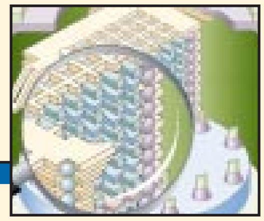

Light Levels and Noise

Guide Detector Choices

by Kenneth J. Kaufmann

Photonics is an enabling technology that creates benefits and value far in excess of the cost of the optoelectronic components that are used in a device or system. As such, photonics is responsible for increasing the length of our lives as well as enhancing them.

We use photonics to diagnose disease, communicate with one another, secure our property and listen to our favorite song. Each of these applications requires a photodetector to convert the optical information into an electrical waveform. Each also has a number of requirements that determine the type of detector best-suited to it.

The three most common photodetectors are the photomultiplier, the photodiode and the avalanche photodiode. The features of the measurement determine which detector it requires. In fact, one generic application might use different detector types depending on the specific implementation. Thus, no one detector is always the best choice.

Three detector types

The **photomultiplier tube** (Figure 1) is a vacuum tube device that uses the photoelectric effect to convert optical photons into electrons. A cascade of dynodes then amplifies the photoelectrons. These dynodes can generate a virtually noise-free gain in excess of 10^6 with a bandwidth greater than 1 GHz.

Because of this gain, photomultiplier tubes can operate at light levels as low as a few photons per second or as high as about a billion photons per second. They're particularly useful for measurements that must be made in a short time or at high frequency; for weak optical signals, where external amplifiers cannot be used; or where very wide dynamic range (~10^5) is required.

The photocathode determines the photomultiplier's spectral response; commercial photocathodes are available from 100 to 1700 nm. Quantum efficiencies are typically 10 to 20 percent, though some newer semiconductor photocathodes have >40 percent efficiency. The photoelectric surface can be very large — in excess of 5000 cm². This can be very important when the light source is diffuse.

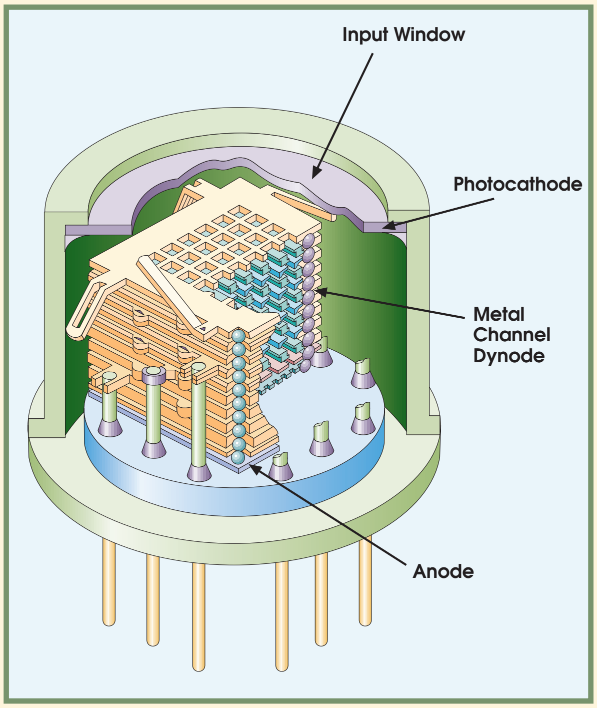

Figure 1. *The photomultiplier tube creates a cascade of photoelectrons from a few photons, effectively amplifying a low-light signal with very low noise.*

The **photodiode** (Figure 2) is a solid-state device. When light with energy greater than the semiconductor material's bandgap energy strikes a photodiode, it excites electrons into the conduction band. This creates a hole in the valence band. An electric field in the depletion layer drives electrons to the N layer and holes to the P layer. An external circuit collects the electrons, returning them to the P layer, where they combine with the holes.

The photodiode has no internal gain, and its signal is usually so small that it needs an external amplifier. Because the amplifier introduces some noise, photodiodes are used for measurements at relatively high light levels — where the detector's photon shot noise is greater than the noise of the external amplifiers. They reach their highest signal-to-noise ratio when operating in high light levels because this ratio is limited only by the shot noise of the photoelectrons. Photodiodes are also used at frequencies much lower than photomultiplier tubes to reduce amplifier noise.

An advantage of photodiodes is that they can operate at light levels many times higher than can photomultiplier tubes. They are also much more robust and considerably less

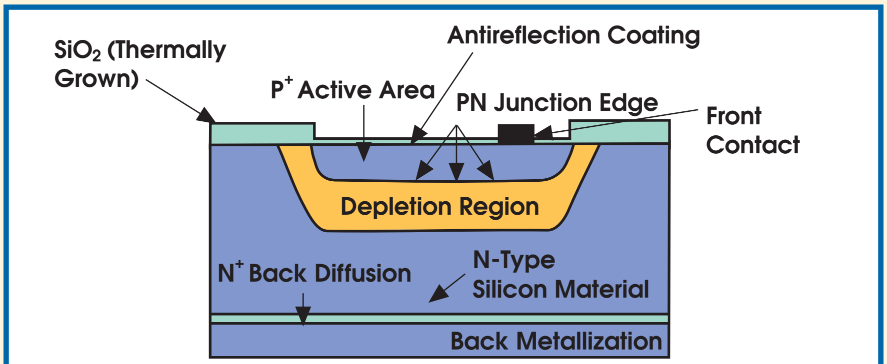

Figure 2. A photodiode converts photons to electrons but usually requires an external amplifier that reduces the detection system's signal-to-noise ratio.

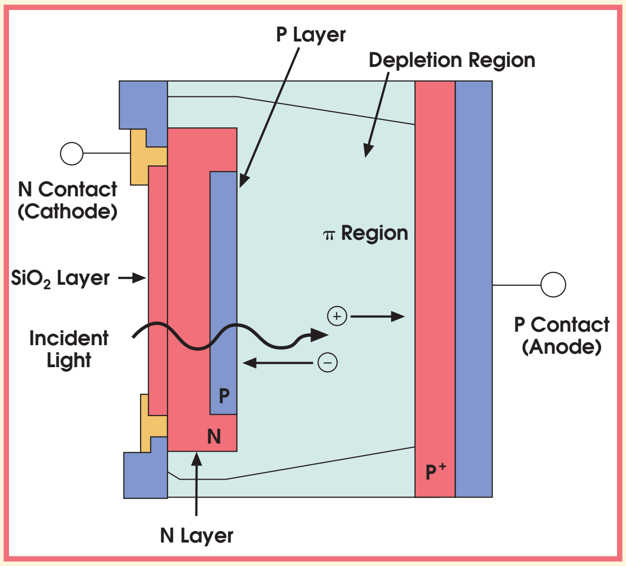

Figure 3. An avalanche photodiode offers internal amplification and thus lower noise than the photodiode, but not as much gain or as fast a response as a photomultiplier tube.

expensive. Their spectral response varies from 180 to 2600 nm, depending on the semiconductor material.

The **avalanche photodiode** (Figure 3) has features of both the photodiode and the photomultiplier tube. It is a solid-state device that generates electron-hole pairs upon exposure to light. A reverse bias of 100 to 1000 V is placed on the PN junction, creating an internal electric field large enough to accelerate the electrons. When the electrons collide with the crystal lattice, they generate electron-hole pairs. This process cascades, amplifying the initial signal by a factor of 50 or more.

The statistical fluctuations in the number of collisions and the yield of electron-hole pairs create more noise than the dynodes in a photomultiplier tube but less noise than a photodiode's external amplifier. Thus, avalanche photodiodes are often used when light levels are too high for photomultiplier tubes but not high enough for photodiodes.

Avalanche photodiodes are inadequate for some applications, such as those in which the lifetime of the photon source is short, a measurement must be made rapidly, few photons arrive at the detector or the photons are spread over a large area. These situations will usually require a photomultiplier tube.

Comparing detectors

An OEM product developer must analyze the needs for bandwidth, sensitivity, signal-to-noise ratio and cost before choosing a detector. Often, the best way to do this is by combining analysis and testing. Some examples of similar applications that require different detectors may offer some insights into how to begin the decision process.

Automated teller machines use photodiodes for several functions.

My favorite is to guarantee dispensing the correct number of bills. A light-emitting diode and a photodiode are placed on opposite sides of the currency path. The detector measures how much light transmits through a bill. If it is too low, then two bills must be stuck together, and they are sent to a reject pile.

Photodiodes are also used in optical storage such as CD-ROM, digital videodiscs and optical storage drives. A six-element photodiode array (Figure 4) detects the signal, maintains the focus of the read laser beam and keeps the read head on track.

The four inner elements measure the shape of the read beam. When the read beam reflected to the detector is circular, the separation between read head and disc is optimum; when it is out of round, the detector signals mechanical systems to change the separation. These four elements can also simultaneously read the data stored on the disc.

Note that, as the data rate increases, the bandwidth of the data detection increases, as does the amplifier noise contribution. In this case, photodiodes can still be used for distance control, but an avalanche photodiode reads the data. At higher bandwidth, the excess noise from the avalanche process is still lower than that of the photodiode preamplifier.

Optical communication is another application that points out the different utility of amplified photodiodes and avalanche photodiodes. Telecommunications providers are rapidly adding bandwidth to their networks, mostly by expanding the number of wavelengths transmitted on a fiber. Photodiodes have been the detector of choice for optical communications because of the need to obtain the maximum signal-to-noise ratio while minimizing cost.

As transmission speeds go from 2.5 to 10 and 40 GHz, it becomes difficult to get the necessary gain bandwidth product in an external preamplifier. At these bandwidths, the amplifier becomes the major contributor of noise. So, despite their higher cost, avalanche photodiodes are often the detector of choice for 10-GHz communications systems. Just as for the optical disc, the avalanche photodiode's internal amplification noise at the high bandwidth is lower than that of an external preamplifier. [The optical disc would use a silicon avalanche photodiode because it operates in the visible spectral range (630 or 400 nm), whereas the optical communications device is made from InGaAs because it operates in the IR (near 1330 or 1550 nm).]

One of the most demanding applications for photodiodes is computed tomography (CT) scanners. An x-ray source moves in a helical pattern

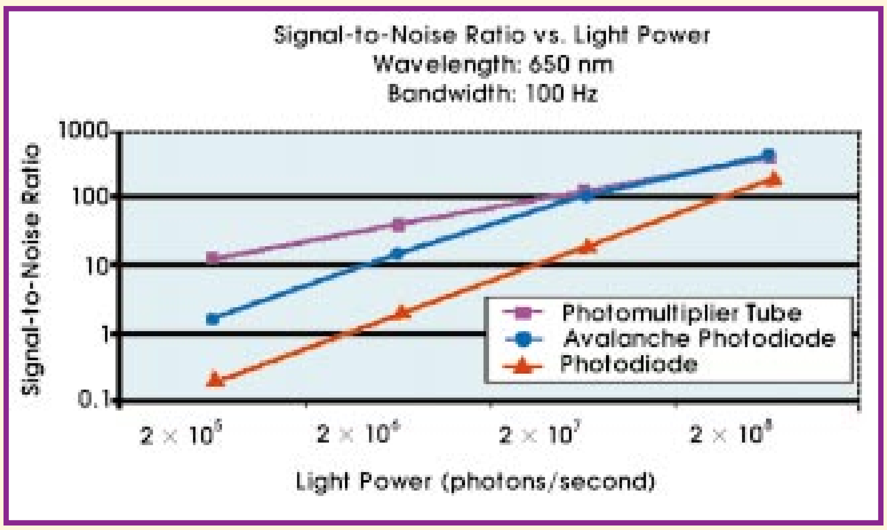

Figure 4. Avalanche photodiodes fill an application space between photodiodes and photomultiplier tubes in terms of signal-to-noise ratio and ability to operate at high or low light levels. As the wavelength or bandwidth changes, these curves will change.

around a patient, and a scintillator converts the x-ray photons to visible light (with a gain of 10 to 40) that a photodiode can detect. The detector assembly quantifies the x-rays to generate a three-dimensional image of the body's x-ray attenuation. Each tissue type has its own attenuation, so a physician can visualize the internal organs of the body.

The quality of the image is directly related to the signal-to-noise ratio of the x-ray detection. Early x-ray CT scanners used photomultiplier tubes operating at relatively high light levels to obtain the necessary signal-to-noise ratios. However, low-capacitance photodiodes have less dark current (noise) so that the photodiode can produce a much better image with only a small increase in dosage.

In a similar application, gamma cameras and positron emission tomography cameras also detect disease inside the body. They use radioactive contrast agents that preferentially accumulate in certain types of tissue. These radioactive probes emit gamma rays over 4π sr, a sharp difference from the x-ray CT beams that do not deviate much from a straight line. These applications, therefore, use an array of detectors, and only photomultiplier tubes can be economically manufactured to cover such a large area.

Photodiodes can also be used in absorption spectrometers to measure the spectrum of a chemical compound. Working at very high light levels, they can measure small absorbancies and hence low concentrations as might be found in high-performance liquid chromatography or capillary electrophoresis.

More demanding chemical detection applications require photomultiplier tubes. For example, immunoassays detect the presence of disease. A person's blood serum is placed on a surface to which an antigen from a virus or bacterium has been immobilized. Antibodies specific to a disease attach to the antigen. A reporter antigen is added. This antigen is bound to a fluorescent or chemiluminescent compound. If the antibody is present, the reporter binds to the surface. A light source excites the fluorescent probe or a chemical is added to initiate the reaction that generates the chemiluminescence.

In either case, the greater the detectivity of the optical detector, the greater the sensitivity. The light must be detected with maximum sensitivity in a short time because the chemical reaction occurs quickly, the fluorescent tag is photolabile or the instrument must have high throughput to be cost-effective. □

Meet the author

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