A PRIMER ON PHOTODIODES: The Dominant Technology for Light Detection Applications.

Introduction

The purpose of any photodetector is to convert electro-magnetic radiation into an electronic signal – ideally one that is proportional to incident light intensity. Because they are compact, versatile and can be produced economically in high volume, PIN photodiodes have become the detector of choice in applications from biomedical instrumentation to telecommunications. This article reviews basic photodiode theory of operation and briefly examines some important recent developments in the technology.

Converting Photons to Electrons (and Holes)

Photodiodes are fabricated from semiconductors – the most popular are silicon (Si) or gallium arsenide (GaAs), and others include InSb, InAs, PbSe. These materials absorb light over a characteristic wavelength range: 250 nm – 1100 nm for silicon, 800 nm – 2.0 microns for GaAs. When a photon of light is absorbed, it excites an electron and produces a single pair of charge carriers, an electron and a hole, where a hole is simply the absence of an electron in the semiconductor lattice. Current passes through a semiconductor by the opposite movement of such charge carriers. The trick in a photodiode is to collect the photon-induced charge carriers (as current or voltage) at the electrodes, before they have a chance to recombine. This is achieved by utilizing a pn or p-i-n diode junction structure – hence the term PIN photodiode.

N-type semiconductor material is doped to produce an excess of electrons, whereas p-type material has an excess of holes (electron deficiency). At the pn junction, this creates a concentration gradient that causes electrons to diffuse into the p-layer and holes to diffuse into the n-layer. This diffusion results in an opposing electrical potential, often referred to as the internal bias. In a region spanning both sides of the junction, this electrical force causes any charge carriers to be rapidly swept to the appropriate layer. Because charge carriers cannot reside in this region, it is termed the “depletion region.”

Light enters the device through the thin p-type layer. (The light intensity drops exponentially with penetration depth, due to absorption.) Any photons absorbed in the depletion region produce charge carriers that are immediately separated and swept across the junction by the natural internal bias. Charge carriers created outside the depletion region will move randomly, many of them eventually entering the depletion region and then being rapidly swept across the junction. (Some of them will recombine and disappear without ever reaching the depletion region). This movement of charge carriers across the junction upsets the electrical balance and produces a small photocurrent, which can be detected at the electrodes.

In many applications it is desirable to maximize the thickness of the depletion region. For example, device response is faster when most of the charge carriers are created in the depletion region. This also increases the device quantum efficiency, since most charge carriers will not have the opportunity to recombine. The quantum efficiency is defined as the ratio of the photocurrent (in electrons) to incident light intensity (in photons).

The thickness of the depletion region can be modified by varying the semiconductor doping levels. However, the easiest way to expand this layer is to apply an external electrical bias (voltage). This is referred as photoconductive operation, since the signal is detected as a current. Conventional unbiased operation is referred to as photovoltaic operation, because the signal is detected as a voltage. This is preferred in applications requiring high linearity of response and/or low dark noise.

Device Optimization and Signal Processing

Photodiodes are manufactured in a very wide range of shapes and sizes, with each design optimized for a unique combination of performance parameters, and/or to meet the special opto-mechanical constraints of the intended application. The most important performance characteristics are response speed, quantum efficiency, the size and shape of the active area, response linearity, spatial uniformity of response, dark noise, and other noise sources which impact the effective sensitivity. Photodiode sensitivity is very important in low light applications and is typically defined by the term Noise Equivalent Power (NEP); this is the optical power that produces a signal-to-noise ratio of 1 at the detector output. NEP is usually specified at a given wavelength and over a frequency bandwidth of 1 Hz, and is therefore expressed in units of $W/Hz^{1/2}$.

Because these various performance parameters are interrelated, device design often involves careful trade-off to achieve optimum performance. For example, an application may require a detector with a large active area, in order to detect an unfocused source of light. If this application requires high speed, then some compromises will have to be made, increasing device area raises capacitance, thereby increasing the RC time constant. As a result, most successful OEM applications utilize photodiodes designed specifically for that application.

In addition, most of the performance parameters (particularly speed and noise) are also strongly influenced by the design of the signal processing electronics. However, the electrical characteristics of even a simple photodiode can be remarkably complex. Consequently, the photodiode is often represented by an “equivalent circuit.” This is a virtual circuit, consisting of multiple components, whose overall behavior matches that of the photodiode. Here the photodiode is represented as a current source in parallel with a diode, in addition to a parallel capacitor, a series resistance and shunt resistance. In more complex models, the various noise sources (shot noise, Johnson noise and 1/f noise) are all represented as additional current sources in parallel to the signal current source.

There are a number of types of signal processing electronics commonly used with photodiodes. For example, a sample and hold circuit may be used in a pulsed application. This circuit acts as a charge integrator, holding this charge until it is read or until the next pulse causes the circuit to reset and resume integration. However, the transimpedance amplifier (TIA) is by far the most common circuit type used with photodiodes. Normally, generating a highly amplified voltage from a given input current requires a high input impedance. However, the downside of high input impedance is that it produces a large RC time constant, thus slowing device response. The TIA uses an operational amplifier to circumvent this problem, and thus delivers a high effective input impedance but with a circuit time constant several orders of magnitude less than a conventional amplifier with the same impedance. Moreover, a well-designed TIA delivers several orders of magnitude of linear response, and therefore will not compromise the inherent high linearity of a photodiode.

Higher Functionality and Specialization

The majority of photodiodes are destined for OEM applications. Advanced packaging and integration technologies (surface mounting, flex circuits, injection molding, etc.) are enabling OEM customers to specify increasing levels of sophistication and functionality. This simplifies the task of integrating the photodiode assembly into the final instrument or machine, saving time and money. Typical examples of integrated products are photodiodes with on-chip TIAs and photodiodes with integrated thermoelectric cooling. Some assemblies also include sophisticated signal processing, for example to ratio or normalize signals from a multi-element photodiode.

These assemblies also often incorporate optical elements to condition the light before it reaches the photodiode active area. Typical examples include filters to separate specific wavelengths, or lenses and lens arrays to concentrate the light at the photodiode(s). A recent important advance in this area is the Filtrode® product line from Advanced Photonix. Here a multilayer dielectric coating is directly deposited on the photodiode itself, eliminating the need for separate optical filters. These devices are ideal for laser applications, such as barcode scanning, where the filter blocks ambient light while transmitting the laser wavelength.

The Avalanche Photodiode

No discussion of photodiodes would be complete without the inclusion of the avalanche photodiode or APD. One limitation of the PIN photodiode is the lack of internal gain – an incoming photon produces only one electron-hole pair. In very low light applications, internal gain is required to boost the signal above the noise floor of subsequent electronics and signal processing. But for many years, the only device that provided such gain was the photomultiplier tube (PMT) based on vacuum tube technology. While offering high gain, the PMT has a number of practical limitations; it is a bulky vacuum tube, offering limited linearity (compared to a photodiode), a narrow spectral response range, and a low QE (typically < 25%). The PMT also generates heat. Fortunately, the avalanche photodiode now offers a solid-state alternative for most PMT applications.

Incoming photons produce electron-hole pairs, as with any other photodiode. However, the APD is operated with a large reverse bias (up to 2 kV for beveled edge designs). The high internal field accelerates the photon-generated electrons. These collide with the atomic lattice releasing additional electrons via secondary ionization. These secondary electrons are also accelerated, resulting in an avalanche of carriers, hence the name. For many years, APDs were only available with small active areas (type < 1mm diameter). This limited their use to tightly focused or fiber-coupled applications. In the past three years however, the large area avalanche photodiode (LAAPD™) has emerged as a mature device, with active areas up to 16 mm diameter and gains as high as 1000. Although the PMT still offers higher gain, the LAAPD features higher quantum efficiency (up to 90%) lower noise, compact packaging, higher linearity and superior electrical efficiency. Furthermore, LAAPDs are available with integrated TE cooling for ultra-low noise operation. As a result, LAAPDs are now displacing PMTs from many traditional applications such as flow cytometry and medical imaging.

Conclusion

While photodiode technology has been available for many years, ongoing advances in areas such as packaging, device integration and thin film coating are continuing to yield more sophisticated and cost effective products. Thus, it is likely that this venerable device will not only continue to dominate the existing light detection market, but will seamlessly adapt into most developing photonics applications.