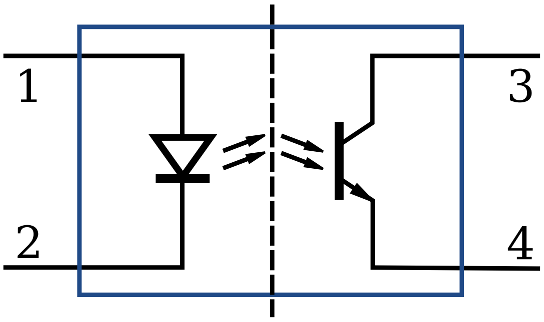
Photosensor

Contents

Chapter 1

Opto-isolator

This article is about the electronic component. For the optical component, see optical isolator.



Schematic diagram of an opto-isolator showing source of light (LED) on the left, dielectric barrier in the center, and sensor (phototransistor) on the right.[note 1]

In electronics, an **opto-isolator**, also called an **optocoupler**, **photocoupler**, or **optical isolator**, is a component that transfers electrical signals between two isolated circuits by using light.[1] Opto-isolators prevent high voltages from affecting the system receiving the signal.[2] Commercially available opto-isolators withstand input-to-output voltages up to 10 kV[3] and voltage transients with speeds up to 10 kV/μs.[4]

A common type of opto-isolator consists of an LED and a phototransistor in the same opaque package. Other types of source-sensor combinations include LED-photodiode, LED-LASCR, and lamp-photoresistor pairs. Usually opto-isolators transfer digital (on-off) signals, but some techniques allow them to be used with analog signals.

1.1 History

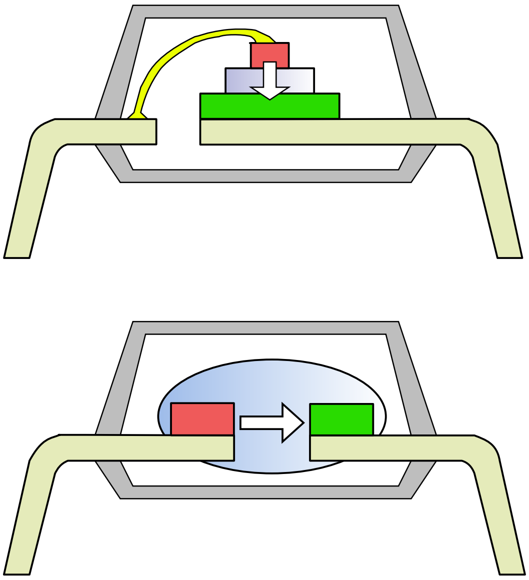
The value of optically coupling a solid state light emitter to a semiconductor detector for the purpose of electrical isolation was recognized in 1963 by Akmenkalns,et al. (US patent 3,417,249). Photoresistor-based opto-isolators were introduced in 1968. They are the slowest, but also the most linear isolators and still retain a niche market in audio and music industry. Commercialization of LED technology in 1968–1970 caused a boom in optoelectronics, and by the end of the 1970s the industry developed all principal types of opto-isolators. The majority of opto-isolators on the market use bipolar silicon phototransistor sensors.[5] They attain medium data transfer speed, sufficient for applications like electroencephalography.[6] The fastest opto-isolators use PIN diodes in photoconductive mode.

1.2 Operation

An opto-isolator contains a source (emitter) of light, almost always a near infrared light-emitting diode (LED), that converts electrical input signal into light, a closed optical channel (also called dielectrical channel[7]), and a photosensor, which detects incoming light and either generates electric energy directly, or modulates electric current flowing from an external power supply. The sensor can be a photoresistor, a photodiode, a phototransistor, a silicon-controlled rectifier (SCR) or a triac. Because LEDs can sense light in addition to emitting it, construction of symmetrical, bidirectional opto-isolators is possible. An optocoupled solid state relay contains a photodiode opto-isolator which drives a power switch, usually a complementary pair of MOSFETs. A slotted optical switch contains a source of light and a sensor, but its optical channel is open, allowing modulation of light by external objects obstructing the path of light or reflecting light into the sensor.

1.3 Electric isolation

Electronic equipment and signal and power transmission lines can be subjected to voltage surges induced by lightning, electrostatic discharge, radio frequency transmissions, switching pulses (spikes) and perturbations in power supply.[8] Remote lightning strikes can induce surges up to 10 kV, one thousand times more than the voltage limits of many electronic components.[9] A circuit can also incorporate high voltages by design, in which case it needs safe, reliable means of interfacing its high-voltage components with low-voltage ones.[10]



Planar (top) and silicone dome (bottom) layouts - cross-section through a standard dual in-line package. Relative sizes of LED (red) and sensor (green) are exaggerated.[note 2]

The main function of an opto-isolator is to block such high voltages and voltage transients, so that a surge in one part of the system will not disrupt or destroy the other parts.[2][11] Historically, this function was delegated to isolation transformers, which use inductive coupling between galvanically isolated input and output sides. Transformers and opto-isolators are the only two classes of electronic devices that offer *reinforced protection* — they protect both the equipment *and* the human user operating this equipment.[12] They contain a single physical isolation barrier, but provide protection equivalent to double isolation.[12] Safety, testing and approval of opto-couplers are regulated by national and international standards: IEC 60747-5-2, EN (CENELEC) 60747-5-2, UL 1577, CSA Component Acceptance Notice #5, etc.[13] Opto-isolator specifications published by manufacturers always follow at least one of these regulatory frameworks.

An opto-isolator connects input and output sides with a beam of light modulated by input current. It transforms useful input signal into light, sends it across the dielectric channel, captures light on the output side and transforms it back into electric signal. Unlike transformers, which pass energy in both directions[note 3] with very low losses, opto-isolators are unidirectional (see exceptions) and they cannot transmit *power*.[14] Typical opto-isolators can only modulate the flow of energy already present on the output side.[14] Unlike transformers, opto-isolators can pass DC or slow-moving signals and do not require matching impedances between input and output sides.[note 4] Both transformers and opto-isolators are effective in breaking ground loops, common in industrial and stage equipment, caused by high or noisy return currents in ground wires.[15]

The physical layout of an opto-isolator depends primarily on the desired isolation voltage. Devices rated for less than a few kV have planar (or sandwich) construction.[16] The sensor die is mounted directly on the lead frame of its package (usually, a six-pin or a four-pin dual in-line package).[7] The sensor is covered with a sheet of glass or clear plastic, which is topped with the LED die.[7] The LED beam fires downward. To minimize losses of light, the useful absorption spectrum of the sensor must match the output spectrum of the LED, which almost invariably lies in the near infrared.[17] The optical channel is made as thin as possible for a desired breakdown voltage.[16] For example, to be rated for short-term voltages of 3.75 kV and transients of 1 kV/μs, the clear polyimide sheet in the Avago ASSR-300 series is only 0.08 mm thick.[18] Breakdown voltages of planar assemblies depend on the thickness of the transparent sheet[16] and the configuration of bonding wires that connect the dies with external pins.[7] Real in-circuit isolation voltage is further reduced by creepage over the PCB and the surface of the package. Safe design rules require a minimal clearance of 25 mm/kV for bare metal conductors or 8.3 mm/kV for coated conductors.[19]

Opto-isolators rated for 2.5 to 6 kV employ a different layout called *silicone dome*.[20] Here, the LED and sensor dies are placed on the opposite sides of the package; the LED fires into the sensor horizontally.[20] The LED, the sensor and the gap between them are encapsulated in a blob, or dome, of transparent silicone. The dome acts as a reflector, retaining all stray light and reflecting it onto the surface of the sensor, minimizing losses in a relatively long optical channel.[20] In *double mold* designs the space between the silicone blob ("inner mold") and the outer shell ("outer mold") is filled with dark dielectric compound with a matched coefficient of thermal expansion.[21]

1.4 Types of opto-isolators

1.4.1 Resistive opto-isolators

Main article: Resistive opto-isolator

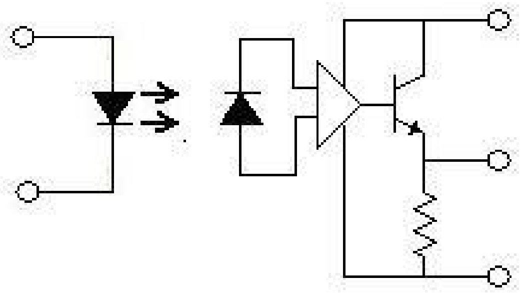
The earliest opto-isolators, originally marketed as *light cells*, emerged in the 1960s. They employed miniature incandescent light bulbs as sources of light, and cadmium sulfide (CdS) or cadmium selenide (CdSe) photoresistors (also called light-dependent resistors, LDRs) as receivers. In applications where control linearity was not important, or where available current was too low for driving an incandescent bulb (as was the case in vacuum tube amplifiers), it was replaced with a neon lamp. These devices (or just their LDR component) were commonly named *Vactrols*, after a trademark of Vactec, Inc. The trademark has since been genericized,[note 8] but the original Vactrols are still being manufactured by PerkinElmer.[24][note 9]

The turn-on and turn-off lag of an incandescent bulb lies in hundreds of milliseconds range, which makes the bulb an effective low-pass filter and rectifier but limits the practical modulation frequency range to a few Hertz. With the introduction of light-emitting diodes (LEDs) in 1968–1970,[25] the manufacturers replaced incandescent and neon lamps with LEDs and achieved response times of 5 milliseconds and modulation frequencies up to 250 Hz.[26] The name *Vactrol* was carried over on LED-based devices which are, as of 2010, still produced in small quantities.[27]

Photoresistors used in opto-isolators rely on bulk effects in a uniform film of semiconductor; there are no p-n junctions.[28] Uniquely among photosensors, photoresistors are non-polar devices suited for either AC or DC circuits.[28] Their resistance drops in reverse proportion to the intensity of incoming light, from virtually infinity to a residual floor that may be as low as less than a hundred Ohms.[28] These properties made the original Vactrol a convenient and cheap automatic gain control and compressor for telephone networks. The photoresistors easily withstood voltages up to 400 volts,[28] which made them ideal for driving vacuum fluorescent displays. Other industrial applications included photocopiers, industrial automation, professional light measurement instruments and auto-exposure meters.[28] Most of these applications are now obsolete, but resistive opto-isolators retained a niche in audio, in particular guitar amplifier, markets.

American guitar and organ manufacturers of the 1960s embraced the resistive opto-isolator as a convenient and cheap tremolo modulator. Fender's early tremolo effects used two vacuum tubes; after 1964 one of these tubes was replaced by an optocoupler made of a LDR and a neon lamp.[29] To date, Vactrols activated by pressing the stompbox pedal are ubiquitous in the music industry.[30] Shortages of genuine PerkinElmer Vactrols forced the DIY guitar community to “roll their own” resistive opto-isolators.[31] Guitarists to date prefer opto-isolated effects because their superior separation of audio and control grounds results in “inherently high quality of the sound”.[31] However, the distortion introduced by a photoresistor at line level signal is higher than that of a professional electrically-coupled voltage-controlled amplifier.[32] Performance is further compromised by slow fluctuations of resistance owing to light history, a memory effect inherent in cadmium compounds. Such fluctuations take hours to settle and can be only partially offset with feedback in the control circuit.[33]

1.4.2 Photodiode opto-isolators



A fast photodiode opto-isolator with an output-side amplifier circuit.

Diode opto-isolators employ LEDs as sources of light and silicon photodiodes as sensors. When the photodiode is reverse-biased with an external voltage source, incoming light increases the reverse current flowing through the diode. The diode itself does not generate energy; it modulates the flow of energy from an external source. This mode of operation is called photoconductive mode. Alternatively, in the absence of external bias the diode converts the energy of light into electric energy by charging its terminals to a voltage of up to 0.7 V. The rate of charge is proportional to the intensity of incoming light. The energy is harvested by draining the charge through an external high-impedance path; the ratio of current transfer can reach 0.2%.[22] This mode of operation is called photovoltaic mode.

The fastest opto-isolators employ PIN diodes in photoconductive mode. The response times of PIN diodes lie in the subnanosecond range; overall system speed is limited by delays in LED output and in biasing circuitry. To minimize these delays, fast digital opto-isolators contain their own LED drivers and output amplifiers optimized for speed. These devices are called *full logic opto-isolators*: their LEDs and sensors are fully encapsulated within a digital logic circuit.[34] The Hewlett-Packard 6N137/HPCL2601 family of devices equipped with internal output amplifiers was introduced in the late 1970s and attained 10 MBd data transfer speeds.[35] It remained an industry standard until the introduction of the 50 MBd Agilent Technologies[note 10] 7723/0723 family in 2002.[36] The 7723/0723 series opto-isolators contain CMOS LED drivers and a CMOS buffered amplifiers, which require two independent external power supplies of 5 V each.[37]

Photodiode opto-isolators can be used for interfacing analog signals, although their non-linearity invariably distorts the signal. A special class of analog opto-isolators introduced by Burr-Brown uses *two* photodiodes and an input-side operational amplifier to compensate for diode non-linearity. One of two identical diodes is wired into the feedback loop of the amplifier, which maintains overall current transfer ratio at a constant level regardless of the non-linearity in the second (output) diode.[38]

A novel idea of a particular optical analog signal isolator was submitted on 3, June 2011. The proposed configuration consist of two different parts. One of them transfers the signal, and the other establishes a negative feedback to ensure that the output signal has the same features as the input signal. This proposed analog isolator is linear over a wide range of input voltage and frequency.[39]

Solid-state relays built around MOSFET switches usually employ a photodiode opto-isolator to drive the switch. The gate of a MOSFET requires relatively small total charge to turn on and its leakage current in steady state is very low. A photodiode in photovoltaic mode can generate turn-on *charge* in a reasonably short time but its output *voltage* is many times less than the MOSFET's threshold voltage. To reach the required threshold, solid-state relays contain stacks of up to thirty photodiodes wired in series.[21]

1.4.3 Phototransistor opto-isolators

Phototransistors are inherently slower than photodiodes.[40] The earliest and the slowest but still common 4N35 opto-isolator, for example, has rise and fall times of 5 µs into a 100 Ohm load[41] and its bandwidth is limited at around 10 kilohertz - sufficient for applications like electroencephalography[6] or pulse-width motor control.[42] Devices like PC-900 or 6N138 recommended in the original 1983 Musical Instrument Digital Interface specification[43] allow digital data transfer speeds of tens of kiloBauds.[44] Phototransistors must be properly biased and loaded to achieve their maximum speeds, for example, the 4N28 operates at up to 50 kHz with optimum bias and less than 4 kHz without it.[45]

Design with transistor opto-isolators requires generous allowances for wide fluctuations of parameters found in commercially available devices.[45] Such fluctuations may be destructive, for example, when an opto-isolator in the feedback loop of a DC-to-DC converter changes its transfer function and causes spurious oscillations,[20] or when unexpected delays in opto-isolators cause a short circuit through one side of an H-bridge.[46] Manufacturers' datasheets typically list only worst-case values for critical parameters; actual devices surpass these worst-case estimates in an unpredictable fashion.[45] Bob Pease observed that current transfer ratio in a batch of 4N28's can vary from 15% to more than 100%; the datasheet specified only a minimum of 10%. Transistor beta in the same batch can vary from 300 to 3000, resulting in 10:1 variance in bandwidth.[45]

Opto-isolators using field-effect transistors (FETs) as sensors are rare and, like vactrols, can be used as remote-controlled analog potentiometers provided that the voltage across the FET's output terminal does not exceed a few hundred mV.[38] Opto-FETs turn on without injecting switching charge in the output circuit, which is particularly useful in sample and hold circuits.[11]

1.4.4 Bidirectional opto-isolators

All opto-isolators described so far are uni-directional. Optical channel always works one way, from the source (LED) to the sensor. The sensors, be it photoresistors, photodiodes or phototransistors, cannot emit light.[note 11] But LEDs, like all semiconductor diodes,[note 12] are capable of detecting incoming light, which makes possible construction of a two-way opto-isolator from a pair of LEDs. The simplest bidirectional opto-isolator is merely a pair of LEDs placed face to face and held together with heat-shrink tubing. If necessary, the gap between two LEDs can be extended with a glass fiber insert.[47]

Visible spectrum LEDs have relatively poor transfer efficiency, thus near infrared spectrum GaAs, GaAs:Si and AlGaAs:Si LEDs are the preferred choice for bidirectional devices. Bidirectional opto-isolators built around pairs of GaAs:Si LEDs have current transfer ratio of around 0.06% in either photovoltaic or photoconductive mode — less than photodiode-based isolators,[48] but sufficiently practical for real-world applications.[47]

1.5 Types of configurations

Usually, optocouplers have a *closed pair* configuration. This configuration refers to optocouplers enclosed in a dark container wherein the source and sensor are facing each other.

Some optocouplers have a *slotted coupler/interrupter* configuration. This configuration refers to optocouplers with an open slot between the source and sensor that has the ability to influence incoming signals. The *slotted coupler/interrupter* configuration is suitable for object detection, vibration detection, and bounce-free switching.

Some optocouplers have a *reflective pair* configuration. This configuration refers to optocouplers that contain a source that emits light and a sensor that only detects light when it has reflected off an object. The *reflective pair* configuration is suitable for the development of tachometers, movement detectors and reflectance monitors.

The later two configurations are frequently referred to as 'optosensors'.

1.6 Alternatives

Further information: Microelectromechanical systems

Alternative isolators are typically built using ultra thin (0.01 mm – 0.02 mm) insulation layers, whereas optocouplers have insulation thicknesses up to 2 mm. The thinner insulation barrier means that alternative isolators experience much higher electric-field stress than optocouplers, and could be less robust under high voltages.

Currently, there are no IEC component level safety standard available for such isolators. As a result, some manufacturers might seek IEC 60747-5-2 (older revision) or IEC 60747-5-5 (current revision) certification (a standard originally intended for optocouplers). Alternative isolators are structurally different from optocouplers and thus do not qualified for full IEC60747-5-2/5 certification, but only for BASIC insulation.[49]

The following are claims from manufacturers of alternative isolators:

- Developers have long recognized that Optocouplers are based on outdated technology, and only recently have cost effective and easy to use alternatives become available. These advanced package and pin compatible drop-in optocoupler replacements provide sustainability higher performance and reliability with none of the technical liabilities of optocouplers. Digital isolators can directly replace 6-pin and 8-pin optocouplers and are suitable for both optocoupler retrofit and new system designs. These devices use CMOS-based isolation architecture that are ten times more reliable than optocouplers, enabling manufacturers to support longer end product warranties and reduce costs associated with repairs or replacement.

- Opto-isolators can be too slow and bulky for modern digital applications. Since the 1990s, researchers have examined and perfected alternative, faster and more compact isolation technologies. Two of these technologies, transformer based isolators and capacitor-coupled isolators, reached the mass market in the 2000s. The third alternative, based on giant magnetoresistance, has been present on the market since 2002 in limited quantities. As of 2010, production models of all three types allow data transfer speeds of 150 Mbit/s and resist voltage transients of up to 25 kV/μs, compared to 10 kV/μs for opto-isolators.[4] Unlike opto-isolators, which are stacks of discrete LEDs and sensors, the new devices are monolithic integrated circuits, and are easily scalable into multi-bit data bus isolators.[50]

Notable events concerning alternative isolators:

- In 2000 Analog Devices introduced integrated magnetic isolators — electrically-decoupled 100 Mbit/s, 2.5 kV isolation circuits employing air core transformers micromachined on the surface of silicon integrated circuits. They featured lesser power consumption, lesser cost[note 13] and were four times faster than the fastest contemporary opto-isolators.[51] In 2010, Analog increased the speed of their magnetic isolators to 150 Mbit/s and offered isolation up to 5 kV.[52] Microtransformer-based isolators can work as dc-dc converters, passing both signal *and* power. Commercially available ICs can carry up to four isolated digital channels and a 2 W isolated power channel in miniature 20-pin packages.[53] According to Analog Devices, by December 2011 the company has more “than 750 million [magnetic isolator] channels deployed”.[53] In the same year NEC and Renesas announced transformer-based CMOS devices with transfer rates of 250 Mbit/s.[54][55]

- High-speed capacitive-coupled isolators[note 14] were introduced in 2000 by Silicon Laboratories and commercialized by Texas Instruments. These devices convert an incoming data stream into an amplitude-modulated UHF signal, pass it through a silicon dioxide isolation layer, and demodulate the received signal. The spectra of spurious voltage transients, which can pass through the capacitive barrier and disrupt operation, lie far below the modulation frequency and can be effectively blocked. As of 2010, capacitive-coupled isolators offer data transfer speeds of 150 Mbit/s and voltage isolation of 560 V continuous and 4 kV peak across the barrier.[56]

- NVE Corporation, the pioneer of magnetoresistive random-access memory, markets an alternative type of isolator based on giant magnetoresistance (GMR) effect (*Spintronic* and *IsoLoop* trademarks). Each isolation cell of these devices is formed by a flat square coil which is micromachined above four spin valve sensors buried in the silicon wafer.[57] These sensors, wired into a Wheatstone bridge circuit, generate binary on/off output signals.[58] At the time of their introduction in 2002, NVE advertised speeds 5 to 10 times higher than the fastest opto-isolators;[57] and in March 2008 commercial devices marketed by NVE were rated for speeds up to 150 Mbit/s.[58]

1.7 Notes

[1] Real-world schematic diagrams omit the barrier symbol, and use a single set of directional arrows.

[2] Based on conceptual drawings published by Basso and by Mims, p. 100. Real-world LEDs and sensors are much smaller; see the photograph in Avago, p. 3 for an example.

[3] A transformer can have as many coils as necessary. Each coil can act as a *primary*, pumping energy into a common magnetic core, or as a *secondary* – picking up energy stored in the core.

[4] The input side circuitry and the LED must be matched, the output side and the sensor must be matched, but there is, usually, no need to match input *and* output sides.

[5] See Horowitz and Hill, p. 597, for an expanded list of opto-isolator types with their schematic symbols and typical specifications.

[6] Current through the photoresistor (output current) is proportional to the voltage applied across it. In theory it can exceed 100% of input current, but in practice dissipation of heat according to Joule's law limits current transfer ratio at below 100%.

[7] Low-cost solid-state relays have switching times of tens of milliseconds. Modern high-speed solid-state relays like Avago ASSR-300 series (see datasheet) attain switching times of less than 70 nanoseconds.

[8] According to the United States Patent and Trademark Office, trademark registered in 1969 for "photocell combined with a light source" is now dead (USPTO database record serial number 72318344. Retrieved November 5, 2010). The same trademark, registered in 1993 for "medico-surgical tubing connector sold as a component of suction catheters" is now live and owned by Mallinckrodt Inc. (USPTO database record serial number 74381130. Retrieved November 5, 2010).

[9] Vactec was purchased by EG&G (Edgerton, Germeshausen, and Grier, Inc.), a defense contractor, in 1983. In 1999 EG&G purchased formerly independent PerkinElmer, and changed own name PerkinElmer (see reverse takeover). An unrelated company, Silonex (a division of Carlyle Group) brands its photoresistive opto-isolators *Audiohm Optocouplers*.

[10] The former semiconductor division of Agilent Technologies operates as an independent company, Avago Technologies, since 2005.

[11] Exception: Ternary and quaternary GaAsP photodiodes can generate light. - Mims, p. 102.

[12] "Even the garden variety signal diodes you use in circuits have a small photovoltaic effect. There are amusing stories of bizarre circuit behavior finally traced to this." - Horowitz and Hill, p. 184.

[13] "Low cost" of components, in industry language, means "low price for the [bulk volume] buyer". It does not necessarily indicate low costs to produce these components, particularly when the manufacturer introduces a new type of device.

[14] Burr-Brown introduced a distinct class of capacitive-coupled analog *isolation amplifiers* in the 1980s. These hybrid circuits attain analog bandwidth of 70 kHz and isolation of 3.5 kV. - Horowitz and Hill, p. 464.

1.8 References

[1] Graf, p. 522.

[2] Lee et al., p. 2.

[3] Hasse, p. 145.

[4] Joffe and Kai-Sang Lock, p. 279.

[5] Graf, p. 522; PerkinElmer, p. 28.

[6] See Ananthi, pp. 56, 62 for a practical example of an opto-coupled EEG application.

[7] Mims, p. 100.

[8] Hasse, p. 43.

[9] Hasse, p. 60.

[10] See Basso for a discussion of such interfacing in switched-mode power supplies.

[11] Horowitz and Hill, p. 595.

[12] Jaus, p. 48.

[13] Jaus, pp. 50–51.

[14] Joffe and Kai-Sang Lock, p. 277.

[15] Joffe and Kai-Sang Lock, pp. 268, 276.

[16] Mataré, p. 174

[17] Ball, p. 69.

[18] Avago Technologies (2007). *ASSR-301C and ASSR-302C (datasheet)*. Retrieved November 3, 2010.

[19] Bottrill et al., p. 175.

[20] Basso.

[21] Vishay Semiconductor.

[22] Mataré, p. 177, table 5.1.

[23] Mataré, p. 177

[24] Weber, p. 190; PerkinElmer, p. 28; Collins, p. 181.

[25] Schubert, pp. 8–9.

[26] PerkinElmer, pp. 6–7: "at 1 fc of illumination the response times are typically in the range of 5 ms to 100 ms."

[27] Weber, p. 190; PerkinElmer, pp. 2,7,28; Collins, p. 181.

[28] PerkinElmer, p. 3

[29] Fliegler and Eiche, p. 28; Teagle and Sprung, p. 225.

[30] Weber, p. 190.

[31] Collins, p. 181.

[32] PerkinElmer, pp. 35–36; Silonex, p. 1 (see also distortion charts on subsequent pages).

[33] PerkinElmer, pp. 7, 29, 38; Silonex, p. 8.

[34] Horowitz and Hill, pp. 596–597.

[35] Porat and Barna, p. 464. See also full specifications of currently produced devices: *6N137 / HCPL-2601 datasheet*. Avago Technologies. March 2010. Retrieved November 2, 2010.

[36] *Agilent Technologies Introduces Industry's Fastest Optocouplers*. Business Wire. December 2, 2002.

[37] Agilent Technologies (2005). *Agilent HCPL-7723 & HCPL-0723 50 MBd 2 ns PWD High Speed CMOS Optocoupler (Datasheet)*. Retrieved November 2, 2010.

[38] Horowitz and Hill, p. 598.

[39] Modern Applied Science Vol 5, No 3 (2011). *A Novel Approach to Analog Signal Isolation through Digital Opto-coupler (YOUTAB)*.

[40] Ball, p. 61.

[41] Horowitz and Hill, p. 596. Ball p. 68, provides rise and fall time of 10 μs but does not specify load impedance.

[42] Ball, p. 68.

[43] *MIDI Electrical Specification Diagram & Proper Design of Joystick/MIDI Adapter*. MIDI Manufacturers Association. 1985. Retrieved November 2, 2010.

[44] Ball, p. 67.

[45] Pease, p. 73.

[46] Ball, pp. 181–182. Shorting one side of an H-bridge is called *shoot-through*.

[47] Mims vol. 2, p. 102.

[48] Photodiode opto-isolators have current transfer ratios of up to 0.2% - Mataré, p. 177, table 5.1.

[49] http://www.avagotech.com/docs/AV02-3446EN

[50] Joffe and Kai-Sang Lock, p. 280.

[51] Bindra 2000.

[52] Selection Data Table: Standard Isolators. Analog Devices. Retrieved November 4, 2010.

[53] Kincaid.

[54] Kaeriyama et al.

[55] Renesas (2010). *Renesas Electronics Introduces New CMOS Isolator Technology that Realizes Highly-Integrated Inverter Circuits for Energy-Efficient Home Appliances and Electric Vehicles*. July 20, 2010. Retrieved November 4, 2010.

[56] Texas Instruments (2010). *ISO721, ISO721M (Datasheet)*. January 2006, revised July 2010. Retrieved November 4, 2010.

[57] Myers; NVE Corporation 2007, p. 1.

[58] NVE Corporation 2007, p. 2.

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1.10 External links

- Optocouplers: When and how to use them PDF (157 KB)
- Trends in Optocoupler Radiation Degradation PDF (89.1 KB)
- How Optical Isolation Works - Illustration

Chapter 2

Photodetector

Photosensors or **photodetectors** are sensors of light or other electromagnetic energy.[1]

2.1 Types

- Active-pixel sensors (APSs) are image sensors. Usually made in a CMOS process, and also known as CMOS image sensors, APSs are commonly used in cell phone cameras, web cameras, and some DSLRs.
- Charge-coupled devices (CCD), which are used to record images in astronomy, digital photography, and digital cinematography. Before the 1990s, photographic plates were most common in astronomy. The next generation of astronomical instruments, such as the Astro-E2, include cryogenic detectors.
- In experimental particle physics, a particle detector is a device used to track and identify elementary particles.
- Chemical detectors, such as photographic plates, in which a silver halide molecule is split into an atom of metallic silver and a halogen atom. The photographic developer causes adjacent molecules to split similarly.
- Cryogenic detectors are sufficiently sensitive to measure the energy of single x-ray, visible and infrared photons.[2]
- LEDs which are reverse-biased to act as photodiodes. See LEDs as Photodiode Light Sensors.
- Optical detectors, which are mostly quantum devices in which an individual photon produces a discrete effect.
- Optical detectors that are effectively thermometers, responding purely to the heating effect of the incoming radiation, such as bolometers, pyroelectric detectors, Golay cells, thermocouples and thermistors, but the latter two are much less sensitive.
- Photoresistors or *Light Dependent Resistors* (LDR) which change resistance according to light intensity. Normally the resistance of LDRs decreases with increasing intensity of light falling on it.[3]
- Photovoltaic cells or solar cells which produce a voltage and supply an electric current when illuminated.
- Photodiodes which can operate in photovoltaic mode or photoconductive mode.
- Photomultiplier tubes containing a photocathode which emits electrons when illuminated, the electrons are then amplified by a chain of dynodes.
- Phototubes containing a photocathode which emits electrons when illuminated, such that the tube conducts a current proportional to the light intensity.
- Phototransistors, which act like amplifying photodiodes.
- Quantum dot photoconductors or photodiodes, which can handle wavelengths in the visible and infrared spectral regions.

2.2 Frequency range

In 2014 a technique for extending semiconductor-based photodetector's frequency range to longer, lower-energy wavelengths. Adding a light source to the device effectively "primed" the detector so that in the presence of long wavelengths, it fired on wavelengths that otherwise lacked the energy to do so.[4]

2.3 See also

- List of sensors
- Optoelectronics

2.4 References

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2.5 External links

- Fundamentals of Photonics: Module on Optical Detectors and Human Vision

Chapter 3

Optoelectronics

Not to be confused with electro-optics.

Optoelectronics is the study and application of electronic devices that source, detect and control light, usually considered a sub-field of photonics. In this context, *light* often includes invisible forms of radiation such as gamma rays, X-rays, ultraviolet and infrared, in addition to visible light. Optoelectronic devices are electrical-to-optical or optical-to-electrical transducers, or instruments that use such devices in their operation. *Electro-optics* is often erroneously used as a synonym, but is a wider branch of physics that concerns all interactions between light and electric fields, whether or not they form part of an electronic device.

Optoelectronics is based on the quantum mechanical effects of light on electronic materials, especially semiconductors, sometimes in the presence of electric fields.[1]

- Photoelectric or photovoltaic effect, used in:
  - photodiodes (including solar cells)
  - phototransistors
  - photomultipliers
  - optoisolators
  - integrated optical circuit (IOC) elements
- Photoconductivity, used in:
  - photoresistors
  - photoconductive camera tubes
  - charge-coupled imaging devices
- Stimulated emission, used in:
  - injection laser diodes
  - quantum cascade lasers
- Lossev effect, or radiative recombination, used in:
  - light-emitting diodes or LED
  - OLEDs
- Photoemissivity, used in
  - photoemissive camera tube

Important applications[2] of optoelectronics include:

- Optocoupler
- Optical fiber communications

3.1 See also

- Interconnect bottleneck
- Non-radiative life time
- OECC (OptoElectronics and Communications Conference)
- Optical amplifier
- Optical communication
- Optical fiber
- Optical interconnect
- Parallel optical interface
- Photoemission
- Photoemission spectroscopy
- Photovoltaic effect
- Stimulated emission

3.2 References

[1] *Physics and Technology - Vishay Optoelectronics*

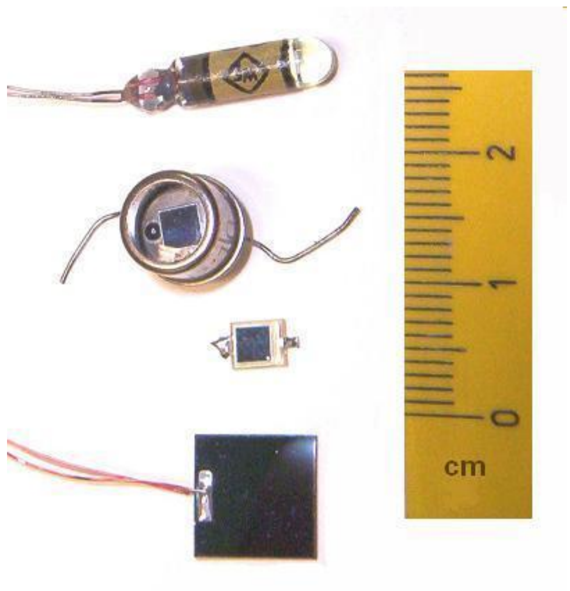
[2] *Optocoupler Application Examples*

3.3 External links

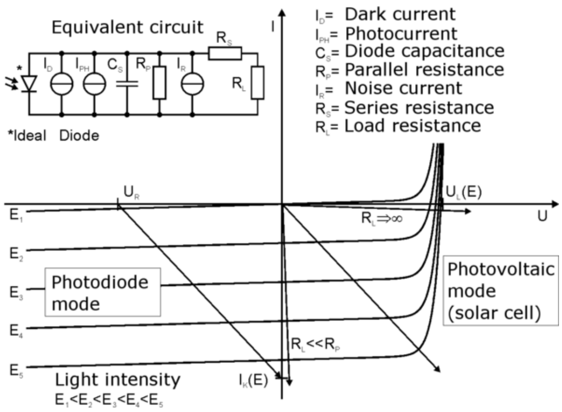
- OIDA (Optoelectronics Industry Development Association)

Chapter 4

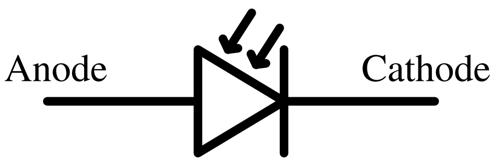
Photodiode



Three Si and one Ge (bottom) photodiodes



I-V characteristic of a photodiode. The linear load lines represent the response of the external circuit: I=(Applied bias voltage-Diode voltage)/Total resistance. The points of intersection with the curves represent the actual current and voltage for a given bias, resistance and illumination.



Symbol for photodiode.

A **photodiode** is a semiconductor device that converts light into current. The current is generated when photons are absorbed in the photodiode. A small amount of current is also produced when no light is present. Photodiodes may contain optical filters, built-in lenses, and may have large or small surface areas. Photodiodes usually have a slower response time as their surface area increases. The common, traditional solar cell used to generate electric solar power is a large area photodiode.

Photodiodes are similar to regular semiconductor diodes except that they may be either exposed (to detect vacuum UV or X-rays) or packaged with a window or optical fiber connection to allow light to reach the sensitive part of the device. Many diodes designed for use specifically as a photodiode use a PIN junction rather than a p–n junction, to increase the speed of response. A photodiode is designed to operate in reverse bias.[1]

4.1 Principle of operation

A photodiode is a p–n junction or PIN structure. When a photon of sufficient energy strikes the diode, it creates an electron-hole pair. This mechanism is also known as the inner photoelectric effect. If the absorption occurs in the junction's depletion region, or one diffusion length away from it, these carriers are swept from the junction by the built-in electric field of the depletion region. Thus holes move toward the anode, and electrons toward the cathode, and a photocurrent is produced. The total current through the photodiode is the sum of the dark current (current that is generated in the absence of light) and the photocurrent, so the dark current must be minimized to maximize the sensitivity of the device.[2]

4.1.1 Photovoltaic mode

When used in zero bias or *photovoltaic mode*, the flow of photocurrent out of the device is restricted and a voltage builds up. This mode exploits the photovoltaic effect, which is the basis for solar cells – a traditional solar cell is just a large area photodiode.

4.1.2 Photoconductive mode

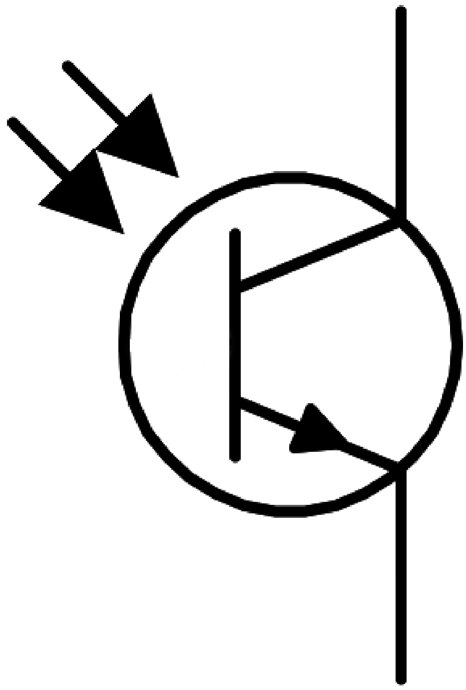
In this mode the diode is often reverse biased (with the cathode driven positive with respect to the anode). This reduces the response time because the additional reverse bias increases the width of the depletion layer, which decreases the junction's capacitance. The reverse bias also increases the dark current without much change in the photocurrent. For a given spectral distribution, the photocurrent is linearly proportional to the illuminance (and to the irradiance).[3]

Although this mode is faster, the photoconductive mode tends to exhibit more electronic noise. [4] The leakage current of a good PIN diode is so low (<1 nA) that the Johnson–Nyquist noise of the load resistance in a typical circuit often dominates.

4.1.3 Other modes of operation

Avalanche photodiodes have a similar structure to regular photodiodes, but they are operated with much higher reverse bias. This allows each *photo-generated* carrier to be multiplied by avalanche breakdown, resulting in internal gain within the photodiode, which increases the effective *responsivity* of the device.

A **phototransistor** is a light-sensitive transistor. A common type of phototransistor, called a photobipolar transistor, is in essence a bipolar transistor encased in a transparent case so that light can reach the *base–collector junction*. It was invented by Dr. John N. Shive (more famous for his wave machine) at Bell Labs in 1948,[5]:205 but it wasn't announced until 1950.[6] The electrons that are generated by photons in the base–collector junction are injected into the base, and this photodiode current is amplified by the transistor's current gain β (or h_{fe}). If the emitter is left unconnected, the phototransistor becomes a photodiode. While phototransistors have a higher responsivity for light they are not able to detect low levels of light any better than photodiodes. Phototransistors also have significantly longer response times. Field-effect phototransistors, also known as photoFETs, are light-sensitive field-effect transistors. Unlike photobipolar transistors, photoFETs control drain-source current by creating a gate voltage.



Electronic symbol for a phototransistor

4.2 Materials

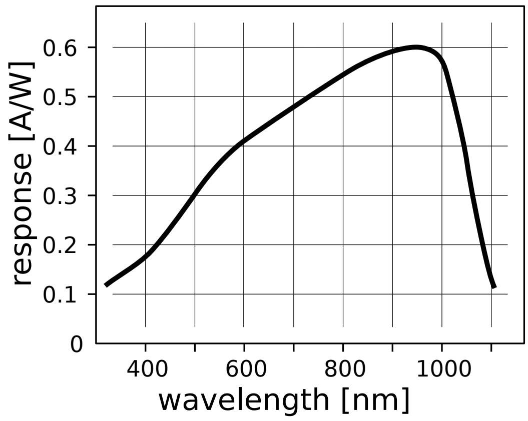
The material used to make a photodiode is critical to defining its properties, because only photons with sufficient energy to excite electrons across the material's bandgap will produce significant photocurrents.

Materials commonly used to produce photodiodes include:[7]

Because of their greater bandgap, silicon-based photodiodes generate less noise than germanium-based photodiodes.

4.2.1 Unwanted photodiode effects

Any p–n junction, if illuminated, is potentially a photodiode. Semiconductor devices such as transistors and ICs contain p–n junctions, and will not function correctly if they are illuminated by unwanted electromagnetic radiation (light) of wavelength suitable to produce a photocurrent;[8][9] this is avoided by encapsulating devices in opaque housings. If these housings are not completely opaque to high-energy radiation (ultraviolet, X-rays, gamma rays), transistors and ICs can malfunction[10] due to induced photo-currents. Background radiation from the packaging is also significant.[11] Radiation hardening mitigates these effects.



Response of a silicon photo diode vs wavelength of the incident light

4.3 Features

Critical performance parameters of a photodiode include:

Responsivity The Spectral responsivity is a ratio of the generated photocurrent to incident light power, expressed in A/W when used in photoconductive mode. The wavelength-dependence may also be expressed as a *Quantum efficiency*, or the ratio of the number of photogenerated carriers to incident photons, a unitless quantity.

Dark current The current through the photodiode in the absence of light, when it is operated in photoconductive mode. The dark current includes photocurrent generated by background radiation and the saturation current of the semiconductor junction. Dark current must be accounted for by calibration if a photodiode is used to make an accurate optical power measurement, and it is also a source of noise when a photodiode is used in an optical communication system.

Response time A photon absorbed by the semiconducting material will generate an electron-hole pair which will in turn start moving in the material under the effect of the electric field and thus generate a current. The finite duration of this current is known as the transit-time spread and can be evaluated by using Ramo's theorem. One can also show with this theorem that the total charge generated in the external circuit is well e and not 2e as might seem by the presence of the two carriers. Indeed the integral of the current due to both electron and hole over time must be equal to e. The resistance and capacitance of the photodiode and the external circuitry give rise to another response time known as RC time constant $\tau = RC$. This combination of R and C integrates the photoresponse over time and thus lengthens the impulse response of the photodiode. When used in an optical communication system, the response time determines the bandwidth available for signal modulation and thus data transmission.

Noise-equivalent power (NEP) The minimum input optical power to generate photocurrent, equal to the rms noise current in a 1 hertz bandwidth. NEP is essentially the minimum detectable power. The related characteristic detectivity (D) is the inverse of NEP, 1/NEP. There is also the specific detectivity ($D^\star$) which is the detectivity multiplied by the square root of the area (A) of the photodetector, ($D^\star = D\sqrt{A}$) for a 1 Hz bandwidth. The specific detectivity allows different systems to be compared independent of sensor area and system bandwidth; a higher detectivity value indicates a low-noise device or system.[12] Although it is traditional to give ($D^\star$) in many catalogues as a measure of the diode's quality, in practice, it is hardly ever the key parameter.

When a photodiode is used in an optical communication system, all these parameters contribute to the *sensitivity* of the optical receiver, which is the minimum input power required for the receiver to achieve a specified *bit error rate*.

4.4 Applications

P–n photodiodes are used in similar applications to other photodetectors, such as photoconductors, charge-coupled devices, and photomultiplier tubes. They may be used to generate an output which is dependent upon the illumination (analog; for measurement and the like), or to change the state of circuitry (digital; either for control and switching, or digital signal processing).

Photodiodes are used in consumer electronics devices such as compact disc players, smoke detectors, and the receivers for infrared remote control devices used to control equipment from televisions to air conditioners. For many applications either photodiodes or photoconductors may be used. Either type of photosensor may be used for light measurement, as in camera light meters, or to respond to light levels, as in switching on street lighting after dark.

Photosensors of all types may be used to respond to incident light, or to a source of light which is part of the same circuit or system. A photodiode is often combined into a single component with an emitter of light, usually a light-emitting diode (LED), either to detect the presence of a mechanical obstruction to the beam (slotted optical switch), or to couple two digital or analog circuits while maintaining extremely high electrical isolation between them, often for safety (optocoupler).

Photodiodes are often used for accurate measurement of light intensity in science and industry. They generally have a more linear response than photoconductors.

They are also widely used in various medical applications, such as detectors for computed tomography (coupled with scintillators), instruments to analyze samples (immunoassay), and pulse oximeters.

PIN diodes are much faster and more sensitive than p–n junction diodes, and hence are often used for optical communications and in lighting regulation.

P–n photodiodes are not used to measure extremely low light intensities. Instead, if high sensitivity is needed, avalanche photodiodes, intensified charge-coupled devices or photomultiplier tubes are used for applications such as astronomy, spectroscopy, night vision equipment and laser rangefinding.

Pinned photodiode is not a PIN photodiode, it has p+/n/p regions in it. It has a shallow P+ implant in N type diffusion layer over a P-type epitaxial substrate layer. It is used in CMOS Active pixel sensor.[13]

4.4.1 Comparison with photomultipliers

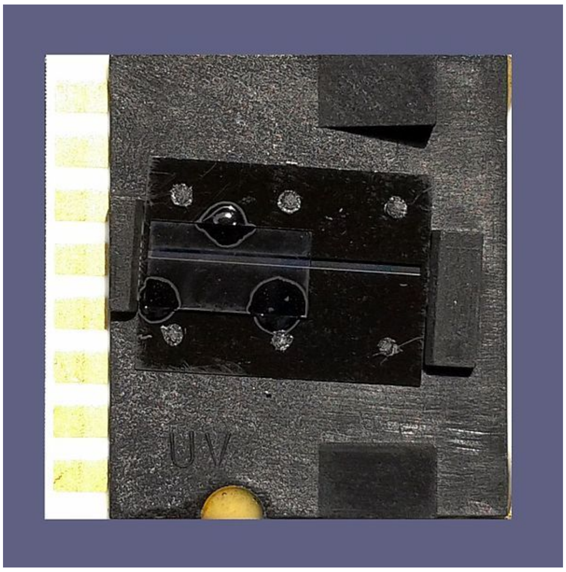
Advantages compared to photomultipliers:[14]

1. Excellent linearity of output current as a function of incident light
2. Spectral response from 190 nm to 1100 nm (silicon), longer wavelengths with other semiconductor materials
3. Low noise
4. Ruggedized to mechanical stress
5. Low cost
6. Compact and light weight
7. Long lifetime
8. High quantum efficiency, typically 60-80% [15]
9. No high voltage required

Disadvantages compared to photomultipliers:

1. Small area
2. No internal gain (except avalanche photodiodes, but their gain is typically 10^2–10^3 compared to up to 10^8 for the photomultiplier)
3. Much lower overall sensitivity
4. Photon counting only possible with specially designed, usually cooled photodiodes, with special electronic circuits
5. Response time for many designs is slower
6. latent effect

4.5 Photodiode array



A 2 x 2 cm photodiode array chip with more than 200 diodes

A one-dimensional array of hundreds or thousands of photodiodes can be used as a position sensor, for example as part of an angle sensor.[16] One advantage of photodiode arrays (PDAs) is that they allow for high speed parallel read out since the driving electronics may not be built in like a traditional CMOS or CCD sensor.

4.6 See also

- Electronics
- Band gap
- Infrared
- Optoelectronics
- Optical interconnect
- Light Peak
- Interconnect bottleneck
- Optical fiber cable
- Optical communication
- Parallel optical interface
- Opto-isolator
- Semiconductor device
- Solar cell
- Avalanche photodiode
- Transducer

- LEDs as Photodiode Light Sensors
- Light meter
- Image sensor
- Transimpedance amplifier

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This article incorporates public domain material from the General Services Administration document "Federal Standard 1037C".

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[12] Graham Brooker, *Introduction to Sensors for Ranging and Imaging*, SciTech Publishing, 2009 ISBN 9781891121746 page 87

[13] http://electronics.stackexchange.com/questions/83018/difference-between-buried-photodiode-and-pinned-photodiode

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[16] Wei Gao (2010). *Precision Nanometrology: Sensors and Measuring Systems for Nanomanufacturing*. Springer. pp. 15–16. ISBN 978-1-84996-253-7.

- Gowar, John, *Optical Communication Systems*, 2 ed., Prentice-Hall, Hempstead UK, 1993 (ISBN 0-13-638727-6)

4.8 External links

- Hamamatsu Application Note
- Using the Photodiode to convert the PC to a Light Intensity Logger
- Design Fundamentals for Phototransistor Circuits
- Working principles of photodiodes
- Excelitas Application Notes on Pacer Website

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