



## Choosing the Detector for your Unique Light Sensing Application

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### Abstract

How do you decide what detector to use for your light sensing application? The choices can seem overwhelming: photodiodes, phototransistors, photodarlingtons, photomultiplier tubes, photoresistors, integrated circuits, various hybrids and even thermopiles. This application note provides insights on selecting the best approach for your ultraviolet, visible and near-infrared light sensing applications. Specific application needs considered include:

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| light source spectral characteristics<br>optical power mating electronics packaging constraints | <ul style="list-style-type: none"> <li>● image size</li> <li>● signal-to-noise ratio</li> <li>● frequency bandwidth</li> <li>● cost</li> </ul> |
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### Introduction

Most companies do not have resident experts in the fields of modern optics - especially light detection. As a result when a new product is being developed the light sensing design project usually gets assigned to a mechanical or electrical engineer. To meet project schedules, these optics non-experts must get up to speed quickly on the various light sensing methods available. This article provides the non-expert with specific guidelines for sorting through a variety of light sensing technologies and options.

### Available Light Sensing Options

Light sensing applications vary widely from specialized scientific instrumentation that needs to detect individual light particles (photons) to systems that control high speed welding and cutting lasers that produce kilowatts of optical power. Fortunately, there are sensors for almost any application imaginable: from a photomultiplier tube which gives a large voltage pulse for every photon it detects, to cooled thermopiles that absorb kilowatts of power providing a thermocouple voltage proportional to the optical power absorbed. The following describes the most popular light sensing technologies. Their characteristics are summarized in Table 1.

Table 1 - Comparison of Light Sensor Characteristics								
Electrical Characteristics	Photo-multiplier	Photo-diodes	Photo-transistors	CdS Photocells	Other Photo-conduct	Integrated Circuits	Hybrids	Sensor Electronic

	Tubes				ors			Assembl y
Available Wavelengths ( $\mu\text{m}$ )	0.2-0.9	0.2-2.0	0.4-1.1	0.4-0.7	2-15	0.2-1.1	0.2-15.0	0.2-15.0
Performance-to-cost ratio	Fair	Good	Excellent	Excellent	Fair	Fair	Fair	Good
Sensitivity	Excellent	Very Good	Very Good	Very Good	Very Good	Very Good	Very Good	Very Good
Linearity	Good	Excellent	Good	Good	Good	Good	Good	Good
Ambient Noise Performance	Fair	Very Good	Very Good	Very Good	Very Good	Excellent	Excellent	Excellent
Dynamic Range	Very Good	Excellent	Very Good	Good	Good	Very Good	Very Good	Very Good
Stability	Very Good	Very Good	Good	Poor	Fair	Very Good	Very Good	Very Good
<b>Other Characteristics</b>								
Reproducibility	Fair	Excellent	Fair	Poor	Fair	Very Good	Very Good	Very Good
Cost	High	Low	Very Low	Very Low	High	Medium	High	Medium
Ruggedness	Poor	Excellent	Excellent	Excellent	Good	Excellent	Very Good	Excellent
Physical Size	Large	Small	Small	Small	Small	Small	Medium	Medium
Ease of Customization	Poor	Easy	Fair	Fair	Poor	Poor	Poor	Fair
Cost of Customization	Very High	Low	Medium	Low	High	Very High	High	Medium
Lead time for Customization (weeks)	40	12	14	12	20	40	30	16

### Photomultiplier Tubes

Photomultiplier tubes are special vacuum tubes that have a light sensing surface (the photocathode) that absorbs incoming light photons and emits secondary electrons. These secondary electrons are accelerated and multiplied within the photomultiplier tube by dynode plates. Each time an electron strikes a dynode, it has gained enough momentum to create a larger number of secondary electrons. This multiplication process continues for each dynode within the tube. Tubes with ten to twelve dynodes can easily generate multiplication's of more than a million, resulting in sufficient current to develop hundreds of millivolts across an output 50 ohm load resistor for a single incident photon.

Photomultiplier tubes provide the ultimate in detection sensitivity. They can sense the smallest amount of optical energy there is: an individual photon. When cooled, it can be

essentially noise free, with at most one false photon pulse in a one second time period. However, there are many tradeoffs for this light sensor:

- It's mechanically fragile
- It needs an extremely stable high voltage power supply
- It's expensive (\$100's)
- Shapes and sizes are very limited
- It's susceptible to external magnetic fields
- The available photocathodes are limited to sensing ultra-violet to near infrared wavelengths (190 to 900 nm, with special's to 1100 nm)

Photomultiplier tubes are generally used to detect the lowest light levels where the application demands their superior sensitivity.

### Photodiodes

Photodiodes are light sensitive semiconductor devices that are manufactured in essentially the same way as semiconductor diodes used in conventional electronic circuits. The primary differences are that photodiode chips are larger and they are packaged to allow light onto the sensitive area of the diode.

Photodiodes offer many conveniences and advantages that make them very practical for a wide range of applications:

- They can easily measure from picowatts to milliwatts of optical power
- They come in standard packages or the package can be tooled to fit your application exactly
- Depending on the semiconductor material used, they can detect wavelengths from 190 to > 2,000 nm
- They are small and light weight
- Almost any photosensitive shape can be fabricated for as little as \$3,000 tooling
- They have very reproducible sensitivity
- They are inexpensive, with million piece pricing for small area detectors less than \$0.25
- Very large areas can be fabricated (> 10cm<sup>2</sup>, but with cost increasing with area)
- They can be very responsive, with risetimes as fast as 10 picoseconds

If noise presents a problem when measuring a few picowatts of light with a standard photodiode, consider the advantages of an avalanche photodiode which offers a current gain internal to the photodiode structure of up to about 100.

Photodiodes generally require a pre-amplifier to give signal gain for applications to detect picowatts of light power. But for high optical power (<10 microwatt) levels, a simple load resistor configuration can give adequate performance and TTL compatible voltage swings.

Silicon based photodiodes cover the wide range of wavelengths from 190 to 1100 nm (the lower limit is set by absorption of ultraviolet light in air). Germanium (Ge) photodiodes overlap the silicon response spectrum and are usable to about 1600 nm. Semiconductors

that are compounds of gallium, arsenide, indium, antimonide and phosphorous can be specially fabricated to cover small sections of the 190 to 2000 nm spectral range. For instance, the fiber optics industry uses indium-gallium-arsenide (InGaAs) detectors for the 800 to 1800 nm range. More exotic and expensive photodiodes can sense energy much further out in the IR spectrum.

Photodiodes are widely used in our high-tech society, in applications ranging from sensors for door openings, assembly line controls, load levelers in luxury cars, to personal blood sugar meters for diabetics, sun-tan exposure meters, smoke detectors, x-ray baggage inspection systems and even cranial pressure sensors for head injury patients.

### **Phototransistors and Photodarlington**

Phototransistors are transistors designed to capture light and are assembled in a transparent package. They are often more convenient than photodiodes because they have built in gain: the absorbed light creates a current in the base region of the phototransistor, resulting in current gains from 100 to several thousands. Photodarlington have two stages of gain, with net gains that can be greater than 100,000.

The built in gain allows the phototransistor to be coupled with a load resistor to accommodate TTL level voltages for a wide range of light levels. Because of their ease of use, low cost and TTL compatible signal levels, phototransistors have become popular for applications where there is more than a few hundred nanowatts of available optical power. These devices however, do have some drawbacks compared to photodiodes. The frequency bandwidth and linearity are relatively limited and spectral response is restricted to between 350 and 1100 nm. In addition, there are very large variations in sensitivity between individual devices and few standard package options.

### **Photoconductive Sensors**

A photoconductive sensor is a thick film semiconductor material whose electrical resistance decreases with increasing incident light. These rugged assemblies that can withstand hundreds of volts are typically smaller than 0.25 inch diameter.

Photoconductive sensors based on cadmium sulfide (CdS) have sensitivity curves that closely match the sensitivity of the human eye. Accordingly, they are useful in applications involving human light perception such as headlight dimmers and intensity adjustments on information displays. These sensors can be designed for measuring microwatts to milliwatts of optical power and are very inexpensive at high volume (less than \$0.10 each). These characteristics make CdS photoconductors the sensor of choice in applications such as street light control and in the toy industry where economy is a major consideration.

There are, however, considerations that limit the use of CdS photoconductors in more sophisticated applications requiring sensitivities over a wide spectral range, small variations between individual parts, or no history-dependent response. The resistance of these sensors depends on the thick-film microstructure, so the resistance specification has a wide tolerance - a max/min ratio of 3 is not uncommon. The resistance also has long term memory which depends, at any given time, on the amount of light actually incident on the sensor plus the sensor light history for the past several days.

Photoconductors made from materials other than CdS such as lead telluride and mercury cadmium telluride are also available. These materials have spectral sensitivities that cover the range that photodiodes cannot: above 2  $\mu\text{m}$  out to 15  $\mu\text{m}$ . This longer wavelength sensitivity is very important for infrared imaging cameras and for long wave instrumentation such as is used to monitor carbon dioxide laser emission and atmospheric physics. These sensors tend to be more expensive than both silicon photodiodes and CdS photoconductors.

## **Integrated Circuits**

Incorporating additional electronics directly onto a semiconductor sensor chip makes it possible to add additional functions to the sensor. An optical IC is an integrated circuit comprising photodiode and electronic-signal-processing-circuits. Such additional functions as current-to-voltage conversion and reference-level sensing (a Schmitt trigger, for example) can be incorporated. Other optical ICs can provide signals highly immune to noise, such as a current-to-frequency conversion.

The principal advantages of an optical IC are ease of use, small size and immunity to electronic noise compared to a photodiode with separate electronics. Typically these devices are much more expensive and offer a very limited active light-sensing area. Custom tooling for specific applications is also expensive.

## **Hybrids**

The electronic functions of an optical IC can also be provided by a hybrid circuit that has unpackaged IC components (die) attached to a substrate that also contains a photodiode. This type of sensor combines the ease of use and immunity to electrical noise of an optical IC with increased design flexibility and lower tooling costs. In addition, the sensitivity can easily be increased with a larger photodiode active area without the added cost of a separate detector.

The primary disadvantages of a hybrid sensor are its cost and reliability. Cost can be several times higher than the electronic-assembly option discussed below and reliability testing is difficult to amortize, so either limited reliability screening is implemented, or the piece cost becomes high.

## **Sensor Electronic Assemblies**

Combining any of the sensors listed above with printed-circuit-based electronic signal processing creates sensor assemblies or black boxes. The user defines specifications for light input and the desired output response; the vendor builds and tests the systems to ensure that the specifications are met. An assembly can also include optical components such as lenses and special wavelength filters. The user just bolts the assembly in place and connects it to the high-level electronics; there are no concerns about mismatch between the purchased sensor and front-end amplifiers or diagnostic electronics. The system is relatively immune from noise and is highly reliable because of the mature manufacturing technologies used.

Sensor electronic assemblies are easy to implement. Experienced vendors can often deliver better reliability and lower cost products compared to an OEMs in-house manufacturing.

Less flexibility in making changes on the fly is the main disadvantage, but this is not an issue for a responsive vendor or mature designs.

## Other Sensors

There are many other types of sensors. These include avalanche photodiodes, bolometers, self-scanned arrays and photon drag detectors. A sensor vendor can provide information about these devices and can discuss the physics and advantages of each detector technology.

## Selecting a Sensor

Reviewing a few key design aspects generally provides enough information for making an optimum choice of detector for a given application (see Figure 1).

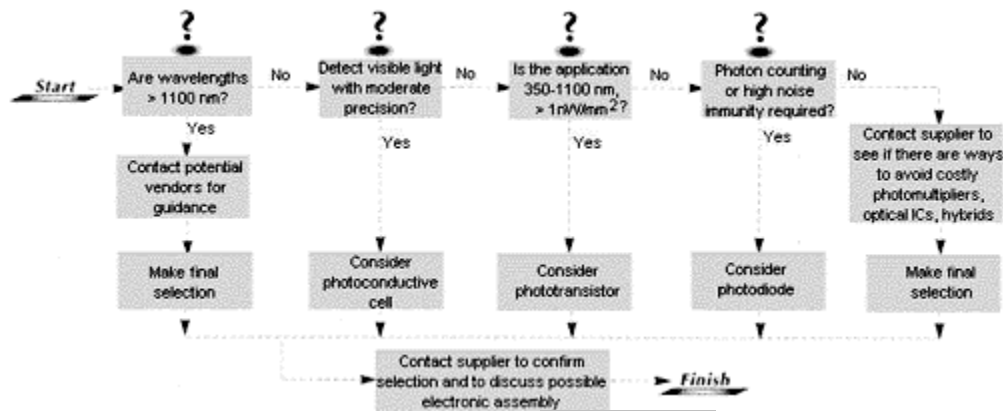


Figure 1

### Is my light in the infrared?

For sensing of wavelengths below 1100 nm, photoconductive cells or a silicon-based detector should be appropriate. At wavelengths above 1100 nm, the costs and technology options are not straightforward, and a detector vendor consulted at the beginning of a design program will provide the most effective guidance.

### Do I have plenty of light in the visible region?

Applications at visible wavelengths with at least microwatts of optical power, in which the sensor is simply required to detect if light is present, can use one of the least expensive and most rugged detectors available - the photoconductive cell. There are many standard devices available as well as custom-design options including complete electronic assemblies.

### Do I have nanowatts of power?

Silicon phototransistors and photodarlington; the second-lowest-cost sensors, are also convenient and should be considered next. At least nanowatts of optical power within a 5 mm diameter spot are required at wavelengths between 350 and 1100nm. The application must also tolerate some unit-to-unit sensitivity variation.

### Should I consider a higher performance photodiode?

For UV to near IR wavelengths, photodiodes offer the best overall performance. They are only slightly more expensive than phototransistors, but their spectral range is broader and they have lower noise, more uniform sensitivity and reproducibility, a larger dynamic range, better linearity and more package options. Also, photodiodes can routinely detect picowatts

of optical power. Thus, if phototransistors or photoconductive cells are not appropriate for an application, more often than not a photodiode will afford the best alternative.

#### **Other Options**

At least 90% of detector applications should be satisfied by one of the sensors discussed above. However, when light levels are extremely low, or ambient electronic noise levels are high, or space requirements are particularly limited, other alternatives, such as optical ICs, hybrids or photomultipliers should be seriously investigated.

#### **What's next?**

After selection, develop a partnership with your opto sensor manufacturer. The manufacturer is the sensor expert, and working together usually results in a successful project design. Most important, supply the vendor with specific application information about technical specifications, ambient light levels, operating lifetime, operation and storage environment, project schedules, anticipated production volumes and cost targets for tooling and unit price objectives. And remember to discuss the electronic assembly operation - you could reduce costs and improve performance! With this information the sensor vendor can help a system designer make informed decisions after considering trade-offs between reliability, technical performance and cost.

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