The Basics of Photodiodes and Phototransistors and How to Apply Them

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Contributed By DigiKey's North American Editors
2022-01-11

There is a class of design problems that can easily be solved by using human vision. Consider sensing the proper location of the paper in a printer. It is easy for a human to see the alignment, but difficult for a microprocessor to verify it. The camera in a cell phone needs to measure the ambient light to determine whether the flash needs to be activated. How can the oxygen level in blood be assessed in a non-invasive manner?

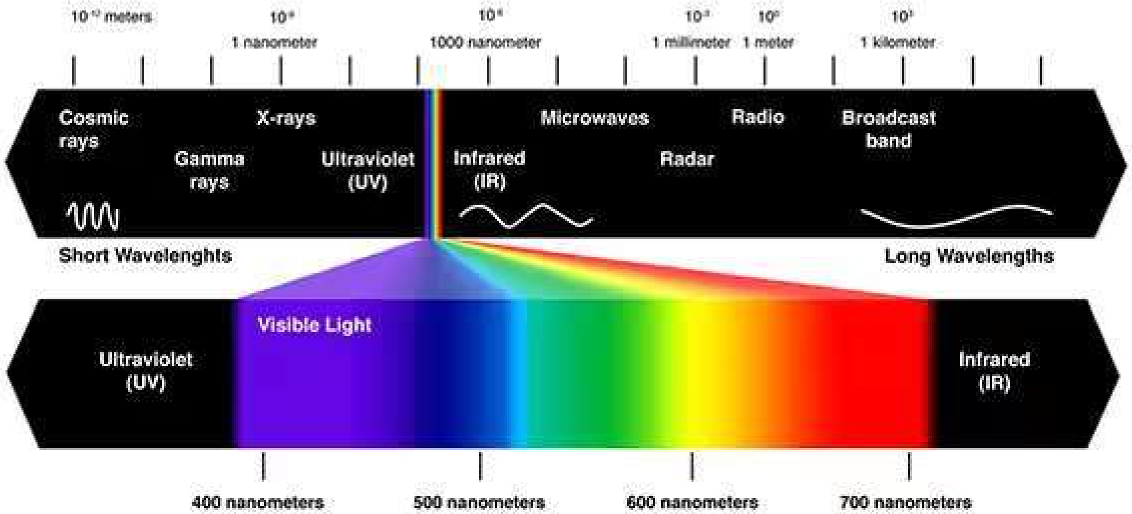
The solution to these design issues is the use of photodiodes or phototransistors. These optoelectronic devices convert light (photons) to electrical signals, and so enable a microprocessor (or microcontroller) to “see”. This allows it to control the positioning and alignment of objects, determine light intensity, and measure the physical properties of materials based on their interaction with light.

This article explains the theory of operation of both photodiodes and phototransistors and provides designers with the basic knowledge of their application. Devices from Advanced Photonix, Inc., Vishay Semiconductor Opto Division, Excelitas Technologies, Genicom Co., Ltd., Marktech Optoelectronics, and NTE Electronics are presented by way of example.

The optical spectrum typically used for photodiodes and phototransistors

Photodiodes and phototransistors are sensitive to a range of optical wavelengths. In some cases, this is a design consideration, for instance, in making the operation invisible to the human eye. The designer should be aware of the optical spectrum in order to match the devices to the application.

The optical spectrum extends from longer wavelength infrared (IR) to shorter wavelength ultraviolet (UV) (Figure 1). The visible wavelengths are in between.



Color	Wavelength (nm)	Frequency (THz)
Ultraviolet (UV)	<380	>789
Violet	380 – 450	618 – 789
Blue	450 – 485	619 – 667
Cyan	485 – 500	600 – 619
Green	500 – 565	530 – 600
Yellow	565 – 590	508 – 530
Orange	590 – 635	472 – 508
Red	625 – 700	428 – 472
Infrared (IR)	>700	<428

Figure 1: Part of the electromagnetic spectrum, the optical spectrum spans UV to IR with the visible spectrum in between. The table lists the visible wavelengths and their associated frequencies. (Image source: Once Lighting (top) and Art Pini (bottom))

Most optoelectronic devices are specified using their operating wavelengths in nanometers (nm); frequency values are rarely used.

Silicon (Si) photodiodes tend to be sensitive to visible light. IR sensitive devices use indium antimonide (InSb), indium gallium arsenide (InGaAs), germanium (Ge), or mercury cadmium telluride (HgCdTe). UV sensitive devices commonly use silicon carbide (SiC).

The photodiode

The photodiode is a two-element P-N or PIN junction that is exposed to light through a transparent body or cover. When light strikes the junction, a current or voltage is developed depending on the mode of operation. The photodiode operates in any of three modes depending on the biasing applied to it. These are the photovoltaic, photoconductive, or avalanche diode modes.

If the photodiode is unbiased, it operates in the photovoltaic mode and produces a small output voltage when illuminated with a light source. In this mode, the photodiode acts like a solar cell. The photovoltaic mode is useful in low-frequency applications, generally under 350 kilohertz (kHz), with low light intensities. The output voltage is low, and the photodiode output requires an amplifier in most cases.

The photoconductive mode requires that the photodiode be reverse biased. The applied reverse bias will generate a depletion region at the P-N junction. The greater the bias, the wider the depletion region. The wider depletion region results in reduced capacitance, compared to the unbiased diode, resulting in faster response times. This mode has higher noise levels and may require bandwidth limiting to control them.

If the reverse bias is increased further, the photodiode operates in avalanche diode mode. In this mode, the photodiodes operate in a high reverse bias condition, permitting the multiplication of each photo-produced electron-hole pair due to avalanche breakdown. This results in internal gain and higher sensitivity in the photodiode. This mode is functionality similar to a photomultiplier tube.

In most applications, the photodiode operates in photoconductive mode with a reverse bias (Figure 2).

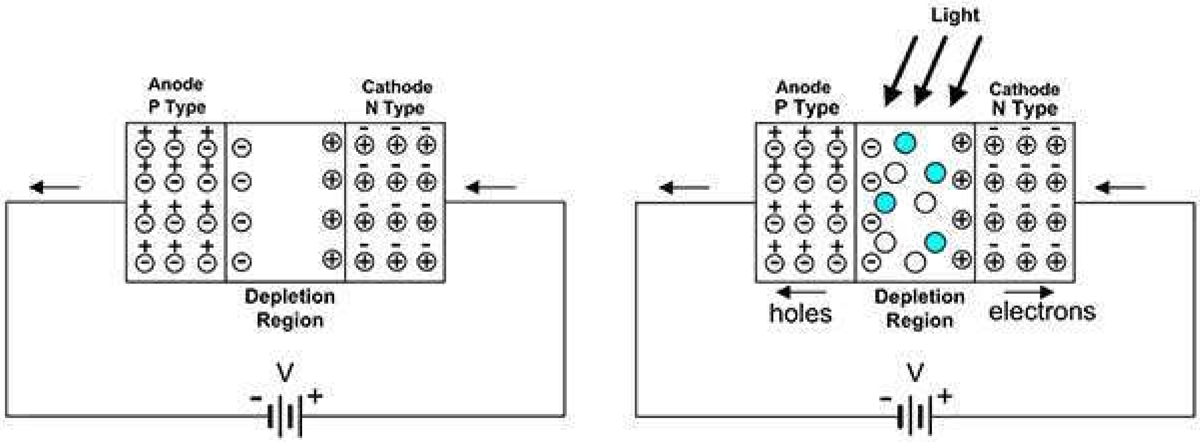


Figure 2: The reverse biased photodiode produces a current proportional to light intensity due to the creation of electron-hole pairs in the depletion region. The blue-filled circles represent electrons and the white circles signify the holes. (Image source: Art Pini)

The reverse biased, unilluminated photodiode junction has a depletion zone with few free carriers. It looks like a charged capacitor. There is a small current caused by thermally excited ionization, called the "dark" current. An ideal photodiode would have zero dark current. Dark current and thermal noise levels are proportional to the temperature of the diode. The dark current can conceal the photocurrent due to extremely low light levels, so devices having low dark currents should be selected.

When light impinges on the depletion layer with sufficient energy, it ionizes the atoms in the crystal structure and generates electron-hole pairs. The existing electric field, due to the biasing, will cause the electrons to move to the cathode and the holes to move to the anode, giving rise to a photocurrent. The greater the light intensity, the greater the photocurrent. The current-voltage characteristic of the reverse biased photodiode shows this in Figure 3.

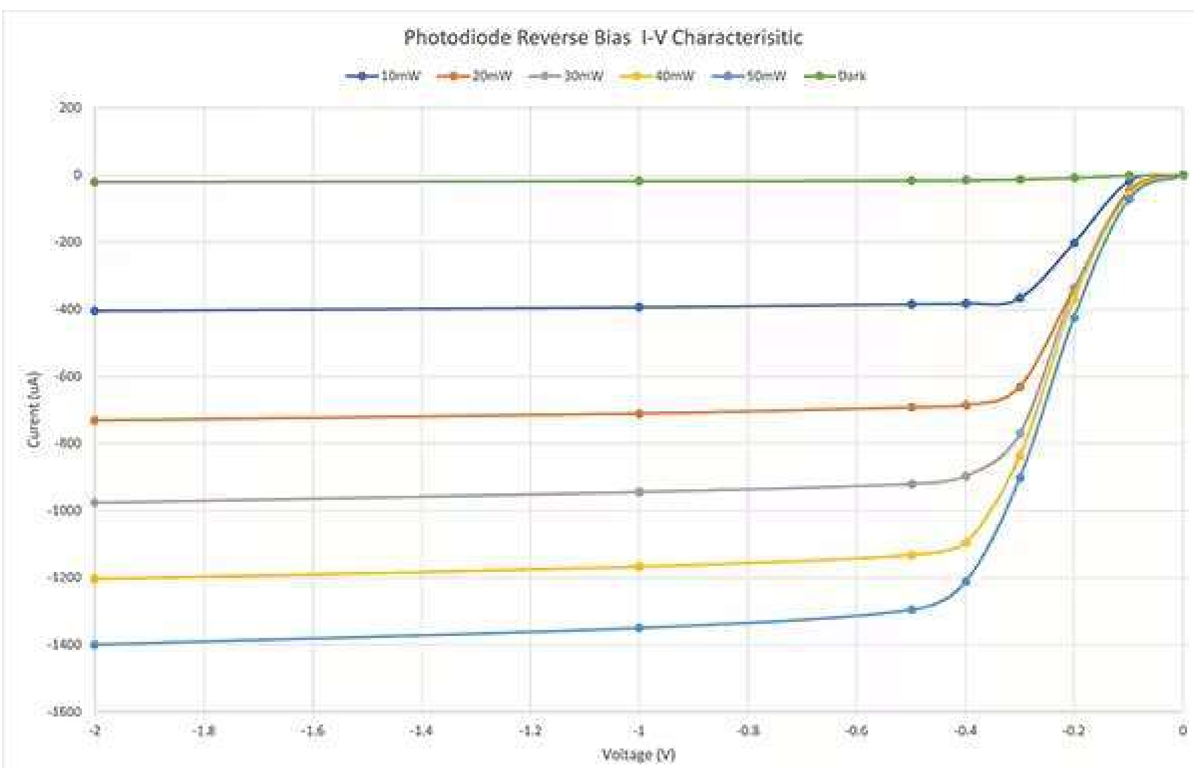


Figure 3: The characteristic V-I diagram for the reverse biased photodiode shows incremental changes in the diode current as a function of the light level. (Image source: Art Pini)

The graph plots the diode reverse current as a function of the applied reverse bias voltage with light intensity as a parameter. Note that increasing light levels produce a proportional increase in the reverse current levels. This is the basis for using photodiodes for measuring light intensity. The bias voltage, when greater than 0.5 volts, has little effect on the photocurrent. The reverse current can be converted to a voltage by applying it to a transimpedance amplifier.

Types of photodiodes

The variety of light detection and measurement applications has given rise to a variety of distinctive photodiode types. The basic photodiode is the planar P-N junction. These devices offer the best performance in unbiased, photovoltaic mode. They are also the most cost-effective devices.

The 002-151-001 from Advanced Photonix, Inc., is an example of a planar diffusion InGaAs photodiode/photodetector (Figure 4). It comes in a surface-mount device (SMD) package measuring 1.6 x 3.2 x 1.1 millimeters (mm), with an active optical aperture measuring 0.05 mm in diameter.

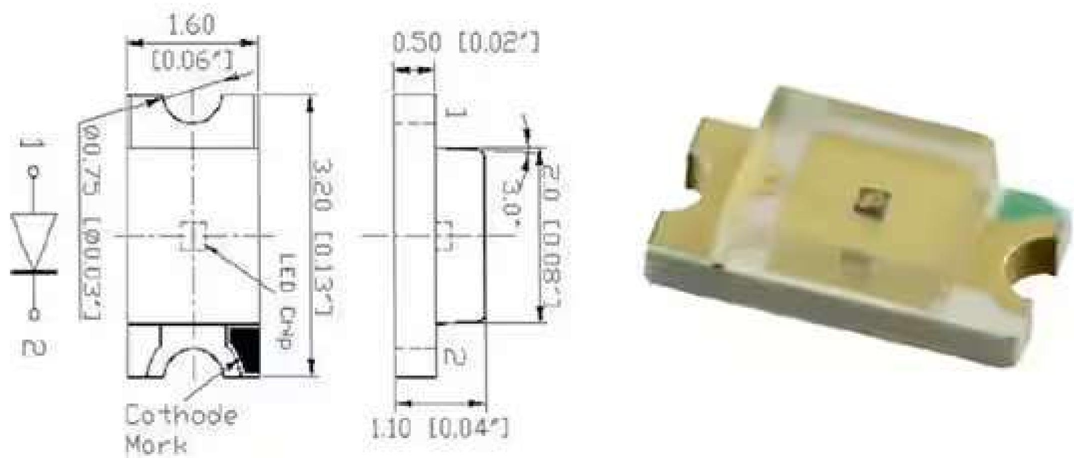


Figure 4: The 002-151-001 is a planar diffusion P-N SMD photodiode measuring 1.6 x 3.2 x 1.1 mm. It has a spectral range of 800 to 1700 nm. (Image source: Advanced Photonix)

This InGaAs photodiode has a spectral range of 800 to 1700 nm, covering the IR spectrum. Its dark current is less than 1 nanoampere (nA). Its spectral responsivity, which specifies the current output for a specific optical power input, is typically 1 ampere per watt (A/W). It is intended for applications including industrial sensing, security, and communications.

The PIN diode is formed by sandwiching a high-resistivity intrinsic semiconductor layer between the P-type and N-type layers of a conventional diode; hence the name PIN reflects the structure of the diode.

The insertion of the intrinsic layer increases the effective width of the diodes depletion layer, resulting in lower capacitance and a higher breakdown voltage. The lower capacitance effectively increases the speed of the photodiode. The larger depletion region offers a larger volume of photon-induced electron-hole generation and greater quantum efficiency.

The Vishay Semiconductor Opto Division's VBP104SR is a silicon PIN photodiode covering the spectral range from 430 to 1100 nm (violet to near IR). It has a typical dark current of 2 nA and a large optically sensitive area of 4.4 mm^2 (Figure 5).

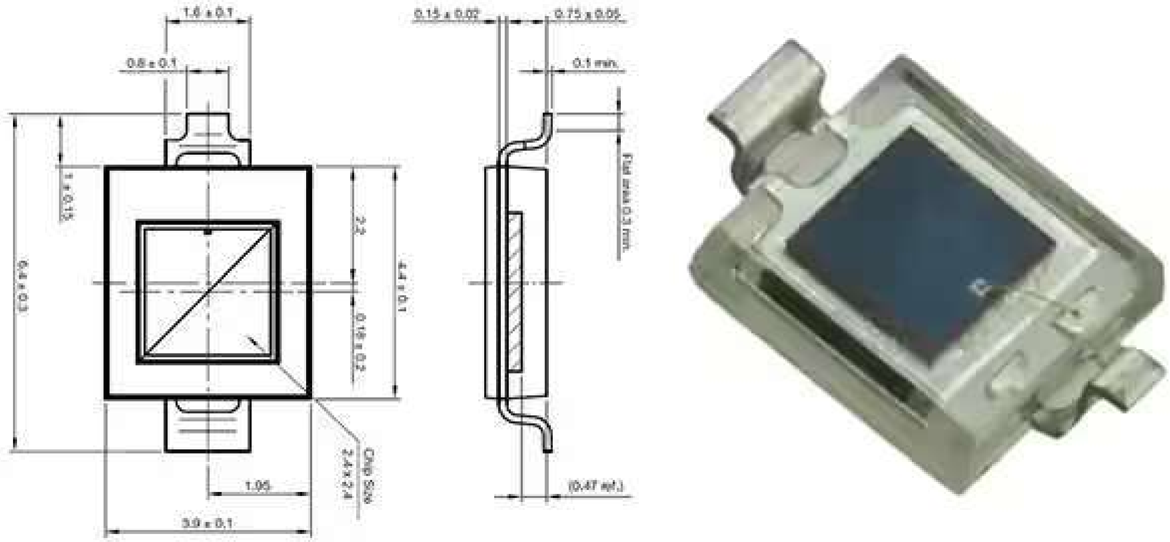


Figure 5: The Vishay VBP104SR is a PIN photodiode with a large optical sensing window intended for high-speed photo detection. (Image source: Vishay Semiconductors)

The avalanche photodiode (APD) is functionally similar to a photomultiplier tube in that it uses the avalanche effect to create gain in the diode. In the presence of a high reverse bias, each hole-electron pair generates additional pairs by means of avalanche breakdown. This results in gain in the form of a larger photocurrent per photon of light. This makes the APD an ideal choice for low light sensitivity.

An example of an APD is the C30737LH-500-92C from Excelitas Technologies. It has a spectral range of 500 to 1000 nm (cyan to near IR) with a peak response at 905 nm (IR). It has a spectral responsivity of 60 A/W @ 900 nm with a dark current less than 1 nA. It is intended for high bandwidth applications such as automotive light detection and ranging (LiDAR) and optical communication (Figure 6).

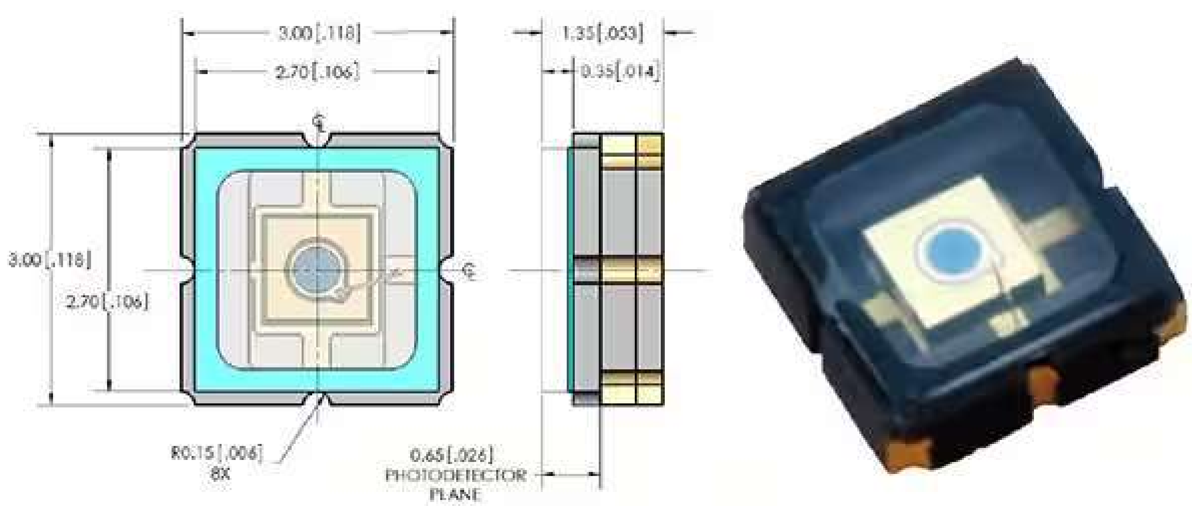


Figure 6: The C30737LH-500-92C avalanche photodiode is a high-bandwidth photodiode aimed at applications such as LiDAR and optical communications. (Image source: Excelitas Technology)

Schottky photodiodes

The Schottky photodiode is based on a metal-to-semiconductor junction. The metal side of the junction forms the anode electrode, while the N-type semiconductor side is the cathode. Photons pass through a partially transparent metallic layer and are absorbed in the N-type semiconductor, freeing charged carrier pairs. These free-charged carriers are swept out of the depletion layer by the applied electric field and form the photocurrent.

A significant characteristic of these diodes is their very fast response time. They generally employ small diode junction structures which are able to respond quickly. Schottky photodiodes with bandwidths in the gigahertz (GHz) range are commercially available. This makes them ideal for high-bandwidth optical communications links.

An example of the Schottky photodiode is the GUVB-S11SD photo sensor from Genicom Co., Ltd. (Figure 7). This UV-sensitive photodiode is intended for applications such as UV indexing. It uses an aluminum gallium nitride (AlGaN)-based material and has a spectral sensitivity range from 240 to 320 nm in the UV spectrum. The device is spectrally sensitive and blind to visible light, a useful feature in brightly lit environments. It has a dark current of less than 1 nA and a responsivity of 0.11 A/W.

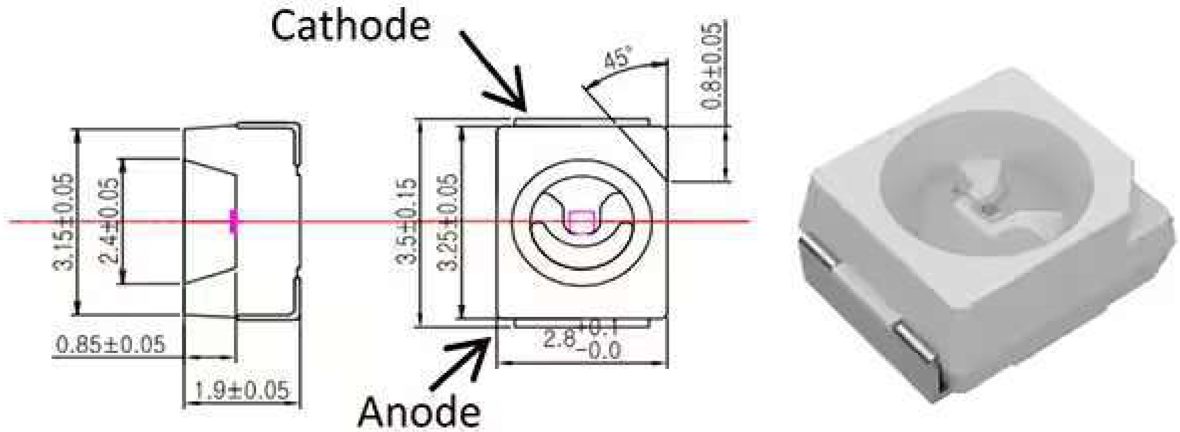


Figure 7: The GUVB-S11SD is an AlGaN-based UV-sensitive photo sensor with an active optical area of 0.076 mm².
(Image source: Genicom Co, Ltd.)

Phototransistors

The phototransistor is a junction semiconductor device similar to the photodiode in that it generates a current proportional to light intensity. It might be thought of as a photodiode with a built-in current amplifier. The phototransistor is an NPN transistor where the base connection is replaced by an optical source. The base-collector junction is reverse biased and exposed to external light through a transparent window. The base-collector junction is purposely made as large as practical to maximize the photocurrent. The base-emitter junction is forward biased, with its collector current being a function of the incident light level. The light supplies the base current, which is amplified through normal transistor action. In the absence of light, a small dark current flows, as in the photodiode.

The Marktech Optoelectronics MTD8600N4-T is an NPN phototransistor with a spectral sensitivity of 400 to 1100 nm (visible to near IR), and a peak photo response at 880 nm (Figure 8).

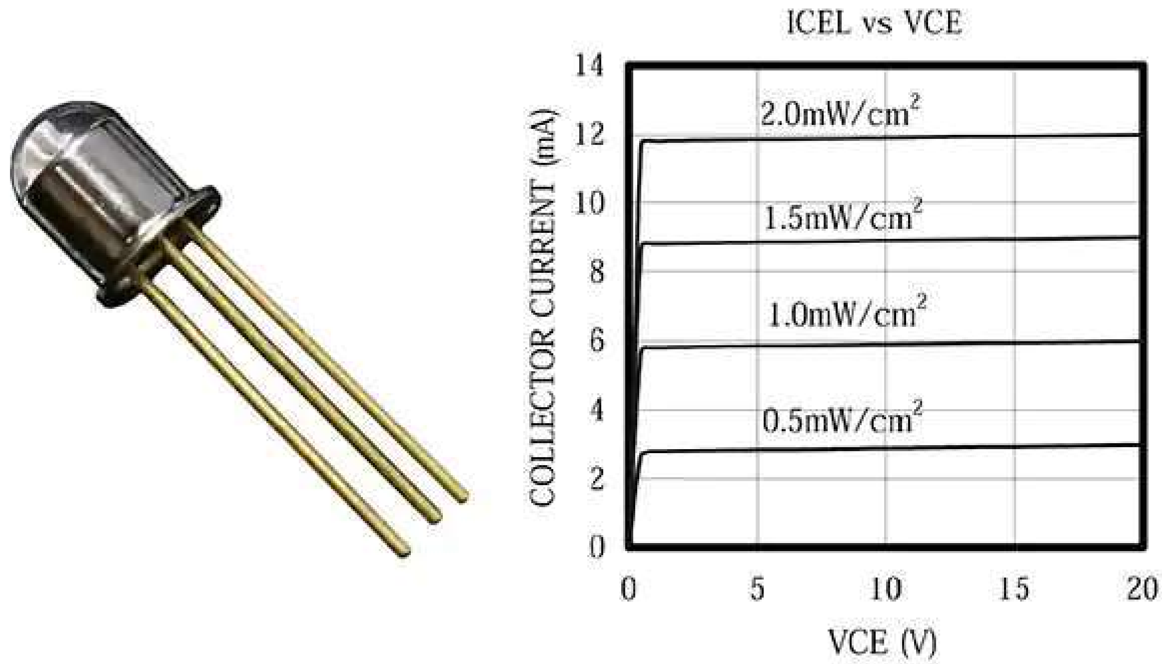


Figure 8: The MTD8600N4-T phototransistor produces a collector current proportional to the incident light level. Note that the collector current is an order of magnitude higher than that of a photodiode due to the current amplification of the transistor. (Image source: Marktech Optoelectronics)

This phototransistor is housed in a metal can with a transparent dome top. The plot is of collector current as a function of collector to emitter voltage, with light irradiance as a parameter. The collector currents are significantly higher than the current in a photodiode due to the current amplification in the transistor.

Phototransistors are available in many package styles. For example, the NTE Electronics NTE3034A NPN phototransistor uses a molded epoxy package which receives light from the side. It also responds to visible to near IR with a peak photo response at 880 nm.

Conclusion

Light detection using phototransistors and photodiodes is one means by which microprocessors or microcontrollers make sense of the physical world and implement control or analysis algorithms accordingly. The phototransistor finds use in the same applications as the photodiode, although they each have their respective advantages. The phototransistor offers a higher output current level than the photodiode, while the photodiode has the advantage of operating at higher frequencies.

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Arthur (Art) Pini is a contributing author at Digi-Key Electronics. He has a Bachelor of Electrical Engineering degree from City College of New York and a Master of Electrical Engineering degree from the City University of New York. He has over 50 years experience in electronics and has worked in key engineering and marketing roles at Teledyne LeCroy, Summation, Wavetek, and Nicolet Scientific. He has interests in measurement technology and extensive experience with oscilloscopes, spectrum analyzers, arbitrary waveform generators, digitizers, and power meters.

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