Avalanche Photodiodes

We can no longer imagine low-light detection, laser radar systems, optical data transmission, bar-code scanners or bio-medical equipment without avalanche photodiodes (APDs).

What is an APD?

APDs differ from "normal" PIN photodiodes in that incoming photons internally trigger a charge avalanche. The prerequisite for this is the application of reverse bias voltage to the APD to broaden the absorption layer "A".

In conventional photodiodes, incoming photons create electron-hole pairs, also called charge carriers, which supply a measurable photocurrent. The power of the incoming photons has been transformed into electrical energy. Here, APDs have taken a significant step forward. The bias potential is much higher than in normal photodiodes. In the APD, the charge carriers set free by the light are accelerated in the electrical field in such a manner that they produce further electron-hole pairs through impact ionization. If the reverse bias voltage is less than the breakdown voltage, the avalanche will die down again due to friction losses. To this point a single photon has generated hundreds or even thousands of electrons. Above the breakdown voltage, the acceleration of the charge carriers is high enough to keep the avalanche alive. A single photon can be sufficient to generate a constant current which can be measured by external electronic equipment.

The current generated is calculated as follows:

$$I = R_0 \cdot M \cdot P_S$$

whereby R_0 (A/W) is the spectral responsivity of the APD, M is the internal gain and P_S (Watt) the incident optical power.

The gain of the APD thereby depends on the reverse bias voltage applied (see Fig. 1).

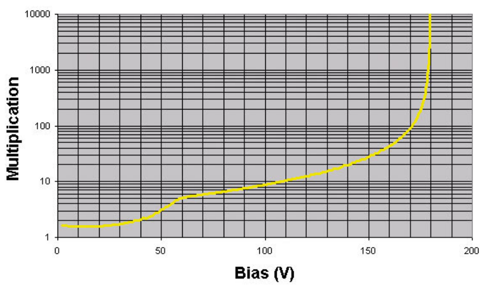

Fig. 1:
typical gain vs. operating voltage
for a Si APD when D = 500 µm

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Selecting the right APD

APDs are generally recommended for very high bandwidth applications or where internal gain is needed to overcome secondary amplifier noise.

The following items must be considered when making a selection:

Spectral Operating Range:

APDs are available in the range from 300 nm to 1700 nm. Silicon APDs are, depending on their structure, suitable between 300 nm and

1100 nm, germanium between 800 nm and 1600 nm and InGaAs from 900 nm to 1700 nm.

Silicon offers the most extensive APD product range. Depending on the manufacturing process, various parameters which offer advantages for the individual applications can be achieved. An overview of the most important specifications can be found in table 1.

Compared to germanium APDs, InGaAs APDs have significantly lower noise characteristics, a higher bandwidth relative to the active area and advantages due to the extended spectral response to 1700 nm. A disadvantage is that InGaAs APDs are more expensive than Ge APDs. Germanium is therefore primarily recommended for cost-sensitive applications or in systems exposed to electromagnetic interference and in which the secondary amplifier noise is significantly higher.

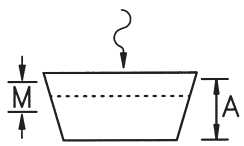
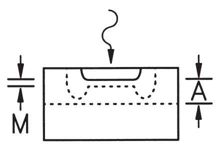
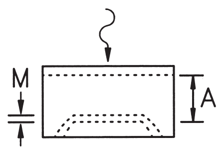
Silizium APD Typen	Bevelled edge	Epitaxial	Reach Through
Struktur			
"Absorption" Region	large	low	middle to large
"Multiplication" Region	large	low	middle to large
Typical size (diameter)	up to 16 nm	up to 5 mm	up to 5 mm
Gain	50 to 1000	1 to 100	15 to 300
"Excess noise" Factor	very good (k= 0.0015)	good (k = 0.03)	good to very good (k = 0.02 bis 0.002)
Operating Voltage	500 to 2000 V	80 to 300 V	150 to 500 V
Rise time	slow	fast	fast
Capacitance	small	large	small
Blue sensitive (400 nm)	good	poor	poor
Red sensitive (650 nm)	good	good	good
NIR sensitive (905 nm)	very good	good	very good

Table 1: Overview of the various Si APD structures and their characteristics.

Detector Area:

It is obvious that small-area APDs are more economical than larger detectors since more chips can be manufactured per wafer. Therefore, the minimum active surface size required to realize the optical structure should first be determined. Sometimes it may be advantageous to use a somewhat larger APD, since special optics for focusing on a small spot may be more expensive than the additional charge for a larger APD.

Bandwidth and Noise:

To compare the efficiency of an APD with a PIN diode, it is not sufficient to merely compare the noise of the detectors.

The signal-to-noise ratio of the entire system is crucial. For PIN diodes, the respective preamplifier must also always be considered. Its noise characteristics are, among other things, frequency dependent. An APD is superior to a PIN diode whenever the APD can substantially boost the signal level without significantly increasing the overall system noise. Thus APDs are preferred wherever low light intensities at middle or high frequencies have to be detected. The optimum internal gain is selected when the detector noise is approximately equal to the input noise of the secondary amplifier (or load resistance), so that the APD does not affect the system noise. Noise increases with the bandwidth of the system for PIN diodes as well as APDs. Therefore it is important to reduce the bandwidth as far as is practicable.

APD Applications

As previously mentioned, APDs are used wherever low light intensities at middle or high frequencies are detected. Among the most common applications are:

Laser Rangefinder:

The most frequent area of operation for APDs is rangefinding, either free-space (LIDAR) or in a fiber (OTDR - Optical Time Domain Reflectometers).

In free-space rangefinder systems, cw laser diodes, pulsed laser diodes or solid state lasers can be found on the transmitter end, depending upon the principle of measurement, the range and the resolution. The highly modulable cw-laser diodes in the visible spectral range enable, in combination with red-optimized Si APDs, measurements of up to more than one hundred meters with a precision within the mm range. With Si APDs optimized for the NIR range, in combination with 905 nm pulsed laser diodes (PLDs) according to the pulsed time-of-flight principle, distances of several km can be measured. InGaAs APDs can detect eye-safe ns pulses from 1550 nm PLDs at a distance of over 10 km.

OTDRs use fiber coupled laser diodes at 1300 or 1550 nm and therefore require InGaAs APDs.

High-Speed Receiver:

In free space and fiber optical data transmission, rise and fall times of

300 ps at a gain of up to 100 make APDs the components of choice for use in high-speed receivers. Small area, low noise InGaAs APDs serve as key components for the construction of highly sensitive receivers, enabling data transfer across several 10 - 100 km at 12.5 Gb/s.

Single Photon Counting:

Specially selected Si APDs can also be used as photon counters in the "Geiger mode" (VR > VBR), whereby a single photoelectron can cause an avalanche pulse of approx. 108 charge carriers. Applications for these APDs can be found in bioluminescence, fluorescence spectroscopy and astronomy. Photomultiplier tubes (PMT) are also widely used in these kinds of applications. The decisive advantage of the APDs is their small, compact design, the large measuring range of 400 nm up to NIR and the unbeatable detection efficiency of up to 70%.

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