p. 63, November 24, 1961

An isolated constant-current generator reduces the time required to obtain resistivity profiles. High accuracy is obtained by reading current from dial settings instead of meters.

P. J. Olshefski 04

A Contactless Method for Measuring Resistivity of Silicon

Semiconductor Products, vol. 4, p. 34, December, 1961

A method for measuring resistivity of zone-refined single crystals has been developed using radio frequency currents and fixed capacitive coupling. Resistivity is determined from an equivalent parallel conductance and its relationship with circuit Q. After an initial calibration, there are no involved equations to solve. Samples can be completely characterized with a minimum of time and effort.

J. Oroshnik 05

A Precision Two-Point Probe for Measuring Resistivity of Semiconductors and Metal-to-Semiconductor Contact Resistance

Sylvania Technologist, vol. 10, p. 17, January, 1957

A two-point probe is described in detail which largely overcomes the major experimental difficulties in making resistivity measurements. Its adaptation to measuring the dc characteristics of soldered contacts to semiconductors is also covered.

J. Oroshnik and A. Many 06

Resistivity Homogeneity Evaluation of Germanium Single Crystals by Photovoltaic Scanning

Journal of the Electrochemical Society, vol. 105, p. 252C (A), December, 1958

The photovoltaic effect due to inhomogeneities in the bulk of Ge single crystals is used to determine the resistivity uniformity of Ge wafers. A plot of photovoltage (microvolt range) vs. position for any one wafer gives a qualitative picture of the resistivity variation throughout it. One can then determine how to cut a wafer such that samples of maximum uniformity may be expected. In addition, by using a sample of rectangular geometry, quantitative results can be obtained. This method is very sensitive and rapid, far more so than the usual resistivity scans. Resistivity variations of less than 0.1% in 10 ohm-cm Ge are easily detected. Results are presented. The photovoltaic method admits measurement of resistivity changes under conditions where ordinary probe methods are extremely difficult.

J. Oroshnik and A. Many 07

Evaluation of the Homogeneity of Germanium Single Crystals by Photovoltaic Scanning

Journal of the Electrochemical Society, vol. 106, p. 360, April, 1959

It is well known that photovoltages due to resistivity gradients in the bulk can exist in semiconducting crystals. This phenomenon is generally referred to as the "bulk photovoltaic effect." Resistivity inhomogeneities constitute small junctions throughout the material which allow charge separation to take place. These junctions give rise to easily observed photovoltages generally of the order of hundreds of microvolts. Photovoltages due to p-n junctions are usually in the range of tenths of a volt.

J. Oroshnik and A. Many 08

Quantitative Photovoltaic Evaluation of the Resistivity Homogeneity of Germanium Single Crystals

Solid-State Electronics, vol. 1, p. 46, March, 1960

An apparatus, based on the bulk photovoltaic effect, is described by means of which quantitative estimates of the resistivity changes throughout germanium single-crystal samples may be realized. The experimental technique consists of scanning the sample with a light spot and recording the photovoltage, or integrated photovoltage, versus position of the light spot. By taking into account the magnitudes of the photovoltages and photoconductance upon illumination, the resistivity changes in ohm-cm can be derived from the scans of integrated-photovoltage versus position. For germanium of 10 ohm-cm resistivity or less, the changes in resistivity determined by the use of this system are usually within 30 per cent of the actual changes determined with the two-point probe. For material that is homogeneous in lifetime, the error may be as little as 3 per cent. With this technique, single-crystal wafers may also be explored so as to determine sections of best uniformity. The method is essentially non-destructive.

P. L. Ostapkovich and M. Ranaldi 09

Relation Between Optical Orientation Accuracy and Etch Time

Journal of Applied Physics, vol. 30, p. 2019, December, 1959

Optical orientation is an easy, accurate way to orient germanium and silicon single crystals and to determine the degree of misorientation of a cut wafer.

Using a light source, a goniometer, and a screen or an eyepiece, we can compare the reflection from a mirror with the reflection from a preferentially etched surface of a crystal. When the reflection from the mirror and the center of the pattern characteristic of a given direction fall on the same point of the screen or eyepiece, the crystal is oriented in that particular direction. The degree of misorientation of a cut wafer may also be measured, using the same technique and reading the amount of angular displacement necessary to make the center of the pattern coincide with the reflection from the mirror.

H. Pagnia P1

On P-Type Conductivity in Vapor Deposited Germanium Films (In German)

Zeitshrift fur Naturforschung, vol. 16a, p. 1261, November, 1961

Electrical conductivity and Hall effect measurements were made with germanium films, vacuum evaporated on fused quartz plates having temperatures of about 450°K. Film thicknesses range from 400 to 2000 Å. Mean hole concentration was of the order $3.5 \times 10^{18}/cm^3$ with a weak dependence on film thickness. The concentration of the light and heavy holes were determined from the dependency of Hall-coefficient on magnetic force. The quotient of these concentrations was 0.045. Qualitatively there was satisfactory agreement with p-type monocrystalline germanium values.

T. Pankey P2

Magnetic Suspension Balance Method for Measuring Resistivities of Metals

The Review of Scientific Instruments, vol. 34, p. 1082, October, 1963

The excellent sensitivity of a permanent-magnet type magnetic suspension balance was utilized in a simple method for measuring the resistivities of bulk quantities of metals and alloys, based on the Arago effect. An estimated accuracy of 2% was obtained on samples 2.85 cm in diameter in the range 10^{-4} to $10^{-6}\Omega$-cm. The sensitivity could be extended at least an order of magnitude by narrowing the separation (approx. 2.5 cm) of the sample pendulum and suspended mass. Skin effects were negligible in samples this size, as the frequency of the excitation field was less than 1 cps.

F. G. Pany P3

Tungsten Needles for Semiconductor Tests

Electronics, vol. 35, p. 102, May, 1962

An electrolytic method is described for producing tungsten needles which typically have points with a radius of the order of 50 μ in. and a taper of 10 to 20 degrees included angle. A larger included angle can be produced for increased strength.

W. Paul P4

The Effect of Pressure on the Properties of Germanium and Silicon

Journal of Physics and Chemistry of Solids, vol. 8, p. 196, January, 1959

Measurements of the pressure dependence, in germanium and silicon, of the intrinsic resistivity, the fundamental absorption edge, the carrier mobilities, the magnetoresistance coefficients, and the dielectric constant are reviewed, and an explanation based on the shift of the band edges presented. Experimental evidence for similar behavior of corresponding band extrema in germanium, silicon and the intermetallics is given. The cases of the (111) and (100) minima in germanium and silicon and the Ge-Si alloys are discussed in detail. The results of measurements of the change of ionization energy of shallow and deep lying impurity levels in germanium and silicon are also reviewed.

W. Paul and H. Brooks P5

Effect of Pressure on the Properties of Germanium and Silicon

Progress in Semiconductors, A. F. Gibson and R. E. Burgess, Editors, vol. 7, p. 135, John Wiley & Sons, Inc., New York, N.Y., 1963

The purpose of this article is to review theoretical and experimental work on the effect of small changes in lattice constant on the electronic band structure of simple semiconductors. This examination will be concerned mostly with the effect of hydrostatic pressure on the band structure of the Group IV semiconductors germanium and silicon, and, to a certain extent, some related intermetallic compounds such as indium antimonide. One section is concerned with conduction measurements on germanium.

C. L. Paulnack and N. J. Chaplin P6

Minimal Maintenance Probe for Precise Resistivity Measurement of Semiconductors

Review of Scientific Instruments, vol. 33, p. 873, August, 1962

A four-point probe apparatus which reduces problems associated with point wear and maintenance of point spacing is described. The novel feature of this apparatus is the use of two expendable plastic moldings into which the current and voltage points are molded.

G. L. Pearson and J. Bardeen P7

Electrical Properties of Pure Silicon and Silicon Alloys Containing Boron and Phosphorus

Physical Review, vol. 75, p. 865, March, 1949

Electrical resistivity and Hall measurements have been made over the temperature range from 87°K to 900°K on pure silicon and on silicon alloys containing from 0.0005 to 1.0 percent boron or phosphorus.

The temperature variations of the concentrations of carriers, electrons and holes, and of their mobilities, are determined from the resistivity and Hall data for the different samples. In the intrinsic range, conductivity results from electrons thermally excited from the filled band to the conduction band. The energy gap is about 1.12 ev. The product of electron and hole concentration of any temperature is

$$n_e n_h = 7.8 \times 10^{32} T^3 \exp(-12{,}900/T)$$

In the saturation range, which occurs just below the intrinsic range, the concentrations are independent of temperature. All donors or acceptors are ionized and the concentration of carriers is equal to the net concentration of significant impurities.

V. A. Petrusevich, V. K. Subashiev and G. P. Morozov P8

An Investigation of Germanium Based on Photoelectric Methods

Soviet Physics - Solid State, vol. 3, p. 1091, November, 1961

It was previously shown that it is possible to determine the surface recombination velocity, diffusion length and absorption coefficient in a relatively simple way from the photoconductive spectral distribution curves of germanium.

In this paper, experimental results are presented which test these methods by comparison with data obtained from measurements of the photomagnetic effect.

Combining the photomagnetic effect and the photoconductive spectral response permits one to evaluate the ambipolar diffusion coefficient and the resistivity, and to determine the conductivity type of the semiconductor.

W. G. Pfann P9

Recent Advances in the Preparation of Semiconducting Materials

Solid State Physics in Electronics and Telecommunications, vol. 1, pt. 1, p. 17, Academic Press Inc., New York, N.Y., 1960

We describe here the compensation method of supressing unwanted fluctuations in the electrical conductivity of a semiconductor that arise from accidental fluctuations in growth conditions as the crystal is grown from a melt or solution. A change in growth-rate or degree of convection in the liquid changes the solute content of the freezing solid by changing the solute distribution in the diffusion layer adjacent to the liquid-solid interface. We describe this by saying that the effective distribution coefficient, k, changes, where k is defined as the ratio of the solute concentration in the freezing solid to that in the main body of liquid. If the solid is a semiconductor and the solute is a donor or acceptor, the electrical conductivity of the solid changes.

W. G. Pfann P10

Improvement of Semiconductor Devices by Elastic Strain

Solid-State Electronics, vol. 3, p. 261, November-December, 1961

The mobilities of current carriers in germanium, silicon and other semiconductors can be changed by approximately 50 per cent or more by elastic strain. The changes in mobility can be positive or negative, and they can be produced in selected directions in the crystal. One can, therefore, improve, or compensate against temperature change, certain electrical properties of junction devices, such as transistors, varactor diodes, tunnel diodes, solar diodes, and perhaps even thermoelectric devices. Some of these possibilities are examined in semi-quantitative fashion.

W. B. Pharo P11

Lapping and Polishing of Silicon Monocrystals

U. S. Army Signal Research and Development Laboratory, Fort Monmouth, N. J., Report No. 2188, April, 1961 (AD 264-249)

Details of an investigation to obtain high-quality silicon microsurfaces by cutting, lapping, and polishing processes and techniques are presented. The material used was low-dislocation-density silicon, grown by the Czochralski method. The cutting, lapping, and polishing techniques described, however, should be applicable to any single-crystal silicon material. Diamond paste and aluminum-oxide grit were the two polishing compounds used. In experiments on etching of polished surfaces, more damage was observed on diamond polished wafers. The heat resulting from the polishing operation caused a plastic deformation on the surface which was removable by a light-diluted CP_4 etch. As a result of this investigation, a completely scratch-free wafer surface was obtained as observed under 85X magnification, dark-field illumination.

C. P'i-huang P12

Measurement of the Resistivity and Hall's Constant of High-Resistance Semiconductors

Instruments and Experimental Technique, p. 939, September, 1960

The technique and apparatus for measuring resistivity and Hall's constant of semiconductor samples whose resistivity is in the range of 10^2 to 10^9 ohm-cm are described. A tube electrometer is used.

B. Pistoulet P13

Measurements of the Electrical Properties of Semiconductors (In French)

L'onde Electrique, vol. 35, p. 71, January, 1955

The purpose of this paper is to measure essentially the Hall effect and lifetime of minority carriers. These results are applied mainly to germanium, but it is evident that they can be applied to semiconductors in general.

N. M. Plakida P14

The Calculation of the Electrical Conductivity Tensor

Soviet Physics - Doklady, vol. 7, p. 1123, June, 1963

As is known, the kinetic coefficients for processes in weak nonequilibrium can be simply expressed in terms of the time correlation functions for the equilibrium state. The calculation of these quantities when the temperature is different from zero, however, is difficult. We will consider the two-time Green's temperature functions (for delay and lead), since the equations for these functions have a simple form and since the kinetic coefficients can be expressed directly in terms of the Fourier components of the Green's delay function. We will consider the example of calculating the electrical conductivity tensor for a system of electrons scattered by the phonons of a network or by contaminants. This problem has been considered by several authors using different methods.

T. O. Poehler and W. Liben P15

Induction Measurement of Semiconductor and Thin-Film Resistivity

Proceedings of the Institute of Electrical and Electronics Engineers, vol. 52, p. 731, June, 1964

Experiments have been conducted in measuring semiconductor wafer resistivity and thin-film resistance by placing samples at the end of an RF solenoid. Measurements were carried out on a modified Q-meter type circuit in which changes in effective coil parameters were detected with a sensitive vacuum tube bridge voltmeter.

M. Pollak and T. H. Geballe P16

Incipient Impurity Conduction in Silicon

Proceedings of the International Conference on Semiconductor Physics, Prague, 1960, p. 212, Academic Press, Inc., New York, N.Y., 1961

Impurity conduction in n-type silicon has been investigated by measuring ac and dc conductivity of samples which have lower impurity concentrations than have been measured before.

M. Pollak and T. H. Geballe P17

Low-Frequency Conductivity Due to Hopping Processes in Silicon

Physical Review, vol. 122, p. 1742, June 15, 1961

The complex conductivity has been measured in n-type silicon with various kinds of impurities at frequencies between 10^2 and 10^5 cps and temperatures between 1°K and 20°K. In most cases it is orders of magnitude larger than the measured dc conductivity and is attributed to polarization caused by hopping processes. The observed frequency dependence in the measured range can be expressed as $A\omega^{0.8}$, where A is a complex constant. At the low-temperature end the conductivity is roughly proportional to minority impurity concentration and is almost independent of the majority impurity concentration. At high temperatures the conductivity becomes approximately proportional to the product of both concentrations. A simple theory, based on the currently accepted model of impurity conduction, is given for the higher temperature range. It accounts well for the observed frequency and concentration dependences. However, only order-of-magnitude absolute agreement is obtained.

R. F. Potter and W. J. McKean P18

An Apparatus for Measuring the Piezoresistivity of Semiconductors

Journal of Research of the National Bureau of Standards, vol. 59, p. 427, December, 1957.

A detailed description is given of an apparatus and procedure designed to measure the piezoresistive effect in semiconductors over an extended temperature range. A tensile force up to 1 kilogram can be applied to the sample by means of a calibrated beam balance. The apparatus has been used for measurements on indium antimonide over the range 78°K to 300°K, and tensile stresses of the order of 5×10^7 dynes per square centimeter can be applied to samples that are cut in a special manner.

R. C. Powell and A. L Rasmussen P19

A Radio-Frequency Permittimeter

Transactions of the Institute of Radio Engineers, vol. I-9, p. 179, September, 1960

The measurement of low-impedance materials, such as conductors, semiconductors, electrolytes and high-permittivity materials has always been difficult, since errors due to electrode impedance, contact potentials, interaction of electrodes with the materials, series inductance and connection impedance can cause errors many times the actual quantity being measured. Methods that have been used at low frequencies involve four-terminal bridges and double transformers using an electrodeless ring of the material as a coupling loop. Such measurements at microwave frequencies have been made in a circular electric field or by using samples large compared to a wavelength. None of these methods are useful at radio frequencies, where many materials exhibit interesting and useful properties.

The RF permittimeter (so-called because of its analogy to the RF permeameter) also utilizes a circular electric field in a ring-shaped sample to eliminate electrode and series inductance problems. The circular electrical field is created in a transformer yoke of appropriate symmetry. This instrument is a two-terminal coaxial system designed for making measurements of conventional HF impedance-measuring equipment.

V. A. Presnov and V. F. Synorov P20

Investigation of the Surface Electrical Conductivity of Single-Crystal Germanium

Soviet Physics - Solid State, vol. 2, p. 357, September, 1960

The effect of various surface treatments on the surface conductivity of germanium is discussed. The type of bonding between surface germanium atoms and both protons and hydroxyl ions is described. The temperature dependence of the surface resistance of etched, sand-blasted, and lacquer-coated surfaces of both n- and p-type germanium is plotted. Coating with a polar lacquer reduced the surface conductivity of p-type, but increased that of n-type. Treating the surface of n-type with methyl alcohol increased the surface resistance of the germanium.

P. J. Price P21

Anisotropic Conduction in Solids Near Surfaces

International Business Machines Journal of Research and Development, vol. 4, p. 152, April, 1960

A reduction in the electrical conductivity of a solid results from "diffuse" reflection of electrons from the surfaces. The effect occurs for specular reflection also, if the operative electron-energy surfaces are not spherical. A theory of the latter case is given here. The average conductivity of a thin crystal tends to a finite limit (rather than zero) as the thickness tends to zero. The Hall effect for the same circumstances is also treated.

E. N. Pugh and L. E. Samuels P22

A Metallographic Investigation of the Damaged Layer in Abraded Germanium Surfaces

Journal of the Electrochemical Society, vol. 108, p. 1043, November, 1961

The structure of the damaged layer produced on {111} surfaces of germanium by several abrasion processes has been studied by a metallographic taper-sectioning technique. The study confirms that the abrasion process involves both cleavage and noncrystallographic fracture and establishes that the surface layers contain many cracks initiated by these fracture processes. Dislocations are not introduced into the surface layers. Measurements of the depth of the layers containing the damage cracks are in sufficiently good agreement with estimates of the depth of damage made by established methods to indicate that the cracked layer is the classical damaged layer.

E. N. Pugh and L. E. Samuels P23

Etching of Abraded Germanium Surfaces with CP-4 Reagent

Journal of the Electrochemical Society, vol. 109, p. 409, May, 1962

The dissolution of the damaged layer has been investigated by a metallographic taper-sectioning technique and by direct microscopic examination of the etched surfaces. It is shown that the reagent penetrated the damage cracks in abraded surfaces, opening them into deep crevices. At the same time, the surface begins to be smoothed out, a characteristic cellular pattern being produced. A completely flat surface is not achieved until well after the damaged layer is removed. A critical comparison of certain methods of estimating the depth of the damaged layer is made in the light of these observations. It is concluded that metallographic methods are the most reliable.

A. P. Ramsa, H. Jacobs and F. A. Brand R1

Microwave Techniques in Measurement of Lifetime in Germanium

Institute of Radio Engineers National Convention Record, vol. 7, pt. 3, p. 159, 1959

New methods of measurement of lifetime of added current carriers in germanium single crystals are described. The techniques utilize the absorption of microwave power upon injection of minority carriers. An analysis is made of possible experimental errors.

A. P. Ramsa, H. Jacobs and F. A. Brand R2

Microwave Techniques in Measurement of Lifetime in Germanium

Journal of Applied Physics, vol. 30, p. 1054, July, 1959

New techniques are proposed for the measurement of lifetime in semiconductors by utilizing the absorption of microwave power by charge carriers. The densities of holes and electrons are varied by irradiation with light or the conduction mechanism. Agreement is found when the microwave absorption methods are compared with the more established photoconductivity decay techniques. One of the new methods offers an advantage in that electrode attachments are no longer required.

P. Ransom R3

High Resistivity N-Type Silicon Crystals Grown From Fused Quartz Crucibles

Solid State Physics in Electronics and Telecommunications, vol. 1, p. 139, Academic Press Inc., New York, N.Y., 1960

It is well known that crystals grown by the Czochralski technique from fused quartz crucibles are contaminated by quartz dissolved in the molten silicon from the crucible walls. Assuming this dissolved quartz to contain an acceptor impurity, then the important parameters controlling the resisitivity at the top of high-resistivity phosphorus-doped crystals are the melting and seeding-on times, and the rate at which the quartz is being dissolved. For a low level of contamination these times must be kept short, and for consistent results they must be controlled as accurately as possible.

R. R. Rau and M. E. Caspari R4

Faraday Effect in Germanium at Room Temperature

Physical Review, vol. 100, p. 632, October 15, 1955

When a plane polarized electromagnetic wave passes through a semiconductor and a static magnetic field is applied along the direction of propagation, there occurs a rotation of the plane of polarization and the transmitted radiation is found to be elliptically polarized. For small losses, weak magnetic fields, and small values of $\omega\tau$ (assuming the relaxation time τ to be energy independent) the angle of rotation of the plane of polarization can be expressed to a first order of approximation by the simple formula: $\theta = 1/2(\mu_o/\epsilon_o)^{1/2}(\sigma_o\mu B/\sqrt{K'})t$, where μ is the Hall mobility, σ_o is the dc conductivity, B is the magnetic field, t is the thickness of sample traversed, K' is the dielectric constant of the material at the frequency employed in the experiments, and ϵ_o and μ_o are the dielectric constant and the permeability of free space respectively. For spherical energy surfaces, the degree of ellipticity, which is a second-order effect, can be expressed by the relation $E=(\mu_o/\epsilon_o)^{1/2}[\sigma_o(\mu B)(\omega\tau)/\sqrt{K'}]t$ where $\omega/2\pi$ is the frequency and τ is the relaxation time. Thus, for small losses the ellipticity is proportional to the latter quantity. Measurement results and applications are presented.

Yu I. Ravich R5

Determining the Characteristic Parameters of Minority Carriers in Semiconductors from Measurements of Photoconductivity and the Photomagnetic Effect

Soviet Physics - Solid State, vol. 3, p. 1162, November, 1961

A calculation is given of photoconductivity and the photomagnetic effect in the presence of capture levels in semiconductors and also for the case of nonlinear recombination and for a cylindrical specimen. There is a discussion of the problem of determining recombination constants and the mobility of minority current carriers from measurements of these effects.

R6

T. G. R. Rawlins

Measurement of the Resistivity of Epitaxial Vapor Grown Films of Silicon by an Infrared Technique

Journal of the Electrochemical Society, vol. 111, p. 810, July, 1964

An infrared reflectivity technique is outlined whereby the reflectivity may be correlated with dc resistivity of thin vapor deposited epitaxial silicon layers. The theory underlying the method is outlined and calculated curves for different planes of polarization are given. Experimental results are described for a range of resistivities between 0.03-60 ohm-cm. Limitations of the equipment used are discussed and the validity of the method examined.

R7

J. M. Reber

Potential Distribution in a Rectangular Semiconductor Bar for Use with Four-Point Probe Measurements

Solid-State Electronics, vol. 7, p. 525, July, 1964

The electric potential distribution is given for an arbitrary placement of current contacts on one side of a rectangular bar of semiconductor material having finite dimensions and two conducting ends. A factor is derived which can be used in conjunction with a four-point probe to correct the measured conductivity of such a bar for the effects of its dimensions and plated ends. This factor is of utility in the correlation of conductivity measurements made on a single specimen by means of two- and four-point probes.

R8

B. Reed, O. A. Weinreich and H. F. Mataré

Conductivity of Grain Boundaries in Grown Germanium Bicrystals

Physical Review, vol. 113, p. 454, January 15, 1959

The conduction of current in the grain boundary of a grown germanium bicrystal has been studied as a function of doping. For all samples, the behavior shows only a small temperature dependence from 2°K to 300°K. The conduction in the grain boundary is ohmic if no secondary effects are introduced by conduction in the bulk material. Samples with no doping and with n-type, p-type, or copper doping are all characterized by having a resistivity of about 3000 to 11,000 ohms per square. The lack of a strong dependence on doping indicates that the grain boundary behavior is not due to the segregation of impurities at the boundary.

R9

F. J. Reid

Electrical Analysis of III-V Compound Semiconductors

Compound Semiconductors, vol. I, Preparation of III-V Compounds, eds.: R.K. Willardson and H. L. Goering, ch. 17, p. 158, Reinhold Publishing Corporation, New York, N.Y., 1962

The purpose of this chapter is to describe and illustrate the use of the electrical properties (principally the Hall effect and carrier mobility) of III-V semiconducting compounds for impurity analyses. The detection of impurities in high-purity germanium and silicon is almost completely limited to the interpretation of measured electrical properties. This is true for evaluating high-purity InSb and will also be true for other III-V compounds as higher-purity materials become available.

F. J. Reid, S. E. Blum and R. K. Willardson R10

The Determination of Impurities in III-V Semiconducting Compounds

The Electrochemical Society Meeting, Philadelphia, May, 1959, Enlarged Abstracts of Papers Presented by the Electronics Division, p. 129

Many of the compounds composed of elements from Groups IIIA and VA exhibit useful semiconducting properties. The possibility of developing these materials for a variety of solid-state devices, including both high- and low-temperature diodes and transistors, is encouraging. However, improvement in the purity of the constituent elements will have to be realized in a manner similar to the development of high-purity silicon and germanium. In the development of the required purification procedures, the evaluation of the process is an important factor, and at a later date, standards for quality control of the material will be necessary. The evaluation of the materials consists of identifying the impurities present and of determining the concentration of impurities. This may be an evaluation of the purity either of the individual elements or of the resulting compounds.

J. E. Reynolds R11

A Treatment of Diffusion Errors Affecting Junction Depth

Transactions of the Institute of Radio Engineers, vol. ED-8, p. 377, September, 1961

An error treatment of the diffusion variables of time, temperature and starting resistivity has been made in regard to their effects upon junction depth. An analytical equation has been derived for engineering usage in determining the percent error in junction depth after diffusion for a specified time with a given surface concentration. A sample calculation using the equation is presented along with a method of estimating errors in junction depth due to heating and cooling in the diffusion cycle.

G. Richter and T. K. Dzong R12

Determination of the Diffusion Constant, the Drift Mobility and the Lifetime of Minority Charge Carriers in Semiconductors by Time of Transit Measurements(In German)

Monatsberichte der Deutschen Akademie der Wissenschaften zu Berlin, vol. 2, no. 8, 1960

It was shown in a previous paper that from time of transit measurements, one can determine the drift mobility μ, the lifetime τ, and the diffusion constant D of minority charge carriers. In the case of a small-time disturbance ($\Delta t \ll \tau$) acting at an arbitrary place in the crystal, one considers solutions of a one-dimensional problem in $n_1(x,t) = f(D,\mu,\tau,E,x,t)$. If the collector is a distance x from the emitter, the collector current is proportional to $n_1(x,t)$. If the time of transit t_m is defined as that time between injection and maximum collector current (i.e. $\partial n_\tau/\partial t = 0$) then

$$\frac{x^2}{t_m^2} = \frac{2D}{t_m} + \frac{4D}{\tau} + \mu^2 E^2.$$

One can then determine μ, D, and t from the solution $t_m = f(x,t)$.

W. Rindner and R. F. Tramposch R13

Plastic Deformation of Germanium at and below Room Temperature

Journal of Applied Physics, vol. 34, p. 758, April, 1963

It is found that Ge can be plastically deformed by indentation at temperatures down to 78°K without introducing cracks. Photomicrographs are presented which show the characteristic etch-pit pattern of dislocation half-loops resulting from annealing and etching of indented (111) surfaces.

D. H. Roberts and B. L. H. Wilson R14

Some Effects of Oxygen on Resistivity in Silicon

Journal of Applied Physics, vol. 30, p. 447, March, 1959

The axial variation of oxygen concentration in a p-type vacuum-growth single crystal of silicon has been determined by measurements of the absorption coefficient at 9 μ. The value of the absorption coefficient, a, has previously been shown to vary linearly with the concentration of dissolved oxygen, the residual adsorption coefficient in oxygen-free silicon being 0.8 cm^{-1}. The crystal was grown in a synthetic quartz crucible by the Services Electronics Research Laboratory, Baldock, from material produced in this laboratory by the pyrolysis of silane. The measurements were compared with resistivity measurements before and after annealing for 100 hr at 450°C. It appeared that the effect of oxygen was to lower the resistivity before annealing and to raise it after annealing.

J. Robin R15

The Influence of Pressure on Some Properties of Semiconductors (In French)

Le Journal de Physique et le Radium, vol. 21, p. 130, February, 1960

Work dealing with the pressure dependence of some properties (e.g., electrical conductivity, resistivity of the p-n junction, and the absorption edge of the fundamental band) of certain semiconductors is summarized. The influence of the pressure is indicated by the variation of the width of the energy gap sometimes accompanied by the change of electron and hole mobilities.

K. Rose R16

A Microwave Technique for the Study of Deviations from Ohm's Law in High Resistivity Semiconductors

University of Illinois, Urbana, Illinois, Technical Report No. 1, Contract Nos. DA 36-039SC-78313 and AF 49(638)-417, June 1, 1962

The development of a microwave technique for the study of deviations from Ohm's law in high-resistivity semiconductors is presented in this report. In this technique a high-level microwave field is used to produce the deviations as well as measure them. A semiconductor sample is placed in a resonant cavity and the conductivity of the sample is inferred from measurements of transmission through the cavity. Preliminary measurements on samples of high-resistivity silicon at temperatures down to the boiling point of liquid nitrogen are reported. The results of these measurements indicate that the technique in its present form is applicable to semiconductors with resistivities up to 600 ohm-cm.

R. L. Rouse R17

Small Scale Impurity Fluctuations in Silicon Crystals Grown from the Melt

Journal of the Electrochemical Society, vol. 105, p. 251C (A), December, 1958

Impurity fluctuations in Si single crystals grown from the melt have been shown up by the technique of solid-state diffusion in compensated samples in which an impurity step was first incorporated by remelting and recrystallization. Fairly regular striations were found with a spacing of a few microns and corresponding to a change in relative impurity concentrations of order 1%.

R. N. Rubinshtein and V. I. Fistul' R18

Surface Conductivity Determination of Semiconductor Crystals by the "Wedge" Method

Soviet Physics - Doklady, vol. 4, p. 431, October, 1959

In the investigations of the surface properties of germanium and silicon it is desirable to have, among other methods, one which would allow a unique determination of the magnitude of the surface conductivity σ_s. It is considered that the surface conductivity may cause some (and sometimes quite substantial) increase of the reverse current in semiconductor diodes. The methods of processing the surface of germanium (silicon) crystals adopted in each particular case should cause changes in the surface conductivity; the literature, however, contains no information about direct methods of its measurement. The direct measurement of the quantity σ_s is possible with the method proposed in this paper, which the authors call the "wedge" method.

H. G. Rudenberg R19

Resistivity Measuring Techniques in Semiconductors

Semiconductor Products, vol. 2, p. 28, September, 1959

The development and design of direct reading apparatus for resistivity measurements are described. Methods of conductive, capacitive and inductive connection to the semiconductor were investigated. For small samples or localized measurements in Ge and Si, four-point probes in a square array are utilized. Spurious rectification at the point contacts and high probe resistances are avoided by use of a small forward-biasing direct current which stabilizes the series resistance of the probes. A tuned detector gave best results with small signal,a-c measurements. In ac/dc measurements with a potentiometer or electrometer, forward bias of both voltage probes is assured by special shielding and proper placement of impedances. Thus,resistivities of 1000 ohm-cm may readily be measured with proper surface preparation of the sample and low enough signals to avoid errors from injection effects. A calibration standard using thin silicon slices with alloyed ohmic contacts is used to check absolute accuracy. The apparatus described can be used to measure the surface sheet resistance of diffused layers, and the bias current here isolates this layer electrically from an opposite-polarity substrate. Accuracies of 5 to 10% in the range of 0.01 to 1000 ohm-cm are obtainable.

F. M. Ryan R20

Rotating Sample Method for Measuring the Hall Mobility

The Review of Scientific Instruments, vol. 33, p. 76, January, 1962

A simple apparatus is described for measuring Hall mobilities. The sample to be measured is rotated in an external dc magnetic field. The sample thus "sees" an ac magnetic field and ac magnetic field Hall techniques may be used. Methods are described for obtaining dc or ac Hall output voltages. Probe misalignment voltages are rejected by this technique, as they are in the standard ac magnetic field method. The method yielding a dc Hall voltage enables one to use simple measurement equipment. The method yielding an ac Hall voltage has all of the advantages of the standard ac magnetic field technique, yet it simplifies the construction of auxiliary equipment and allows one to investigate low-mobility samples in the high magnetic field region by using a powerful dc electromagnet. The increased signal level found at the higher magnetic fields might extend the useful range of Hall measurements to lower mobilities than presently measurable. The results of some Hall mobility measurements using a rotating sample are compared with the values obtained by conventional techniques.

O. Ryuzan R21

Activation Energy of Acceptors Introduced into Germanium by Plastic Twisting

Journal of the Physical Society of Japan, vol. 16, p. 2339, November, 1961

It has been known that dislocation acceptors can be introduced into germanium crystal by plastic bending at temperatures above 500°C. Pearson, Read, Morin, and Twcet found that the acceptor levels lie 0.2 eV below the conduction band and 0.15 eV above the valence band. Acceptors can be introduced in the same way by plastic twisting. One of these acceptor levels was determined in this note from the measurements of temperature variation of Hall coefficient and resistivity.

G. A. Samara and H. G. Drickamer S1

Pressure Induced Phase Transitions in Some II-VI Compounds

Journal of the Physics and Chemistry of Solids, vol. 23, p. 457, May, 1962

Pressure induced phase transitions have been found for a number of II-VI compounds. Transitions to a conducting state have been found for ZnS(240-245 kbars), ZnSe(165 kbars) and ZnTe(140-145 kbars). All these compounds have the zinc blende structure at low pressure. It is believed that these are all solid - solid transitions. CdTe, which is also initially in the zinc blende structure, has a transition with a relatively small drop in resistance at 30 kbars; at 100 kbars there is a transition to a conducting state. CdS which is initially wurtzite, has a transition with a very sharp drop in resistance at about 20 kbars. The resistance rises again and levels near 375 kbars. There is then a relatively sharp cusp at 465 kbars. This cusp makes a very good high pressure calibration point.

O. Sandus S2

Comments on "Electrodeless Measurements of Semiconductor Resistivity at Microwave Frequencies"

Proceedings of the Institute of Radio Engineers, vol. 50, p. 473, pt. 1, April, 1962

H. Jacobs, et al., have described a method, employing microwaves, that determines the conductivity of semiconductors. This method is of particular interest in those cases where four-point probe techniques may be difficult. However, the authors fail to mention the limitations imposed by measurements at microwave frequencies when the measurements are used to obtain data at dc and low frequencies.

In general, the conductivity, as measured at any frequency, is composite. It consists of the desired dc conductivity plus the conductivity due to dispersion (not considering the interfacial-polarization contribution of inhomogeneous materials). The microwave method is applicable, then, to those substances that do not have a dispersion region of the order of magnitude of the dc conductivity at the frequency of measurement. This limitation may not be of significance for a great many semiconductors, such as some oxides and sulfides where the lowest dispersion frequency lies in the infrared, but this is not necessarily true a priori. Other considerations as to choice of frequency are also important.

L. G. Sapogin and V. M. Ivko S3

Circuit for Measuring and Recording the Resistance of Semiconductors in Coordinates log R = f(1/T)

Soviet Physics - Solid State, vol. 2, p. 1346, January, 1961

The equipment comprises a logarithmic and a hyperbolic amplifier, circuit details of which are given.

W. Sasaki, M. Shibuya and K. Mizuguchi S4

Anisotropy of Hot Electrons in N-type Germanium

Journal of the Physical Society of Japan, vol. 13, p. 456, May, 1958.

Electromotive force perpendicular to the current flowing in n-type germanium samples is observed. The deviation angle of electric field vector from current vector is a function of current orientation, temperature, and field strength, and in some cases exceeds 20°. This effect can be attributed to the anisotropy in electric conduction due to the ellipsoidal energy surfaces.

E. J. Scheibner S5

Solid-State Physical Phenomena and Effects: Part I

Transactions of the Institute of Radio Engineers, vol. CP-8, p. 133, December, 1961

This first part of a four-part paper describes fifteen solid-state phenomena and physical effects. These phenomena are part of a group whose effects depend upon either the transport of electrons and holes or upon the band structure of the material.

E. J. Scheibner S6

Solid-State Physical Phenomena and Effects - Part II

Transactions of the Institute of Radio Engineers, vol. CP-9, no. 1, p. 19, March, 1962

This is the second in a series of four articles designed to provide ready information to workers in the field of molecular electronics. Fifteen additional solid-state phenomena and physical effects are described. Each of these phenomena belongs to a group whose effects depend either upon the transport of electrons and holes or upon the band structure of the material.

E. J. Scheibner S7

Solid-State Physical Phenomena and Effects - Part III

Transactions of the Institute of Radio Engineers, vol. CP-9, p. 61, June, 1962

This is the third in a series of four articles describing solid-state phenomena. Twelve solid-state phenomena and physical effects are provided. All of the twelve phenomena belong to a group which includes effects related to the dielectric properties of materials and transport phenomena for particles other than electrons or holes.

E. J. Scheibner S8

Solid-State Physical Phenomena and Effects - Part IV

Transactions of the Institute of Radio Engineers, vol. CP-9, p. 119, September, 1962

This is the fourth in a series of articles dealing with phenomena of the solid state. Nineteen solid-state phenomena and physical effects are described. This group of phenomena includes primarily the resonance effects, that is, those effects which can be described in terms of discrete energy levels rather than energy bands.

P. A. Schumann, Jr. and J. F. Hallenback, Jr. S9

Measurement of Silicon Epitaxial Layer Resistivity with a Four-Point Probe

Journal of the Electrochemical Society, vol. 109, p. 210C (A), August, 1962

A nondestructive technique for the measurement of silicon epitaxial layer resistivity with a four-point probe is described. Conventional probe points are mounted so that the voltage drop is measured through the wafer. The relationship between the epitaxial layer resistivity and the physical parameters of the probe and wafer are discussed. Measurements evaluating the performance of the probe are described, and it is shown that epitaxial films on highly doped substrates can be readily characterized by this technique.

P. A. Schumann, Jr. and J. F. Hallenbeck, Jr. S10

A Novel Four-Point Probe for Epitaxial and Bulk Semiconductor Resistivity Measurements

Journal of the Electrochemical Society, vol. 110, p. 538, June, 1963

A novel configuration for a four-point probe with points on opposite sides of the wafer is proposed. The potential distribution from a small area contact on a two-resistivity epitaxial structure is given. The effects of the layer and substrate parameters on this potential distribution are discussed. A consideration of these potential distributions indicates that a probe of this design would be usable for epitaxial layer resistivity measurement under the design considerations discussed. These same potential distributions indicate that a two-point probe is also usable. Brief experimental results of the over-under four-point probe on bulk silicon are given. The two-point probe is contrasted experimentally with the p-type control wafer, and three-point breakdown for measurement of N on N+ epitaxial silicon.

P. A. Schumann, Jr. and L. S. Sheiner S11

Precision Over-Under Four-Point Probe with a Small Probe Spacing

The Review of Scientific Instruments, vol. 35, p. 959, August, 1964

The design of an over-under four-point probe for resistivity measurement of semiconducting material is given. The minimum probe spacing obtainable with this probe is 2.0 mils (50.8μ). A comparison between this four-point probe at a spacing of 5.3 mils (135μ) and others for the measurement of nonepitaxial slices is given. A thickness correction factor for these slices is calculated. The small probe spacing obtainable with this probe makes it possible to map the resistivity variations across slices accurately and to measure N/N+ or P/P+ epitaxial layer resistivity.

G. Schwabe S12

The Measurement of Small Diffusion Depths in Semiconductor Materials (In German)

Zeitschrift für angewandte Physik, vol. 14, p. 297, May, 1962

A simple method for obtaining a sharp edge in grinding the semiconductor specimen is described; this, in conjunction with a process of Cu plating to make the p-n boundary visible, facilitates the measurement of diffusion depths. The plating method is also applicable to n^+-n junctions.

G. H. Schwuttke S13

Routine Crystal Orientation of Germanium and Silicon by High-Intensity Reflectograms

Sylvania Technologist, vol. 11, p. 2, January, 1958

Two optical methods developed in the Research Laboratories for the orientation of single crystals of Ge and Si are described. Both methods employ light beams to produce reflectograms from the principal crystal faces. With samples mounted on a goniometer built into the instruments the measurement of orientation and tilt angle can be made in a few minutes with an accuracy of ±0.5 degree of arc.

G. H. Schwuttke S14

Study of Copper Precipitation Behavior in Silicon Single Crystals

Journal of the Electrochemical Society, vol. 108, p. 163, February, 1961

The precipitation behavior of copper in silicon single crystals containing different amounts of oxygen has been investigated within the temperature range of 900° -1300°C. Precipitation which occurs during the cooling period on structural defects and at random sites throughout the bulk crystal has been detected by infrared transmission microscopy. The shape and crystallographic relationship of the precipitate as related to the silicon matrix was determined. The reliability of the method of copper decoration for the determination of low dislocation densities in the presence of oxygen was investigated by comparing copper decoration pictures with x-ray diffraction photomicrographs.

G. H. Schwuttke S15

X-Ray Diffraction Microscopy Study of Imperfections in Silicon Single Crystals

Journal of the Electrochemical Society, vol. 109, p. 27, January, 1962

The application of x-ray diffraction microscopy to the study and control of crystal perfection of silicon is discussed. The major significance of this technique in establishing standards by which the validity of other methods, such as etch-pit counting and decoration techniques, can be gauged is pointed out. The method previously used only for the mapping of dislocations in single crystals is now applied for the detection of impurities, segregation effects, cluster formation, and second phases. Segregation effects are studies in crystals containing oxygen. It is shown that, due to microsegregation of oxygen, the silicon lattice can become strongly anisotropic. The influence of such a lattice on the diffusion properties is shown. Precipitation effects are investigated in crystals containing copper precipitates. The results are verified by infrared microscopy. Experimental details of a method unique for the investigation of large crystal wafers are given.

G. H. Schwuttke S16

X-Ray Observations of Partial Dislocations in Epitaxial Silicon Films

Journal of Applied Physics, vol. 33, p. 1538, April, 1962

Crystal perfection of epitaxial silicon films has been studied by x-ray diffraction microscopy. X-ray observations indicate the presence of defects in (111) planes with [112] Burgers vectors. The x-ray image associated with these defects is interpreted as due to stacking faults bounded by partial dislocations. Large stacking faults, the faulted area between the partials being as wide as 10 μ, have been found to be the principal imperfections in epitaxially grown silicon films.

G. H. Schwuttke S17

Direct Observation of Imperfections in Semiconductor Crystals by Anomalous Transmission of X-Rays

Journal of Applied Physics, vol. 33, p. 2760, September, 1962

An experimental technique for the direct observation of imperfections in single crystals is described. It is based on the anomalous transmission effect of x-rays observed in crystals of high perfection. The parallel-beam method previously used only for the mapping of dislocations has been improved so that large-area x-ray topographs are recorded. It can now be applied to the detection of impurities, segregation, and precipitation effects in semiconductor materials. Microsegregation of oxygen in silicon, precipitation of copper in silicon, and arsenic segregation in germanium were used to study the influence of segregation and precipitation on the anomalous transmission. Working conditions of x-ray diffraction microscopy are discussed, and it is shown that segregation phenomena produce typical impurity contrast which is reflection-dependent if the impurities are in solid solution. For precipitated impurities, this relation does not exist.

A. Seeger S18

Recent Advances in the Theory of Defects in Crystals

Physica Status Solidi, vol. 1, no. 7, p. 669, 1961

The present report is an extension and up-to-date version of lectures and mimeographed notes presented at the summer school on "Defects in Crystalline Solids" held in 1959 at the University of Cambridge, England. The director of the summer school, Professor N. F. Mott, had asked the author to emphasize in that course the possibility of carrying out quantitative calculations on defects and of obtaining reliable numerical results on activation and interaction energies etc. This feature has been preserved in the present paper. The paper is not intended to be a report on the literature of the field, but it attempts rather to present in a coherent and unified way some recent developments with which the author and his collaborators have been associated. References have frequently been given to summaries or to recent papers which reflect the present situation of the field. References to earlier work can easily be obtained from these.

A. Seeger and H. Statz S19

The Electrical Resistivity of Stacking Faults

Physica Status Solidi, vol. 2, no. 7, p. 857, 1962

A one-electron theory of the scattering of electrons from infinitely extended stacking faults in f.c.c. metals is given for an arbitrarily shaped Fermi surface. The corresponding linearized transport problem is then solved without approximation. The wave functions are represented by expansions in terms of Wannier functions. The method could be used for a self-consistent calculation of the potential of a stacking fault, and extended to related problems of plane interfaces. The scattering of electrons from the stacking fault is expressed in terms of a generalized reflection coefficient R. The dependence of R on the wave-vector of the incident electrons is studied for a Fermi surface of the type typical of noble metals, certain simplifying assumptions concerning the number of matrix elements between Wannier functions being made. The average R is found to be relatively large, which agrees with experiment and earlier theoretical estimates.

B. Selikson S20

Anomalous Resistivity Measurements on Tunnel Diode Materials

Journal of the Electrochemical Society, vol. 107, p. 199C (A), August, 1960

Four-point-probe resistivity measurements have been made on a number of germanium single crystal slices. Samples chosen had resistivities ranging from 2 ohm-cm to 0.006 ohm-cm. It was observed that while the apparent resistivities rose as the slice was lapped down, the corrected resistivity remained constant until a certain thickness was reached. On further reduction of thickness the corrected resistivity started to increase. The percentage increase of resistivity and the thickness at which the increase was initiated is resistivity-dependent.

C. B. Sharpe S21

A Graphical Method for Measuring Dielectric Constants at Microwave Frequencies

Transactions of the Institute of Radio Engineers, vol. MTT-8, p. 155, March, 1960

This paper describes a graphical method for measuring the real and imaginary parts of the dielectric constant of materials at microwave frequencies. The method is based on the network approach to dielectric measurements proposed by Oliner and Altschuler, in which the dielectric sample fills a section of transmission line or waveguide. In contrast to their method, the network representing the dielectric sample is analyzed in terms of the bilinear transformation

$$r' = (ar + b)/(cr + d), \quad ad - bc = 4.$$

The analysis proceeds from the geometric properties of the image circle in the plane obtained by terminating the output line in a calibrated sliding short. The technique described retains the desirable features of the network approach but avoids the necessity of measuring both scattering coefficients. As a result the procedure is more direct and, in the case of the TEM configuration, leads to an entirely graphical solution in which the complex dielectric constant can be read from a Smith chart overlay.

A. I. Shelykh S22

Determination of the Sign, Concentration, and Mobility of Current Carriers in Semiconductors

Soviet Physics - Solid State, vol. 4, p. 2349, May, 1963

A method is proposed for ascertaining the main parameters determining kinetic effects in conductors -- the sign, concentration, and mobility of current carriers. The method is based on compensation of the motion of the current carriers in an electric field (drift) by motion of the entire conductor in the opposite direction in a magnetic field. The transverse magnetic field, relative to which the current carriers move under the influence of the indicated factors, is used only in determining whether the conditions of compensation are met, and does not enter into the final calculation formulas. The case of a semiconductor with current carriers of one sign is considered.

W. Shockley and A. Goetzberger S23

The Role of Imperfections in Semiconductor Devices

Metallurgy of Semiconductor Materials, vol. 15, J. B. Schroeder, ed., conference, Los Angeles, 1961, p. 121, John Wiley and Sons, Inc., New York, N. Y., 1962

Recent work covering the role of imperfections in semiconductor devices is reviewed in this paper. The discussion includes the effect of metal precipitates and their influence on junction characteristics, avalanche effect, and microplasmas occurring at irregularities in the diffusion pattern caused by dislocations. Pipes through diffused layers are shown to be caused by a diffusion mechanism. The statistical limitations of junction uniformity and thinness of base layers are compared with the existing technology.

W. Shou-wu S24

Measurement of the Lifetime of Minority Current Carriers in Semiconductors by Observing the Photoconductive Decay of the Spreading Resistance under a Point Contact (In Chinese)

Acta Physica Sinica, vol. 19, no. 3, p. 176, March, 1963

A new method for measuring the lifetime of minority current carriers in semiconductors is described. Measurements are made by observing the photoconductive decay of the spreading resistance under a point contact. This method possesses the following advantages: (1) It is not necessary to cut the specimen into a special form. (2) No electrode has to be fixed to the specimen. (3) It is applicable for testing inhomogeneous specimens. (4) No particular surface treatment is necessary. (5) Apparatus used is simple and easy to operate. (6) Adequate accuracy is obtainable. A theoretical analysis is given of the effects of surface recombination velocity and of varying absorption depth of the light in the specimen. Experimental details and discussions are given for Ge and Si specimens. Results are in agreement with those obtained by other methods.

Yu. N. Shuvalov S25

The Relationship between Electrical Conductivity and Electron Density Distribution in Germanium Crystals

Soviet Physics - Solid State, vol. 1, p. 187, February, 1959

A comparison was made of the x-ray reflection intensities of germanium crystals of different conductivity at room temperature and at higher temperatures. A marked one-sided variation in reflection intensity was observed on changing to specimens of higher conductivity and also as a result of heating the specimens. This variation was interpreted on the basis of a Fourier synthesis as due to a redistribution of the electron density in the crystal, which finally results in an increased electron density along the line of the chemical bond during the increase in conduction.

V. G. Sidyakin and E. T. Skorik S26

Measuring the Resistance of Semiconductors at High Frequencies

Instruments and Experimental Techniques, 1960, no. 2, p. 326, December, 1960

A simple method of measuring the resistance of semiconductors at high ac frequencies by means of an ordinary Q-meter is described. A formula is given for calculating the resistance of the sample from measurements of the Q and capacitance of the Q-meter tank in which the sample is placed.

S. J. Silverman and C. L. Paulnack S27

Precision Resistivity Measurements to Evaluate Silicon Single Crystals

Journal of the Electrochemical Society, vol. 105, p. 253C (A), December, 1958

The development of a precision resistivity measurement technique has permitted an exact study of both the radial and the axial variations in Si single crystals as a function of growth parameters. Both n- and p-type specimens in the resistivity range from 30 to 0.05 ohm-cm have been investigated. The precision of a particular measurement at any one position on the specimen is sufficiently high to detect small fluctuations solely attributed to the impurity distribution within the material.

A more complete discussion is presented to enumerate the pertinent factors affecting these observations. This information is essential in optimizing those crystal growing conditions which influence resistivity homogeneity.

R. Simon, J. H. Cahn and J. C. Bell S28

Uniformity of Electrical Current Flow in Cylindrical Semiconductor Specimens with Cylindrical Metallic End Caps

Journal of Applied Physics, vol. 32, p. 46, January, 1961

The distribution of current is computed in a cylindrical semiconductor specimen provided with cylindrical metallic end caps of the same diameter as that of the specimen and electrical lead wires of much smaller diameter. Nonuniformity of the longitudinal current density of 1% or less can be obtained in specimens with electrical resistivities at least 200 times greater than that of the end caps if the lengths of the specimens are at least equal to their diameters and if the length of each end cap is at least 0.3 diam.

M. H. Sirvetz and W. W. Oldfield, Jr. S29

An Investigation of the Microwave Properties of Diamond

Hyletronics Corporation, Report No. AFCRL-62-159, Contract No. AF 19(604)-8838, March 14, 1962, (AD 275138)

An X-band resonant cavity apparatus has been built and applied to the study of the microwave dielectric properties of naturally occurring diamond crystals. The microwave dielectric constant of several insulating diamonds has been measured and found to be only slightly higher than the optical value. The resistivity of a semiconducting diamond has been deduced from microwave measurements. The activation energy obtained from the temperature dependence of the microwave losses is in good agreement with that reported by other workers using dc techniques.

M. J. A. Smith S30

Microwave Discriminator for the Frequency Stabilization of a Reflex Klystron

Journal of Scientific Instruments, vol. 39, no. 3, March, 1962

A microwave discriminator has been used very successfully to stabilize the microwave frequency from a reflex klystron in an X band 100 kc/s magnetic field modulation spectrometer. The instrument may be attached to any existing microwave system and requires a minimum of adjustment and maintenance.

The discriminator consists of two identical H_{012} cylindrical cavities having adjustable plungers which are tuned to frequencies just above and just below the microwave frequency.

R. C. Smith S31

Dendritic Growth Studies by Pulse Plating Techniques

The Electrochemical Society Meeting, Chicago, May, 1960, Electronics Division Abstracts, vol. 9, no. 1, p. 159

Pulse electroplating is used to reveal sharp variations of resistivity on germanium dendrites. Good resolution of these variations is obtained in the plate deposited in the meniscus region of the plating solution. Since such resistivity variations must occur during the formation of the dendrite, certain of the growth processes can be deduced from their configuration. At least two processes are indicated, and the volution of edge structure from small serrations to larger ones is shown to occur.

R. C. Smith S32

A Study of Growth Processes in Germanium Dendrites Using Pulse Electroplating Techniques

Journal of the Electrochemical Society, vol. 108, p. 238, March, 1961.

Pulse electroplating is shown to reveal resistivity variations in germanium dendrites. The evolution of the edges of the dendrites is deduced from the configuration of the resistivity variations. The results suggest that dendritic growth involves at least two processes.

F. M. Smits S33

Measurements of Sheet Resistivities with the Four-Point Probe

Bell System Technical Journal, vol. 37, p. 711, May, 1958

Correction factors are evaluated for the measurement of sheet resistivities on two-dimensional rectangular and circular samples with the four-point probe. Diffused surface layers can be treated as two-dimensional structures, but the factors are also useful in obtaining body resistivities on thin samples.

W. R. Smythe S34

Static and Dynamic Electricity

McGraw-Hill Book Company, Inc., New York, N. Y., 1950

Useful principles and mathematical techniques are presented here, especially on pages 230 to 249.

R. J. Snodgrass S35

Hall and Resistivity Measurements on Thin Diffused Layers of Germanium

Diamond Ordnance Fuze Laboratories, Washington, D.C., Report No. TR-710, May 1, 1959 (AD 217214)

Measurement of conductivity and Hall effect from 77°K to 300°K on n-type germanium samples are reported. The data from two types of samples, bulk and thin film, are analyzed and compared. The thin film was prepared by diffusion and thus contains a nonuniform distribution of impurity atoms. Four-point probe resistivity measurements were made on the thin-film sample as a function of depth to determine the resistivity profile.

W. G. Spitzer and M. Tanenbaum S36

Interference Method for Measuring the Thickness of Epitaxially Grown Films

Journal of Applied Physics, vol. 32, p. 744, April, 1961

In the case of a lightly doped epitaxial layer grown on a heavily doped substrate, incident infrared radiation is reflected at the surface and at the interface to produce interference fringes.

R. Stickler and G. R. Booker S37

Surface Damage Associated with Abraded Silicon Specimens

Journal of the Electrochemical Society, vol. 109, p. 209C (A), August, 1962

Silicon specimens were abraded on one side, chemically thinned from the other side, and examined in transmission in an electron microscope. The examination showed that the damaged layer consisted mainly of dislocation networks. Further silicon specimens were abraded, known amounts were removed from the abraded surfaces, and the specimens were chemically thinned and examined as before. In this manner the depths of damage for various abrasive treatments were determined directly. The effect of annealing on the damaged layers, was also investigated.

R. Stickler and G. R. Booker S38

Transmission Electron Microscope Investigation of Removal of Mechanical Polishing Damage on Si and Ge by Chemical Polishing

Journal of the Electrochemical Society, vol. 111, p. 485, April, 1964

Electron microscope investigation of mechanical polishing damage in silicon and germanium has shown that the amount of damage produced by 0.25μ abrasive particles depends on the condition of the abrasive powder and the direction of the abrading motion with respect to crystallographic directions. Further, the mechanical damage produced is removed after only a few seconds of etching in CP-4; further etching produces wider grooves due to preferential etching at the edges of scratches giving the appearance that the scratch-mark structure is still present although no mechanical damage remains.

T. Stubb S39

The Measurement of Conductivity in Semiconductors with the Aid of Microwaves

Acta Polytechnica Scandinavica, Physics Including Nucleonic Series No. 2, The State Institute for Technical Research, Helsinki, Finland, 1959

If one measures the dielectric losses in a semiconductor with the aid of microwaves, one has an opportunity to determine the conductivity of the substance in question at those frequencies. The method described in this paper is applicable to thin, disc-shaped samples of substances having a conductivity between 0.1 and 200 $(ohm\text{-}cm)^{-1}$. The procedure is based on Drude-Zener's theory and on a measuring method reported by Horner.

This method presents the advantage that no contacts are required between the sample substance and the measuring equipment, as is the case with the various dc methods. In the present instance a cavity resonator is employed for the determination of the requisite values of measurement.

B. Stuttard S40

A Simple Laboratory Method for the Measurement of Some Properties of a Semiconductor

International Journal of Electrical Engineering Education, vol. 1, p. 15, June, 1963

Techniques for the measurement of some semiconductor properties are outlined. A simplified method for obtaining quantitative results for Hall coefficient, carrier concentration, mobility and the energy gap is described with a qualitative assessment of magnetoresistance and the effect of light. The relevant theory is discussed and typical results quoted.

V. K. Subashiev S41

Determination of Semiconductor Parameters from the Photomagnetic Effect and Photoconductivity

Soviet Physics-Solid State, vol. 5, p. 405, August, 1963

The basis is given for an improved variant of the method for determining the parameters of a uniform semiconductor from the photoconductivity and photomagnetic effect response spectra.

V. K. Subashchiev and S. A. Poltinnikov S42

Determination of Carrier Mobility and Density in the Surface Layer of a Semiconductor

Soviet Physics - Solid State, vol. 2, p. 1059, December, 1960

This paper describes a method of determining surface density and mobility in a semiconductor layer formed by impurity diffusion in the starting material. The method is based on Hall effect and conductivity data and the relationship between the carrier mobility and density. The experimental data relate to diffusion layer measurements in a silicon photocell.

M. V. Sullivan S43

New Electrochemical Technique for Polishing Semiconductor Wafers

Bell Laboratories Record, vol. 39, p. 107, March, 1961

A new electrochemical technique for rapid scratch-free polishing of germanium and silicon wafers for transistors is described. The new polishing method is much faster and more efficient than conventional polishing methods. In addition to the anticipated savings of more than 50 per cent of the polishing cost, there is a distinct improvement in the electrical characteristics of certain types of devices as well.

M. V. Sullivan S44

A Simple Method for Detecting Microvariations in the Surfaces of Polished Flat Materials

Electrochemical Technology, vol. 1, p. 51, January-February, 1963

The image which is formed when a point source of light is reflected from the surfaces of polished germanium or silicon reveals many minor deviations in those surfaces.

M. V. Sullivan, D. L. Klein, R. M. Finne, L. A. Pompliano and G. A. Kolb S45

An Electropolishing Technique for Germanium and Silicon

Journal of the Electrochemical Society, vol. 110, p. 412, May, 1963

An electrochemical technique has been developed for polishing germanium and silicon to yield smooth and flat semiconductor surfaces. This technique is based on the anodic dissolution of a semiconductor whose surface is close to a moving cathode. The average surface roughness of electropolished semiconductors was found to be $\pm$25Å and the deviation from flatness was typically 1 µ/cm.

For n-type samples, the holes necessary to support uniform electrolysis of the surface were injected by illuminating the anode surface. For both n- and p-type anodes the average current efficiencies were found to be between 103% and 105%. Practical current densities are about 0.1 amp/cm^2. At this value, the etch rates were about 2.2 µ/min for germanium and 1.9 µ/min for silicon.

E. D. Sunde S46

Earth Conduction Effects in Transmission Systems

D. Van Nostrand Company, Inc., New York, N.Y., 1949

The presentation is primarily concerned with fundamental methods in the analysis of earth conduction effects and basic principles underlying protective measures against resultant circuit disturbances. Chapter II, "Earth Resistivity Testing and Analysis", deals with the principles of the four-point probe and its application under conditions of a variably stratified medium or of an exponential variation in resistivity with depth.

L. J. Swartzendruber S47

Correction Factor Tables for Four-Point Probe Resistivity Measurements on Thin, Circular Semiconductor Samples

National Bureau of Standards Technical Note 199, April 15, 1964

Extensive tables of the geometrical correction factors for four-point probe resistivity measurements on thin, circular semiconductor samples with all surfaces insulating are given, (1) for an in-line probe array displaced radially with points along a diameter, (2) for an in-line probe array displaced radially with the line of points perpendicular to a diameter, and (3) for a displaced square probe array.

L. J. Swartzendruber S48

Calculations for Comparing Two-Point and Four-Point Probe Resistivity Measurements on Rectangular Bar-Shaped Semiconductor Samples

National Bureau of Standards Technical Note 241, June 1, 1964

Fortran codes are given which enable the calculation of four-point probe correction factors for use with bar-shaped samples. Samples with either plated or unplated ends are considered. The errors that arise due to probe misplacement, inaccurate sample size and shape, and non-uniform end plating are also considered. Use of the results permits accurate comparison of two-point and four-point probe resistivity measurements. The codes are in Fortran II language and were written for an IBM 7090 computer.

L. J. Swartzendruber S49

Four-Point Probe Measurement of Non-Uniformities in Semiconductor Sheet Resistivity

Solid-State Electronics, vol. 7, p. 413, June, 1964

Equations and graphs are presented to aid in the evaluation of resistivity non-uniformities when measured by use of the four-point probe. Both the in-line and square array four-point probes are considered. To enable a circular disc to be probed for non-uniformities, correction factors for a displaced probe are given for an in-line array displaced with points on a diameter, for an in-line array displaced with points perpendicular to a diameter, and for a displaced square array.

J. Swiderski S50

Application of the Photovoltaic Effect in the Study of the Homogeneity of Germanium

Translated by Research Language Center, Emmanuel College, Boston, Massachusetts, Contract No. AF 19(604)-8505, January, 1963 (AD 411114)

This work describes a method of studying the homogeneity of germanium by measuring the volumetric photoelectromotive force. It presents the mathematical limits of their application. It also discusses the measuring equipment used, and a number of practical examples of the study of the homogeneity of germanium monocrystals and several samples of germanium used to study the structure of the elements.

S. Tanaka and H. Y. Fan T1

Impurity Conduction in P-Type Silicon at Microwave Frequencies

Physical Review, vol. 132, p. 1516, November 15, 1963

The microwave conductivity of boron-doped silicon has been studied at low temperature at ∿9000 Mc. The samples measured had boron concentrations ranging from 6.7×10^{15} to 1.6×10^{17} cm^{-3}. In the impurity conduction range, the microwave conductivity varied much more slowly than the dc conductivity, becoming orders of magnitude larger in comparison at 4.2°K. Calculations based on the hopping model give microwave conductivity of the right order of magnitude as measured. However, pronounced nonohmic behavior was observed in samples of impurity concentrations less than $\sim 10^{16}$ cm^{-3}, and the measured temperature dependence of conductivity for the samples of high-impurity concentrations was too strong. These observations cannot be accounted for by the hopping model. It is shown that the nonohmic behavior may be attributed to the direct absorption of microwave power for which phonon interaction is not the essential part of the process. The strong temperature dependence is explained on the basis of carrier trapping by closely spaced impurity centers. Some measurements were made at lower frequencies. The results are consistent with the interpretation.

S. Tanaka, M. Kobayashi, E. Hanamura and K. Uchinokura T2

Microwave Absorption in Silicon at Low Temperatures

The Physical Review, vol. 134, p. A256, April 6, 1964

The microwave conductivity of p-type and n-type silicon was studied at low temperatures at ∿9000 Mc/sec. Samples measured had impurity concentrations ranging from 6.7×10^{15} to 2.2×10^{16} cm^{-3}. In the impurity conduction range, the microwave conductivity varies much more slowly than the dc conductivity, becoming orders of magnitude larger in comparison at 4.2°K. Furthermore, the conductivity showed strong non-ohmic characteristics in all the samples. The experimental results indicated that the microwave conductivity in the low-concentration range consists of two parts, one the conductivity due to direct absorption process in ionized impurity pairs, which shows saturation at low electric-field intensity, and the other, the conductivity due to hopping process, which does not show a non-ohmic character. A simple theory of the microwave absorption in the ionized impurity pairs was developed, supporting the experimental conclusions.

M. Tanenbaum T3

Uniform N-Type Silicon

U. S. Patent 3,076,732, Issued Feb. 5, 1963

The preparation of uniform resistivity n-type silicon by nuclear transmutation is described. High resistivity p-type silicon is subjected to a thermal neutron bombardment in which thermal neutrons are captured by the stable isotope silicon-30. The resultant unstable isotope, silicon-31, decays, by the emission of a ß-particle, to the stable isotope phosphorus-31. A wide range of resistivities can be produced by the process. The unstable isotope has a relatively short half life; as a result, the semiconductor can be handled safely after a few days. Crystal damage introduced by neutron bombardment is annealed out in typical device fabrication processes.

M. Tanenbaum and A. D. Mills T4

Preparation of Uniform Resistivity N-Type Silicon by Nuclear Transmutation

Journal of the Electrochemical Society, vol. 108, p. 171, February, 1961

By the capture of a thermal neutron, the natural isotope Si^{30} can be transmuted into the unstable isotope Si^{31}, which decays by beta emission with a 2.62-hr half-life to the stable isotope P^{31}. By means of this reaction, donors can be produced in a silicon crystal. Because of the uniformity of flux which can be obtained in large nuclear reactors, this technique lends itself to the preparation of uniformly doped n-type silicon. After irradiation the silicon crystal is heavily damaged by the emitted betas, by the recoil of the decaying Si^{31}, and by the high-energy neutrons that are unavoidably present in the reactor. However, this damage can be removed by annealing at temperatures near 600°C. The technique has been used to produce n-type silicon with nominal resistivities between 0.1 and 20 ohm-cm. The resistivity of the resulting crystals was uniform over dimensions of 5 cm to within $\pm$5%.

U. Tarnick T5

Electrical Measurements on Monocrystalline Germanium (In German)

Radio und Fernsehen, vol. 11, p. 478, August, 1962

The principles and some methods of measurement of electrical conductivity and minority carrier lifetimes and their importance to germanium rectifiers and transistors are briefly discussed. To assist in measuring resistivity by use of a four-point probe, a simple resistive circuit to give a null-method covering the ranges 0.1, 1.0 and 10 ohm-centimeters is given.

Y. Tarui T6

Method for Measuring the Resistivity of High-Purity Silicon

The Journal of the Institute of Electrical Communication Engineers of Japan (English Edition of Denki Tsushin Gokkai Zasshi) vol. 46, p. 46, January, 1963

Modifications of the four-point probe method of measuring the local resistivity of high-purity silicon are described which eliminate the effects of the rectification at the contact between the probe and the silicon. All the four probe contacts are biassed in the forward direction, and a pair of transistors are used as an impedance convertor to avoid error due to the unbalanced current in the transformer. Results obtained with the modified equipment indicate that the maximum error of measurement will be <3% when the bias current is <100μA for a sample of about 6310Ωcm resistivity. It appears that a bias current of 10μA and a signal current of 5μA will be satisfactory for the measurement of resistivity up to 10,000Ωcm.

J. Tauc T7

The Theory of a Bulk Photo-Voltaic Phenomenon in Semi-Conductors

Czechoslovak Journal of Physics, vol. 5, p. 178, April, 1955

It is shown theoretically that for a photo-voltaic phenomenon in semiconductors neither the presence of localised potential barriers with rectifying properties nor the presence of non-rectifying contacts is necessary. The case is considered that the illuminated part of the semiconductor is sufficiently distant from both contacts so that these will not assert themselves; further, it is assumed that there are no localised potential barriers in the semiconductor. Under these conditions a photo-voltage is produced in a semiconductor if its conductivity varies throughout its length in such a way that in the dark it is different at the beginning and end of the illuminated part. The underlying law of this phenomenon, the general procedure for calculating the photo-voltage, an approximation for weak illumination and the dependence on the intensity of illumination are derived and its physical aspects are discussed.

C. O. Thomas, D. Kahng and R. C. Manz T8

Impurity Distribution in Epitaxial Silicon Films

Journal of the Electrochemical Society, vol. 109, p. 1055, November, 1962

A differential capacitance-voltage method for determining doping profiles in depth in epitaxial semiconductor films is described. Experimental profiles, in which the doping level generally is not flat but decreases with film thickness, are shown for several film growth conditions. A possible explanation for the observed distribution is discussed.

J. L. Thomas T9

Precision Resistors and Their Measurement

National Bureau of Standards Circular 470, 1948

This circular contains information on the construction and characteristics of wire-wound resistors of the precision type. There are also included descriptions of the methods used at the National Bureau of Standards for the test of precision resistors and the calibration of precision resistance measuring apparatus. Although the presentation is nontechnical, there is a considerable amount of information on the characteristics and limitations of apparatus of this type that should be of interest to any one making accurate measurements of electrical resistance.

B. A. Thompson, B. M. Strause and M. B. Leboeuf T10

Gamma Spectrometric and Radiochemical Analysis for Impurities in Ultrapure Silicon

Analytical Chemistry, vol. 30, p. 1023, June, 1958

Methods have been developed to determine many impurities in a single sample of transistor-grade silicon by neutron activation analysis. The methods utilize both gamma spectrometry and radiochemical separations with beta counting. Their applicability to the determination of specific elements is discussed and detection limits, in the part per billion range in most cases, are presented for some 29 elements. Advantages and disadvantages of different neutron sources are discussed. Measurement of short-lived impurities are described and evaluated. For many of the elements of greatest interest in transistor production, activation analysis seems to be the best available analytical method that can be applied effectively on a semiroutine basis.

F. D. Thornton T11

Electrical Measurements on Heat-Treated Silicon

Associated Electrical Industries, Ltd., Research Laboratory, Aldermaston, Berkshire, England, C.V.D. Report No. RR.53, Admiralty Contract No. CP. 7053/49, March, 1963 (AD 299888)

The presence and precipitation of oxygen is necessary for the large scale precipitation of aluminium in silicon due to heat treatment in the temperature range 1000°C to 1200°C. The oxygen, and hence the aluminium, only precipitates during this treatment if a short preliminary heat treatment and quench from a higher temperature (1350°C) is given. Large donor concentrations were found in all samples, probably molecular aluminium/oxygen donor complexes in the unheated samples formed during crystal growth. These would be dissociated by high temperature heat treatment but would be replaced by spurious contamination, probably copper, of about the same concentration.

P. R. Thornton T12

Electrical Effects of Dislocations in High Resistivity GaAs

Solid-State Electronics, vol. 6, p. 677, November-December, 1963

Experiments were carried out on material prepared in three ways to discover whether inhomogeneities in the resistivity were associated with the defect structure Only in material prepared by the Bridgman method and subsequently zone refined in vitreous carbon was such a connection established.

C. D. Thurmond, W. G. Guldner and A. L. Beach T13

Hydrogen and Oxygen in Single-Crystal Germanium as Determined by Vacuum Fusion Gas Analysis

Journal of the Electrochemical Society, vol. 103, p. 603, November, 1956

Concentrations of hydrogen from 3 to 4 x 10^{18} at./cc have been found by vacuum fusion gas analysis in specially prepared single crystals of Ge. In these same crystals oxygen concentrations of 1 to 2 x 10^{18} at./cc were also found.

Three special preparations of Ge were made by the hydrogen reduction of GeO_2 in graphite. In the first, Ge was melted once under hydrogen, in the second, 12 times, and in the third, 42 times. Single crystals were grown from portions of these ingots in graphite crucibles under an atmosphere of hydrogen. Resistivities of the n-type crystals were in the range 1-10 ohm-cm, and lifetimes of several hundred microseconds were observed. There was no significant variation in hydrogen and oxygen concentration from one crystal to the other. Since the ratio of hydrogen to oxygen is around two, the possibility exists that these elements may be present in the crystal as H_2O.

Vacuum crystal growing lowered the hydrogen and oxygen content 20-30 fold.

P. M. Tomchuck T14

Influence of Electric Field on Electron Temperature, Electrical Conductivity and Thermionic Emission of Semiconductors - II. Effect of Plasma Oscillations and Short Range Collisions

Soviet Physics - Solid State, vol. 3, p. 740, October, 1961

The distribution function of an electron gas in the presence of a constant electric field is found from the kinetic equation. The reactions of the electrons with each other (including both far and near collisions) and with plasma oscillations are taken into consideration. The relation between the moments in the Chapman-Cowling method and those derived from the Landau equation is established. The effect of plasma oscillations on electric conductivity is estimated. The limits of applicability of the Landau method are discussed.

M. Tomono T15

Direct Viewing of Imperfections in Germanium P-N Junction

Journal of the Physical Society of Japan, vol. 15, p. 2254, December, 1960

A p-n junction was made by alloying indium on an n-type germanium pellet, and it was put into an electrolyte solution of copper salt. When suitable reverse voltage was applied on the junction by a charged condenser, copper shaded pattern was deposited on the opposite side of the alloyed surface in accordance with the density of the reverse current flowing through every part of the p-n junction. By this method, the breakdown at the imperfections of p-n junction due to the defects in the germanium crystal, those at the periphery of p-type recrystallized layer, and those inside p-n junction grown in alloying process were observed. Then, the cross section was made referring to the pattern, and several kinds of the imperfections of p-n junction were observed under microscope.

A. Trainor and P. T. Harris T16

The Control of Resistivity in Pulled Silicon Crystals

Proceedings of the Physical Society, vol. 74, p. 669, November, 1959

The control of the impurity concentration along pulled crystals is important where material within certain closely defined resistivity limits is required. The impurity distribution along a crystal is determined by the effective segregation coefficients of the impurities present, loss by evaporation and by contamination from the crucible material and surroundings. With the high-purity quartz available and careful design of the apparatus, contamination can be reduced to negligible limits for silicon with resistivity below about 200 ohm-cm. Thus the impurity distribution is determined by the other two factors. Boron can be used to make uniform p-type material. The segregation coefficient is near unity, and crystals with a near uniform resistivity distribution can be readily grown. For n-type material the commonly used donor impurities, arsenic and phosphorus, have segregation coefficients of 0.3 and 0.35 respectively. This leads to considerable variation in resistivity over the useful region of the crystal. The loss by evaporation for crystals pulled in an atmospheric pressure of inert gas is small.

F. A. Trumbore T17

Effect of P-Type Germanium Arsenide Occlusions on the Resistivity of Heavily Doped N-Type Germanium

Journal of the Electrochemical Society, vol. 107, p. 198C (A), August, 1960

Optical examination and thermal probing has revealed the presence of occlusions of p-type germanium arsenide in low-resistivity arsenic-doped germanium. The presence of such occlusions leads to measured resistivities which are lower than the true resistivity of the bulk germanium. It is postulated that these occlusions are the cause of the difficulties encountered in obtaining material of resistivities lower than 0.006 to 0.007 ohm-cm, thus explaining the anomalous results of five different types of crystal growth experiments.

O. N. Tufte T18

Evaluation of the Surface Concentration of Diffused Impurity Layers in Silicon

Journal of the Electrochemical Society, vol. 108, p. 175C (A), August, 1961

The relation between the surface concentration of a diffused layer and the electrical conductivity and Hall coefficient of the layer has been calculated for a complementary error function impurity distribution in silicon. The results show that the Hall coefficient is very nearly independent of the mobility values used in the calculation. This allows accurate values of the surface concentration to be determined without knowing exactly the variation of the mobility with impurity concentration. An experimental comparison of the surface concentration values obtained by the conductivity and Hall effect methods is made.

O. N. Tufte T19

The Average Conductivity and Hall Effect of Diffused Layers on Silicon

Journal of the Electrochemical Society, vol. 109, p. 235, March, 1962

The relation between the average conductivity and Hall Coefficient of a diffused layer on silicon and the surface concentration of the layer has been calculated for a complementary error function impurity distribution. The results show that the Hall coefficient is almost completely determined by the surface concentration of the layer and is only a very weak function of the mobility values used in the calculation. An experimental comparison of the surface concentration values obtained by the two methods is made.

A. S. Tulk T20

Resistivity, Crystal Perfection, and Lifetime Measurements for Germanium and Silicon Monocrystals

Semiconductor Products, vol. 3, p. 27, October, 1960

Present developments in the semiconductor industry include increased reliance of device manufacturers on sources of monocrystals other than their own materials department. One of the problems which must be faced by the purchaser of crystals from an "outside" source is the degree of trust which he can place in the evaluation by the supplier. Not only must the identity of the measurement be known to the purchaser, but much of the detail of the measurement method must also be familiar to him.

In this paper, a measuring procedure for germanium and silicon monocrystals is outlined in considerable detail.

D. R. Turner T21

Electropolishing Silicon in Hydrofluoric Acid Solutions

Journal of the Electrochemical Society, vol. 105, p. 402, July, 1958

Silicon is electropolished in hydrofluoric acid solutions if a critical current density is exceeded. Below the critical current density, silicon dissolution is largely divalent, and a thick solid layer forms. This film is unstable and reacts slowly with the electrolyte to form tetravalent silicon and hydrogen gas. In the electropolishing region, silicon dissolution is mainly tetravalent with the formation of a very thin high-resistance type of film.

Experimental results on the effect of HF concentration, viscosity, and temperature indicate that electropolishing begins when the HF concentration at the silicon becomes limited by the rate of "mass transfer" of HF from the solution bulk to the surface.

B. M. Turovskii T22

On the Problem of Revealing the Shape of the Crystallization Front in Silicon Single Crystals by the Method of Selective Etching

Soviet Physics - Solid State, vol. 5, p. 1273, December, 1963

The shape of the crystal-melt interface, reflecting thermal conditions of the growth process, substantially predetermines the temperature gradient at the crystallization front, the density and distribution of dislocations, and the distribution of impurities in cross sections of semiconductor single crystals. "Growth bands" are revealed by selective chemical etching of a longitudinal section due to periodic resistivity variations corresponding to the periodic impurity distribution. For the most part, selective etching is more difficult with p-type silicon than n-type.

Selective etching of crystals of p-type silicon will also occur in cases where, along with boron, there is a relatively large content of donor impurity (conductivity type in this case being determined by the excess boron) nonuniformly distributed over the length of the crystal. Consequently, the revelation of the shape of the crystallization front in longitudinal sections of single crystals of p-type silicon by the selective etching method is possible also with presence of impurities having effective distribution coefficients less than one, in particular aluminum or compensating donor impurities.

B. M. Turovskii and M. G. Mil'vidskii T23

Growth Features of Crystals Grown from the Melt by the Czochralski Technique

Soviet Physics - Solid State, vol. 3, p. 1834, March, 1962

Certain features of the macrostructure of crystals grown by the Czochralski method are examined. It is assumed that the periodic heterogeneity in the distribution of impurities over the volume of the ingots is due to the asymmetry of the thermal field in the melt and to the specific effect of the impurities of the equilibrium temperature of crystallization of melts of different composition.

N. Tzoar T24

High-Frequency Resistivity of Degenerate Semiconductors

The Physical Review, vol. 133, p. A1213, February 17, 1964

The high-frequency and long-wavelength resistivity due to the electron-phonon (optical) interaction is calculated for degenerate semiconductors. This result is compared with the resistivity arising from electron-ion collisions calculated previously.

A. Uhlir, Jr. U1

The Potentials of Infinite Systems of Sources and Numerical Solution of Problems in Semiconductor Engineering

Bell System Technical Journal, vol. 37, p. 105, January, 1955

Tables and charts are given of mathematical functions related to the potential of a line of point charges. The use of these functions is illustrated by applications to semiconductor resistivity measurements and to calculations of the base resistance of point-contact transistors.

L. B. Valdes V1

Effect of Electrode Spacing on the Equivalent Base Resistance of Point-Contact Transistors

Proceedings of the Institute of Radio Engineers, vol. 40, p. 1429, November, 1952

A theoretical expression for the equivalent base resistance r_b of point-contact transistors is derived here. This expression is shown to check experimental values reasonable well if the severity of some assumptions made for purposes of analysis is considered. Electrode spacing, germanium-slice thickness, and resistivity of the semiconductor are shown to be the properties that affect r_b primarily.

L. B. Valdes V2

Resistivity Measurements on Germanium for Transistors

Proceedings of the Institute of Radio Engineers, vol. 42, p. 420, February, 1954

This paper discusses a laboratory method which has been found very useful for measuring the resistivity of the semiconductor germanium. The method consists of placing four probes that make contact along a line on the surface of the material. Current is passed through the outer pair of probes and the floating potential is measured across the inner pair. There are seven cases considered, the probes on a semi-infinite volume of semiconductor material and the probes near six different types of boundaries. Formulas and curves needed to compute resistivity are given for each case.

L. B. Valdes and K. D. Smith V3

Measurement of the Properties of Starting Materials

Transistor Technology, H. E. Bridgers, J. H. Scaff and J. N. Shive, eds., vol. 1, ch. 12, p. 264, D. van Nostrand Company, Inc., Princeton, N.J., 1958

This chapter discusses the evaluation of the material in order to determine whether given crystals will yield devices having characteristics within a particular acceptance range, as predicted by the design theory. This chapter also includes data obtained by synthesis of devices to check design theory predictions. Therefore, it discusses not only measurements of the basic properties of crystals, such as resistivity, lifetime, and junction properties, but evaluation of the crystals on the basis of the properties of devices made of them. A table shows the properties of the crystals which have to be measured and which are discussed in this chapter. Obviously, more measurements are needed for junction material, which includes n-p-n as well as n-p crystals, than for material of a single conductivity type. The first part of this chapter describes the evaluation measurements on single-conductivity type material. The second part describes the additional measurements required on junction material, as well as any precautions required in the use of previously described tests on junction material.

L. J. van der Pauw V4

A Method of Measuring Specific Resistivity and Hall Effect of Discs of Arbitrary Shape

Philips Research Reports, vol. 13, p. 1, February, 1958

A method of measuring specific resistivity and Hall effect of flat samples of arbitrary shape is presented. The method is based upon a theorem which holds for a flat sample of arbitrary shape if the contacts are sufficiently small and located at the circumference of the sample. Furthermore, the sample must be singly connected i.e., it should not have isolated holes.

L. J. van der Pauw V5

An Analysis of the Circuit of Dauphinee and Mooser for Measuring Resistivity and Hall Constant

Review of Scientific Instruments, vol. 31, p. 1189, November, 1960

The Dauphinee and Mooser circuit, Review of Scientific Instruments, vol. 26, p. 660, July, 1955, for the measurement of resistivity and the Hall effect is liable to certain systematic errors due to capacitive effects in the switches. The magnitude of these errors is estimated, and it is shown how they may be eliminated by the use of suitably placed trimming capacitors and by a suitable switching sequence. The sensitivity of the circuit is also calculated.

L. J. van der Pauw V6

Determination of Resistivity Tensor and Hall Tensor of Anistropic Conductors

Philips Research Reports, vol. 16, p. 187, April, 1961

The resistivity tensor of an anisotropic conductor with respect to an arbitrarily chosen rectangular coordinate system can be described by six constants. It is shown that these six constants are related to the "sheet resistivities" of six plane-parallel samples by six linear equations. The plane-parallel samples may be of arbitrary shape and cut in arbitrary but known directions. The Hall effect can most generally be described by nine constants. For the determination of these nine constants, only three such samples are required, combined however with three different orientations of the magnetic induction.

G. F. Vasil'yev V7

Penetration of an Electric Field into a Semiconductor

Radio Engineering and Electronic Physics, vol. 6, p. 1551, October, 1961

Formulas are obtained describing the penetration of an external electric field into a semiconductor. The calculation is made under the assumption that the temperature of the electrons in a semiconductor is always equal to the lattice temperature.

D. E. Vaughan V8

Four-Probe Resistivity Measurements on Small Circular Specimens

British Journal of Applied Physics, vol. 12, p. 414, August, 1961

General formulae are presented for square and linear probe arrays on circular specimens which permit the calculation of sheet resistivity from voltage and current measurements made with the probes in any position. From these formulae it is deduced that the square probe array is preferable on small specimens on the grounds of accuracy, as well as from spatial considerations.

V. S. Vavilov, V. M. Patskevich, B. Ya. Yurkov and P. Ya. Glazunov V9

The Effect of Fast-Electron Bombardment on the Electrical Conductivity of Silicon and the Dependence of the Rate of Defect Formation on the Orientation of a Crystal with Respect to the Electron Beam

Soviet Physics - Solid State, vol. 2, p. 1301, January, 1961

To obtain new information about the nature of defect formation in p-type silicon monocrystals, rectangular samples, oriented in various ways with respect to the electron beam, were subjected to bombardment with fast electrons of 500 kev initial energy. Before irradiation the samples were very homogeneous, as judged by their resistivity, which was 160 ohm-cm. The bombardment and subsequent measurements were carried out at room temperature. During irradiation the samples were cooled with running water.

J. K. D. Verma V10

A Four-Point Probe for Resistivity Measurements of Semiconductors

Indian Journal of Physics, vol. 37, p. 241, May, 1963

The constructional details of a four-point probe for determining the resistivity of semiconductors are given. The method for electrolytic pointing of tungsten wires used in the probe is also described.

R. M. Vinetskii and E. G. Miselyuk V11

Determination of the Impurity Concentration in Germanium

Soviet Physics - Solid State, vol. 2, p. 60, July, 1960

A method based on the effect of impurity scattering on resistivity is described. The impurity concentration is calculated from the measured values of resistivity at two temperatures, and the values are given for change in the resistivity due to lattice scattering on lowering the temperature from 290°K to 100°K in p- and n-type Ge.

L. K. Vodop'yanov V12

Measurement of Electrical Properties of Dielectrics Irradiated by Neutrons

Instruments and Experimental Techniques, 1961, no. 4, p. 738, February, 1962

An apparatus which permits the measurement of the dielectric constant, the tangent of the dielectric loss angle, and the electrical conductivity of highly radioactive samples is described. Measurements are made in a vacuum over a wide range of temperatures and frequencies.

B. A. Volchock and V. Ya. Frenkel' V13

Some Peculiarities of the Zone Purification Process

Soviet Physics - Solid State, vol. 3, p. 1461, January, 1962

In this paper we show that because of the dependence of the width of the liquid zone upon the heater location (with respect to the sample) the limiting impurity distribution is not constant along the length of the sample. We can establish a constant-impurity concentration along the length of the sample by means of special conditions (by programming the power delivered to the heater). We derive the corresponding limiting formulas for the concentration; the concentration at a point within the sample varies for even and odd passages.

P. Wagrez and A. Soffa W1

A New Technique for Measuring the Resistivity of Individual Semiconductor Dice

Semiconductor Products, vol. 6, p. 23, February, 1963

This article describes a technique and a machine for handling, measuring resistivity and sorting individual semiconductor dice prior to their assembly into transistors and other electronic devices. Each individual die is picked up by a vacuum arm and placed in position on a measuring head. Its edges are then contacted by four square-ended blades, and two voltage measurements are taken as a constant current is impressed. The readings are compared and averaged, and the die is removed and placed in one of 13 groups according to its average resistivity. The entire operation is automatic; round, square or rectangular dice, from 80 to 1,000 microns thick, can be sorted at rates up to 6,000 pieces per hour, with virtually no damage. Resistivities measured can range as low as 0.01 ohm-cm to as high as 100 ohm-cm.

A. L. Ward W2

Dependence of Metal-to-Semiconductor Contact Resistance upon Contact Loading

Diamond Ordnance Fuze Laboratories, Washington, D.C., Report No. TR-731 July 30, 1959 (AD 228744)

A study was conducted on the variation of contact resistance of moderate area metal-to-semiconductor contacts with repeated variable loading. The spreading resistance was shown to be modified by the injection of minority carriers at the contact. The piezoresistance matrix is used to study the effect of contact stress on the semiconductor resistivity. The apparatus and experimental procedures used are described. The mechanism of a large observed change of contact resistance with loading is shown to be due to the change of the effective contact area. Several applications are discussed briefly.

J. D. Wasscher W3

Note on Four-Point Resistivity Measurements on Anisotropic Conductors

Philips Research Reports, vol. 16, p. 301, August, 1961

Van der Pauw has shown that a simple transformation of coordinates can map an anisotropic conductor on an isotropic conductor in such a way that the voltages between corresponding points and the currents through corresponding surface elements are the same. In this note this transformation is used in calculating the voltage differences across two probes when the current is passed through two other probes placed in a collinear or square arrangement on an anisotropic conductor. The two cases of a sample, thick and thin compared to the probe distances, are considered. It turns out that the square arrangement is appreciably more sensitive to anisotropies than the collinear arrangement. Another result is that the three principal values of a resistivity tensor can be calculated from measurements on only the plane perpendicular to a direction corresponding to one of these principal values. The use of corrections for finite dimensions already calculated for isotropic conductors is discussed.

F. W. Weaver W4

Achievement of Measurement Agreement Among Electrical Standards Laboratories

Instruments and Control Systems, vol. 36, p. 128, July, 1963

Trained measurement personnel with a determination and a planned program, good equipment, and good laboratories can achieve near measurement agreement with the National Bureau of Standards over a period of years. Details are given whereby the NBS Electronic Calibration Center, Boulder, Colorado, established and maintains the low-frequency units and achieves measurement agreement with NBS, Washington. Other laboratories can follow this precedent.

J. K. Webb W5

The Scope of the Measurement and Control Section

Proceedings of the Institution of Electrical Engineers, pt. A, vol. 106, p. 11, January, 1959

The scope of the Measurement and Control Section has been greatly extended since its early days, and although it has never flagged in its concern for the more fundamental measuring devices, the impact of improved analytical methods, the continuous urge towards ever greater precision in the definition of our standards, the advent of new materials, nucleonics and improved measuring techniques, computers, data-processing and servo mechanisms, have all added to the complexity of its interests.

An example of modern materials measurements is the evaluation of the quality of highly purified silicon which is a big subject by itself since the most sensitive chemical and physical tests, including mass spectrometry and activation analysis, are of little avail. We therefore must depend on electrical measurements on single crystals (resistivity and Hall measurements at various temperatures). These can determine impurity levels down to one part in 10^{12}, equivalent to a single grain in 1000 cubic yards of sand, and designate the various elements contributing to this impurity.

I. R. Weingarten and M. Rothberg W6

Radio-Frequency Carrier and Capacitive Coupling Procedures for Resistivity and Lifetime Measurements on Silicon

Journal of the Electrochemical Society, vol. 108, p. 167, February, 1961

By use of a radio-frequency carrier and capacitive coupling it has been possible to measure the resistance and lifetime of silicon rods without making direct ohmic contact to the samples. Even with contacts, the use of an RF carrier to observe lifetime by photoconduction decay eliminates the need for insuring solid ohmic contacts, as is required with a dc carrier. With low-loss insulation between coupling capacitors and sample, an RF bridge will measure separately both the sample resistance between the coupling capacitors and the value of this coupling capacitance.

M. Weinstein, S. D. Axelrod and A. I. Mlavsky W7

The Travelling Solvent Method of Crystal Growth - Quarterly Report #3

Materials Research Laboratory of Tyco, Inc. Bear Hill, Waltham, Massachusetts, Report No. AFCRL-62-156, Contract No. AF 19(604) 8803, March 8, 1962 (AD 274275)

Consideration of the Ga-GaAs system is in three parts: Characterization of the zone movement process (including the study of variables such as temperature, temperature gradient, zone thickness and surface preparation), evaluation of regrown GaAs by van der Pauw disc technique, and preparation of ohmic contacts to GaAs. For the Cr-SiC system there is described the construction of a radiant heating zone passing furnace, the deposition of a thin zone of Cr from chromium-dicumene, and the preparation of ohmic contacts to SiC.

L. R. Weisberg W8

Anomalous Mobility Effects in Some Semiconductors and Insulators

Journal of Applied Physics, vol. 33, p. 1817, May, 1962

The Hall mobility in semiconductors and insulators can be greatly affected by inhomogeneous impurity distributions. This is due to the formation of large space charge regions surrounding local inhomogeneities. The scattering cross section of Coulombic centers can be increased by over an order of magnitude when inhomogeneously distributed. The mobility resulting from scattering from inhomogeneities varies roughly as $T^{-1/2}$ and decreases with decreasing carrier concentration. Assuming that inhomogeneities can occur frequently, various anomalous Hall mobility effects can be explained, such as mobility "killers" in GaAs, InAs, and InP; giant scattering cross sections in GaAs, InP, CdS, and CdSe; abnormally low mobilities in compensated InAs; and low mobilities in ZnO containing precipitates.

F. Wenner W9

A Method of Measuring Earth Resistivity

Bulletin of the Bureau of Standards, vol. 12, p. 469, May 25, 1916

The fundamental principles of the four-point probe are developed and applied to the measurement of bulk resistivity of the earth.

J. H. Westbrook and J. J. Gilman W10

An Electromechanical Effect in Semiconductors

Journal of Applied Physics, vol. 33, p. 2360, July, 1962

The resistance of semiconducting crystals to indentation deformation has been found to be lowered significantly (up to 60%) by the simultaneous presence of a small potential (0.05 to 10 V) between the indenter and the crystal surface. This electromechanical effect appears to be confined to the plastic strain region of a surface layer of material 2-3 μ deep.

A large body of experiments of varied nature have established that the effect is real and not spurious. Similar effects are observed in a number of different semiconductors (Ge, Si, InSb and SiC) but not in metals or ionic crystals. The effect disappears at elevated temperatures but becomes enhanced below room temperature. It is not sensitive to the type of current carrier. The roles of surface preparation, crystallographic orientation, kind and concentration of charge carrier, geometry, and time have also been examined. Other and possibly related experiments show significant enhancement of the surface photovoltage (the Dember potential) by a longitudinal electric field. All of these experiments are extensively documented and discussed but no satisfactory model or mechanism has yet been conceived.

J. H. Westbrook, A. U. Seybolt and A. J. Peat W11

A Thermal Probe for Segregation Detection

Journal of the Electrochemical Society, vol. 111, p. 888, July, 1964

This is a report of the adaptation of a technique advanced by V. N. Novogrudskii and I. G. Fadikov ("Determination of Electromotive Force with a Modified Microhardness Tester", Physics of Metals and Metallography, vol. 7, p. 99, 1959-1960) to the detection of grain boundary segregation.

A sharp tungsten point is heated and used to probe along the sample, producing a thermal emf upon contact. Under proper conditions of sample preparation and impurity segregation, the thermal emf drops about 25% in the vicinity of a grain boundary.

Advantages claimed for this technique are: dependence on a different group of properties than other grain boundary probe methods, improved resolution, and the possibility of automated recording.

W. N. Whitten, Jr., A. Heitz and J. E. McNamara W12

Depth of Work Damage Resulting from Shaping Operations of Silicon

Journal of the Electrochemical Society, vol. 111, p. 196C(A), August, 1964

The depth of work damage beneath silicon surfaces is discussed as a function of the standard shaping operations: sawing, lapping, and polishing. The depth of damage was measured by first etching the surfaces to a known depth. The etched wafers were subjected to a heat cycle and treated with Saylor etch. After etching, dislocation density was determined by microscopic examination. This procedure was followed for all samples, with the depth of etching continued until the dislocation density decreased to a constant value. Both a shallow and a deeper type of damage were observed and are discussed.

M. Wintenberger W13

Measurement of the Electrical Conductivity of Crystals: Work on Copper Pyrites (In French)

Comptes Rendus de L'Academie des Sciences, vol. 244, p. 1801, March 25, 1957

A four-point probe method can be used to determine the resistivity along the principal axes of a single crystal. Measurements can be made on two non-parallel planes of the crystal or on a single plane parallel to the crystal. The method is used to study copper pyrite with resistivities of the order of tenths of an ohm-centimeter.

M. Wintenberger W14

Measurement of the Hall Effect in Anisotropic Media with the Four-Point Probe (In French)

Comptes Rendus de L'Academie des Sciences, vol. 246, p. 2366, April 21, 1958

It is shown that a four-point probe method may be applied to the measurement of Hall effect in anisotropic media, and the application of the method to chalcopyrites is described.

G. H. Wolfe W15

The Use of High Pressure in the Study of Semiconducting Materials

Solid State Design, vol. 3, p. 26, November, 1962

This is a summary of the applications of high pressure in the study of semiconducting materials with reference to the study of band structure and a short review of results for germanium and silicon.

J. F. Woods W16

Measurements of Semiconductor Parameters

Handbook of Semiconductor Electronics, L. P. Hunter, ed., 2nd ed., sec. 20, p. 2, McGraw-Hill Book Company, Inc., New York, N. Y., 1962

Methods of measurement are reviewed for resistivity, conductivity type, Hall effect, drift mobility, and lifetime. The problems associated with these measurements are discussed, as well as the analysis of resistivity and Hall measurement data. Low-temperature resistivity measurement methods are presented, and the determination of impurity activation energy and impurity density from the various measurements is analyzed.

E. C. Wurst Jr. and E. H. Borneman W17

Rectification Properties of Metal-Silicon Contacts

Journal of Applied Physics, vol. 28, p. 235, February, 1957

Area contacts of twenty different metals were made on n- and p-type silicon. The contacts were applied by the use of jet plating techniques, with the exception of alkali metal contacts which were pressure contact or mercury amalgam contact. A qualitative correlation is shown to exist between the work function of the metals and the rectification of these metals on n- and p-type silicon. I-V characteristics taken on eleven of these metal-silicon contacts lend further support to this picture. Consideration of a quantitative work function model is made difficult due to the many errors and interpretations involved in using metal work function values.

Transistor structures were made and studied for several of the metal-silicon contacts. From analysis of this transistor data it is found that an excess current, three orders of magnitude greater than theory predicts, must be present in the diodes made from these metals. This excess current is not adequately explained by any presently known mechanism.

S. J. Yosim, L. F. Grantham, E. B. Luchsinger and R. Wike Y1

Electrodeless Determination of Electrical Conductivities of Melts at Elevated Temperatures

Review of Scientific Instruments, vol. 34, p. 994, September, 1963

An electrodeless method for measuring the electrical conductivities of metallic and semiconductor melts at elevated temperatures is described. The transformer "eddy current" method, which was capable of measuring conductivities from one to greater than 10,000 $(ohm\text{-}cm)^{-1}$, was used. The system was calibrated with Hg at 25°C and tested with Hg to 300°C and Bi to 550°C. The specific conductivities of various compositions of Bi-BiI_3 solutions were measured at 500°C and compared with those measured by an electrode method. The accuracy of the method decreased with decreasing conductivity.

V. A. Zhuravlev and M. I. Kozak Z1

The Conductivity of Semi-Conductors in an Ultrasonic Field

Journal of Experimental and Theoretical Physics (U.S.S.R.), vol. 36 (9), p. 236, July, 1959

We have examined the influence of ultrasonics on the conductivity of a number of semiconductors, and have studied specimens of selenium, cadmium sulphide, lead sulphide, cuprous oxide, stannic oxide and germanium, irradiated with 10 w/cm^2 of ultrasound at 600 KC. In all cases a change of conductivity was found on irradiation, but analysis of these changes shows that the ultrasound does not have a specific action on the conductivity, but that the effects follow from the heating of the specimen. The conductivity did not change immediately on switching on the ultrasound, but increased or decreased (depending on the sign of the temperature coefficient for the specimen) during the heating of the sample on irradiation.

J. E. Zimmerman Z2

Measurement of Electrical Resistivity of Bulk Metals

Review of Scientific Instruments, vol. 32, p. 402, April, 1961

This paper describes a method of measuring the electrical resistivities of metals by ac induction methods, in which the specimen is in bulk form and no direct contact to it is required. Theoretical expressions are given for a sphere and for an infinite circular cylinder in a uniform applied ac field, and an experimental method is described which is applicable to any shape or applied field configuration.

J. Zucker, V. J. Fowler and E. M. Conwell Z3

High-Field Conductivity in Germanium and Silicon at Microwave Frequencies

Journal of Applied Physics, vol. 32, p. 2606, December, 1961

The effect on the conductivity of germanium and silicon samples of 2.85-kMc electric fields up to peak values of 10,000 v/cm was measured. These measurements differ from earlier ones in that: (1) the microwave field was in the form of progressive rather than standing waves, which made possible more accurate determination of the field strength in the sample, and (2) to determine whether any frequency effects occur at 2.85-kMc conductivity was measured at high dc fields on the same samples. From the average conductivity under microwave excitation the instantaneous conductivity was calculated and found to agree, within experimental error, with the dc conductivity, indicating that the conductivity can still follow the 2.85-kMc field at least up to peak fields of 10,000 v/cm.

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ADDENDUM
to accompany
NBS TECHNICAL NOTE 232

Bibliography on the Measurement of Bulk Resistivity of Semiconductor Materials for Electron Devices

Judson C. French

The following references, not included in the Bibliography, should be noted. Reference (1) should be assigned the identification number K4.1, added to the Index to Subject Matter under categories 3 and 7, and added to the Author Index following Keller, J.B. Reference (2) should be assigned the identification number D16.1, added to the Index to Subject Matter under category 2, and added to the Author Index following Dunsmuir, R.

Reference 1:

W. Keller

Measurement of the Specific Resistance of Semiconductor Crystals Using High Frequencies (In German)

Zeitschrift für angewandte Physik, vol. 11, p. 346, September, 1959

Several methods for the measurement of resistivity of semiconductor materials using high frequency techniques are briefly reviewed. These include an induced current method, a two-point (currentless voltage probe) method, an oscillator method and a bridge method. A method is then described in detail for measurements of rod-shaped samples in which no contact is made to the silicon crystal. The crystal may be wrapped in a protective material. Resistance is indicated by the degree of damping of a tuned circuit which is capacitively coupled to the sample. It is necessary to calibrate the measurement using crystals of known resistivity.

Reference 2:

J. Dušek

Measurement of the Hall Coefficient and Electrical Conductivity in Semiconductors by the Method of an Alternating Magnetic Field and Alternating Current

Czechoslovak Journal of Physics, vol. 9, p. 250, 1959

A description is given of electronic equipment which enables the simultaneous measurement of the Hall coefficient and the electrical conductivity by using a low frequency alternating magnetic field and alternating current. The instrument is adapted for measuring a minimum Hall coefficient of 3×10^{-11} Vcm/AG and electrical resistance $10^{-5}\Omega$ to $10^{3}\Omega$; the smallest measurable Hall voltage is 1μV. Deviations from the results obtained by the classical dc method do not exceed 5%.

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