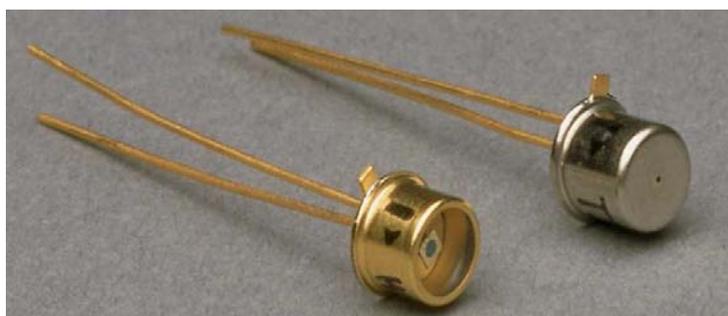# Avalanche photodiode
A User Guide

Understanding Avalanche photodiode for improving system performance

Introduction

Avalanche photodiode detectors (APD) have and will continue to be used in many diverse applications such as laser range finders, data communications or photon correlation studies. This paper discusses APD structures, critical performance parameter and excess noise factor.

For low-light detection in the 200- to 1150-nm range, the designer has three basic detector choices - the silicon PIN detector, the silicon avalanche photodiode (APD) and the photomultiplier tube (PMT).

APDs are widely used in instrumentation and aerospace applications, offering a combination of high speed and high sensitivity unmatched by PIN detectors, and quantum efficiencies at >400 nm unmatched by PMTs.

Contents

➤ APD structures
➤ APD noise
➤ Photon counting technique

Applications

➤ Light detection
➤ Laser range finder
➤ Photon counting
➤ Datacomm
➤ Optical Tomography
➤ LIDAR
➤ Fluorescence detection
➤ Particle sizing

PerkinElmer®
precisely.

Table of Contents

What is an Avalanche Photodiode?
APD Structures

In order to understand why more than one APD structure exists, it is important to appreciate the design trade-offs that must be accommodated by the APD designer. The ideal APD would have zero dark noise, no excess noise, broad spectral and frequency response, a gain range from 1 to 10^6 or more, and low cost. More simply, an ideal APD would be a good PIN photodiode with gain! In reality however, this is difficult to achieve because of the need to trade-off conflicting design requirements. What some of these trade-offs are, and how they are optimized in commercially available APDs, are listed below.

Consider the schematic cross-section for a typical APD structure shown in Figure 1. The basic structural elements provided by the APD designer include an absorption region "A", and a multiplication region "M". Present across region "A" is an electric field "E" that serves to separate the photo-generated holes and electrons, and sweeps one carrier towards the multiplication region. The multiplication region "M" is designed to exhibit a high electric field so as to provide internal photo-current gain by impact ionization.

This gain region must be broad enough to provide a useful gain, M, of at least 100 for silicon APDs, or 10-40 for germanium or InGaAs APDs. In addition, the multiplying electric field profile must enable effective gain to be achieved at field strength below the breakdown field of the diode.
Figure 1 shows the "reach-through" structure used by PerkinElmer which offers the best available combination of high speed, low noise and capacitance, and extended IR response.
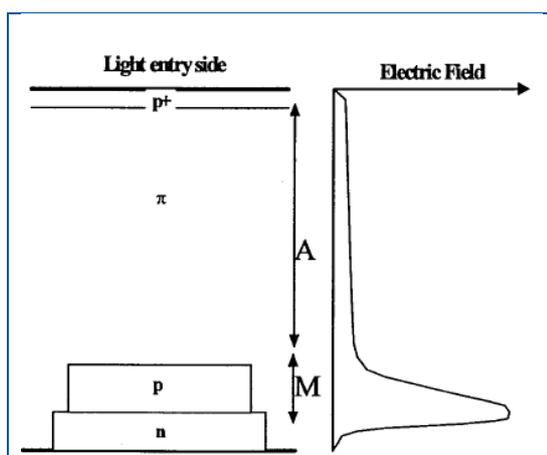

Figure 1 Reach-through structure
The multiplication region "M" is designed to exhibit a high electric field so as to provide internal photo-current gain by impact ionization.

A variation of the reach through structure is PerkinElmer's epitaxial silicon APD (EPI-APD). PerkinElmer's EPI-APD is a front entry device and represents a trade off between optimum performance and price. The EPI-APD allows simpler and cheaper manufacturing methods resulting in a lower cost device relative to the standard reach through device. The trade off is a higher *k* factor resulting in a higher excess noise factor for equivalent gain (see table 1).

Critical Performance Parameters

An APD differs from a PIN photodiode by providing internal photo-electronic signal gain. Therefore, output signal current, I_s, from an APD equals $I_s = M \cdot Ro (\lambda) \cdot P_s$, where $Ro(\lambda)$ is the intrinsic responsivity of the APD at a gain M=1 and wavelength λ, M is the gain of the APD, and P_s is the incident optical power. The gain is a function of the APDs reverse voltage, V_R, and will vary with applied bias. A typical gain-voltage curve for a silicon APD manufactured by PerkinElmer is shown in Figure 2.
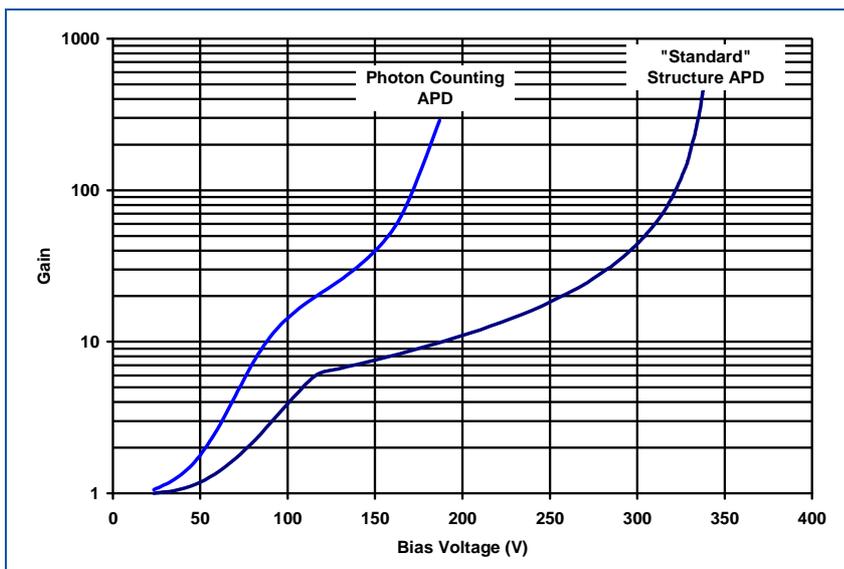
One of the key parameters to consider when selecting an APD is the detector's spectral noise. Like other detectors, an APD will normally be operating in one of two noise-limited detection regimes; either detector noise limited at low power levels, or photon shot noise limited at higher powers. As an APD is designed to be operated under a reverse bias, sensitivity at low light levels will be limited by the shot noise and the APD's leakage current. Shot noise derives from the random statistical Poissonian fluctuations of the dark current, I_D (or signal current). Dark current shot noise ($I_{N(SHOT)}$) is normally given by $i_{N(SHOT)} = (2 \cdot q \cdot B \cdot I_D)^{\frac{1}{2}}$, for a PIN detector, where B is the system bandwidth. This differs for an APD however, as bulk leakage current, I_{DB}, is multiplied by the gain, M, of the APD[4]. Total leakage current I_D is therefore equal to:

$$I_D = I_{DS} + I_{DB} \cdot M \qquad (1)$$

where I_{DS} is the surface leakage current.

In addition, the avalanche process statistics generate current fluctuations, and APD performance is degraded by an "excess noise factor" (F) compared to a PIN (see equation 4 for more details). The total spectral noise current for an APD in "dark" conditions is thus given by:

$$i_n = \left[2 \cdot q \cdot \left(I_{DS} + I_{DB} \cdot M^2 \cdot F \right) \cdot B \right]^{0.5} \qquad (2)$$

where q is the electron charge.

At higher signal light levels, the detector transitions to the photon shot noise limited regime where sensitivity is limited by photon shot noise on the current generated by the optical signal.

Total noise from the APD in "illuminated" conditions will therefore equal the quadratic sum of the detector noise plus the signal shot noise. For a given optical signal power, P_s, this is given by:

$$i_n = \left[2 \cdot q \cdot \left(I_{DS} + \left(I_{DB} \cdot M^2 + R_0(\lambda) \cdot M^2 \cdot P_s \right) \cdot F \right) \cdot B \right]^{0.5} \qquad (3)$$

In the absence of other noise sources, an APD therefore provides a signal-to-noise ratio (SNR) which is √F worse than a PIN detector with the same quantum efficiency.

Noise equivalent power (NEP) cannot be used as the only measure of a detector's relative performance, but rather detector signal-to-noise (SNR) at a specific wavelength and bandwidth should be used to determine the optimum detector type for a given application. Note that optimum signal-to-noise occurs at a gain M where total detector noise equals the input noise of the amplifier or load resistor.

The optimum gain depends in part on the excess noise factor, F, of the APD, and ranges from M= 50 to 1000 for silicon APDs, and is limited to M = 10 to 40 for germanium and InGaAs APDs.

Selecting an APD
Specifying your requirement
APDs are generally recommended for high bandwidth applications or where internal gain is needed to overcome high preamplifier noise. The following is a simple guide that can be used to decide whether an APD is the most appropriate for one's light detection requirements.

1) Determine the wavelength range to be covered. See section "Types of APDs " below to determine the specific APD type useful for the wavelength range to be covered.
2) Determine the minimum size of the detector that can be used in the optical system. Effective optics can often be more cost-effective than the use of an overly large PIN or Avalanche photodetectors
3) Determine the required electrical frequency bandwidth of the system; again, over-specifying bandwidth will degrade the SNR of the system.

Types of APDs
Avalanche photodiodes are commercially available that span the wavelength range from 300nm to 1700nm. Silicon APDs can be used between 300nm to 1100nm, germanium between 800nm and 1600nm, and InGaAs from 900nm to 1700nm.

Although significantly more expensive than germanium APDs, InGaAs APDs are typically available with much lower noise currents, exhibit extended spectral response to 1700nm, and provide higher frequency bandwidth for a given active area. A germanium APD is recommended for environments applications in high electro-magnetic interference (EMI), where amplifier noise is significantly higher than the noise from an InGaAs APD, or for applications where cost is of primordial consideration.

Understanding the Specifications
Responsivity and Gain
APD gain will vary as a function of applied reverse voltage, as shown in Figure 2. In addition, for many APDs, it is not possible, or practical, to make an accurate measurement of the intrinsic responsivity, $Ro(\lambda)$, at a gain M=1. It is therefore inappropriate to state typical gain and diode sensitivity at M=1 as a method for specifying diode responsivity at a given operating voltage. In order to characterize APD response, one must specify APD responsivity (in Amps/Watt) at a given operating voltage. However, because of diode to diode variations in the exact gain voltage curve of each APD, the specific operating voltage for a given responsivity will vary from one APD to another. Manufacturers should therefore specify a voltage range within which a specific responsivity will be achieved. An example of a typically correct specification for diode responsivity, in this case for an InGaAs APD, is as follows:

R_{MIN} (1300nm) = 9.0 A/W, V_{OP} = 50V to 90V, M ≈ 10

Dark Current and Noise Current

As can be seen from the noise equation (Equation 2), total APD dark current (and corresponding spectral noise current) is only meaningful when specified at a given operating gain. Dark current at M=1 is dominated by surface current, and may be significantly less than I_{DB} x M. Since APD dark and spectral noise current are a strong function of APD gain, these should be specified at a stated responsivity level. An example of a typically correct specification for diode dark current and noise current, in this case for an InGaAs APD, is as follows:

I_D (R = 9.0A/W) = 10 nA (max), M ≈ 10
i_N (R = 6.0 A/W, 1 MHz, 1 Hz BW) = 0.8 pA/√Hz (max), M > 5

Excess Noise Factor

All avalanche photodiodes generate excess noise due to the statistical nature of the avalanche process. The 'Excess Noise Factor' is generally denoted as 'F'. As shown in the noise equation (Equation 2), √F is the factor by which the statistical noise on the APD current (equal to the sum of the multiplied photocurrent plus the multiplied APD bulk dark current) exceeds that which would be expected from a noiseless multiplier on the basis of Poissonian statistics (shot noise) alone.

The excess noise factor is a function of the carrier ionization ratio, k, where k is usually defined as the ratio of hole to electron ionization probabilities (k ≤ 1). The excess noise factor may be calculated using the model developed by McIntyre[3] which considers the statistical nature of avalanche multiplication. The excess noise factor is given by:

$$F = k_{eff} \cdot M + \left(1 - k_{eff}\right)\left(2 - \frac{1}{M}\right)$$

(4)

Therefore, the lower the values of k and M, the lower the excess noise factor. The effective k-factor, k_{eff}, for an APD can be measured experimentally by fitting the McIntyre formula to the measured dependence of the excess noise factor on gain. This is best done under illuminated conditions. It may also be theoretically calculated from the carrier ionization coefficients and the electric field profile of the APD structure.

The ionization ratio k is a strong function of electric field across the APD structure, and takes its lowest value at low electric fields (only in Silicon). Since the electric field profile depends upon the doping profile, the k factor is also a function of the doping profile. Depending on the APD structure, the electric field profile traversed by a photo-generated carrier and subsequent avalanche-ionized carriers may therefore vary according to photon absorption depth. For indirect bandgap semiconductors such as silicon, the absorption coefficient varies slowly at the longer wavelengths, and the 'mean' absorption depth is therefore a function of wavelength. The value of k_{EFF}, and gain, M, for a silicon APD is thus a function of wavelength for some doping profiles.

The McIntyre formula can be approximated for a k < 0.1 and M > 20 without significant loss of accuracy as:

$$F = 2 + k \cdot M$$

(5)

Also often quoted by APD manufacturers is an empirical formula used to calculate the excess noise factor, given as:

$$F = M^x \qquad (6)$$

where the value of X is derived as a log-normal linear fit of measured F-values for given values of gain M. This approximation should be used with extreme caution since x varies with the gain of the APD. Using the k-factor is simpler and more accurate in all operating conditions.

The table below provides typical values of k and F for silicon, germanium and InGaAs APDs. PerkinElmer offers Silicon APDS with three different values of ionization ration: 1) The Super-Low k (SLiK ^{TM}) APDs used in photon counting modules
2) The high performance reach through structure with k=0.02 for applications requiring extremely low noise APD and high gain, and finally 3) The low cost Silicon Epitaxial APD with k=0.06 ideal for high SNR applications. Note that for germanium and InGaAs, a k-value is generally quoted at M=10, which somewhat overestimates F at M < 10 and underestimates F at M > 10.

Typical values of k, X and F for Si, Ge and InGaAs

Detector Type	Ionization Ratio	Typical Gain	Excess Noise Factor (at typical gain)
	(k)	(M)	(F)
Silicon ("reach-through" structure)	0.02	150	4.9
Silicon Epitaxial APDs	0.06	100	7.9
Silicon (SLiK^{TM} low-k structure)	0.002	500	3.0
Germanium	0.9	10	9.2
InGaAs	0.45	10	5.5

Geiger Mode

In the Geiger mode [2],[4], an APD is biased above its breakdown voltage ($V_R > V_{BR}$) for operation at very high gain (typically 10^5 to 10^6). When biased above breakdown, an APD will normally conduct a large current. However, if this current is limited to less than the APD's "latching" current, there is a strong statistical probability that the current will fluctuate to zero in the multiplication region, and the APD will then remain in the "off" state until an avalanche pulse is triggered by either a bulk or photo-generated carrier. If the number of bulk carrier generated pulses is low, the APD can therefore be used to count individual current pulses from incident photons. The value of the bulk dark current is therefore a significant parameter in selecting an APD for photon-counting, and can be reduced exponentially by cooling.

Applications

In both modes of APD operation, i.e. Linear and Geiger, APDs have and will continue to be used in many diverse applications. In the linear mode operation, the APD is well suited for applications which require high sensitivity and fast response times. For example, laser range finders which incorporate APD detectors result in more sensitive instruments than ones which use conventional PIN detectors. In addition, APDs used in this application can operate with lower light levels and shorter laser pulses, thus making the range finder more 'eye safe'.

Other applications for linear mode APDs include fast receiver modules for data communications, high speed laser scanner (2D bar code reader), speed gun, ceilometers (cloud height measurement), OTDR (Optical Time Domain Reflectometry), PET Scanner, confocal microscopy and particle detection.

Silicon APDs operated in the Geiger mode are used to detect single photons for photon correlation studies and are capable of achieving very short resolving times. Operated in this mode, PerkinElmer SLiK^{TM} detector provides gains of up to 10^8 and quantum efficiencies of -70% at 633nm and 50% at 830nm. Other applications in which APDs operated in this mode are used include: Lidar, Astronomical observations, Optical range finding, Optical fiber test and fault location, ultra sensitive fluorescence, etc

References:

1) Cova, S. *et ai, 'Avalanche photodiodes for near infrared photon-counting',* SPIE Proc. vol. 2388 (1995)

2) Dautet, H., et ai, *'Photon-counting techniques with silicon avalanche photodiodes',* Applied Optics, 32 (21), pp. 3894-3900 (1993)

3) Mclntyre,R.J., *'Multiplication Noise in Uniform Avalanche Diodes',* IEEE Trans. Electron Devices, ED13, pp. 164-168 (1966)

4) Product Datasheet ED-0017/03/88: C30902 - 921 E/S, EG&G Canada Ltd