White Paper

High Performing Photodiodes for Demanding Applications

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ABSTRACT

Demanding applications like Laser Range Finding, Proximity Fuses, Laser Designation, Smart Munitions and Laser Warning Systems all have the following in common:

- Detection of short pulses of light; more sensitive the detector the better.
- Ability to operate in harsh environments and over a wide temperature range.
- Requirement for large dynamic range to minimize blind time/distance.

In this paper we will examine how to design modules and package these photodiodes for the above applications. In particular, we will focus on InGaAs APD's for laser range finding, as well as on an InGaAs PIN array for a laser-warning module.

Keywords: LADAR, LRF, TIA, APD, OPTICAL RECEIVER, FAST RECOVERY, EXTENDED DYNAMIC RANGE, DUAL SLOPE RECEIVER

INTRODUCTION

Detecting laser pulses that are in the order of 10 to 20ns and which have peak powers from the nanowatt to the megawatt level require that both the detector and the supporting electronics be high performance. When detecting these pulses it should be noted that the detector rise is not very fast when compared to what is required for Telecom applications. If one were to use an off-the-shelf telecom module to detect these pulses, one would find that they would not provide the best sensitivity and performance.

In this paper we will explore detector modules for demanding applications like Rx modules for laser range finding and laser warning systems. We will examine what detector parameters are important and why; furthermore, we will illustrate some of the key parameters and highlight their importance.

BASIC PROPERTIES OF DETECTORS

The basic principle of a photo detector is to convert the light signal to a current; however, depending on the application, the detector can be optimized to obtain the best performance. For example, building a device with a thin junction results in very fast transit times but leads to lower QE, especially at the longer wavelengths and higher capacitance, which in turn leads to higher Rx noise. Also, depending on the application, using a detector with internal gain (Avalanche Photodiode) will lead to better overall sensitivity of the Rx module.

The APD structure is designed to multiply the primary photoelectron, this is illustrated in figure 1, left. This multiplication, or gain, varies with the bias voltage and temperature as illustrated in figure 1, right. In addition, small changes in the fabrication process, junction thickness or implantation dose will result in a "Gain-Voltage" variation even at the wafer level. Because of this, each APD will require a different voltage for the same gain, and in some cases the difference in the voltage required from APD to APD can be many volts (Si APDs). This is not the case if one were to use a PIN as they will all exhibit the same responsivity for a given voltage; therefore, if using an APD or multiple APD's which all share the same bias voltage – it is very important to minimize the Gain-Voltage variation from APD to APD.

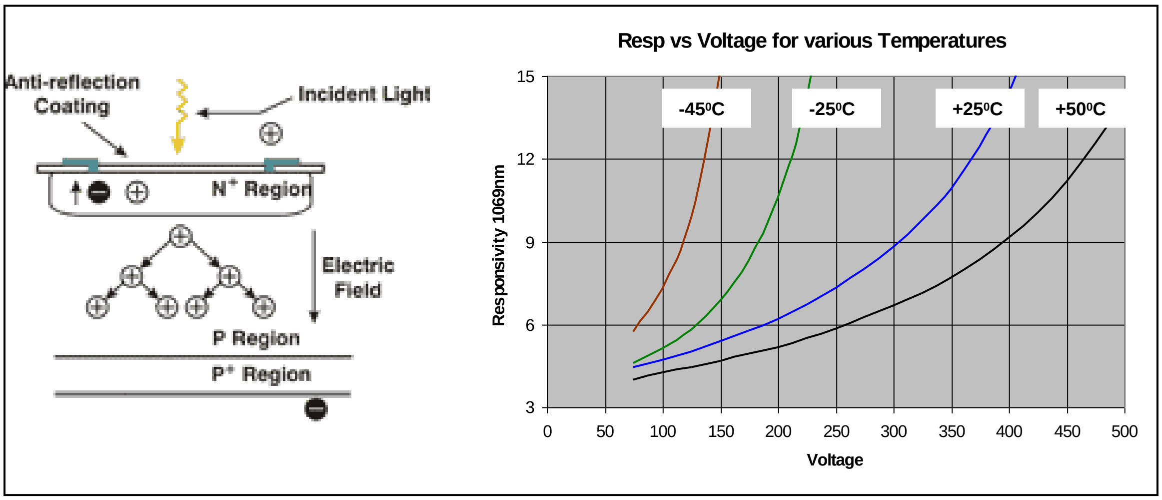

Figure 1: Gain illustration and Gain vs. Voltage at various temperatures

The increase in signal due to the gain is well understood and if there were no noise associated with the increase in gain, operating the APD at high gains would always provide better sensitivity. However, because of the excess noise and the dark current, the highest gain is not always the optimal gain. Paul Webb, Dr. R.J.McIntyre and J.Conradi did a very detailed analysis of the properties of Avalanche Photodiodes back in 1974 – in this section we will just summarize some of the important parameters:

RECEIVER MODULES USING APDs

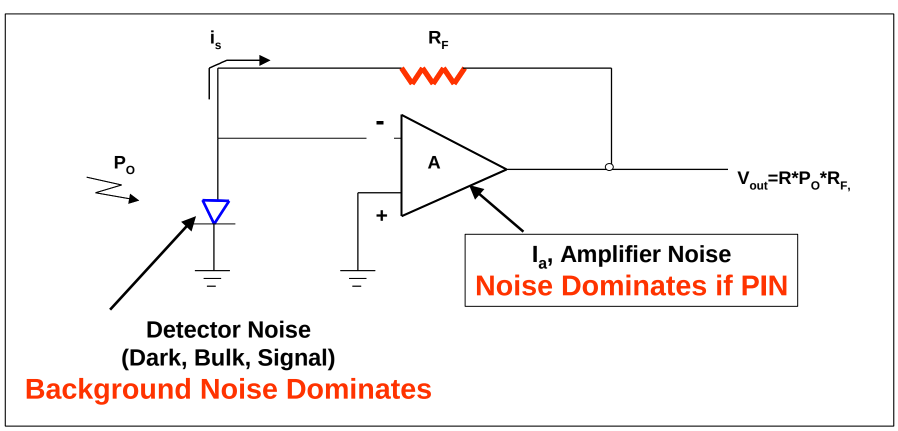

Figure 2: APD + Amplifier combination

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In the implications mentioned above, a large field of view is usually required and, thus, a large area detector. This results in large input capacitance for the amplifier and "background –gain" limited for the APD.

NOISE AND EXCESS NOISE FACTOR

Is due to the statistical nature of the APD gain. Not every electron-hole undergoes the same multiplication, in fact the variation can be quite large. This results in excess noise that is approximated by the following equation:

$$\mathbf{F = kM + (1-k)(2-1/M)}$$

Where:

k = ionization coefficient, average value for Si, 0.02, for InGaAs, 0.2-0.45.
M = gain

This equation shows that the higher the gain the higher the excess noise. Also, given that InGaAs has a much higher ionization coefficient, the APD's will be noisier and cannot be operated at high gain even if they were able to reach high gain – most InGaAs APD's have a maximum gain of 20.

The total noise of an APD + amplifier combination is given by:

$$\langle \text{Noise Total} \rangle^2 = 2q[I_{ds} + (P_o R_o F + P_b R_o F + I_{bd} F)M^2]B + Ina^2$$

Where:

I_{ds} = Bulk dark current which does not get multiplied.
P_o = Signal power to detect
P_b = Background radiation
R_o = Responsivity at unity gain
I_{bd} = Bulk dark current which is multiplied by the gain
F = Excess noise
B = Bandwidth of operation
I_{na} = Amplifier noise

Note the following:

- Using an APD makes sense when the amplifier noise is larger than the PIN detector noise. For applications requiring the detection of short pulses this will be the case, therefore, using an APD in these applications leads to better sensitivity. For example a range finding customer was able to double the ranging distance by replacing the PIN with an APD.

- It is very important to reduce the background as both the excess noise and the gain multiply the background. Also because of this, under background the optimal gain will be lower than if there is no background. Figure 3 shows the optimal gain with various background levels.

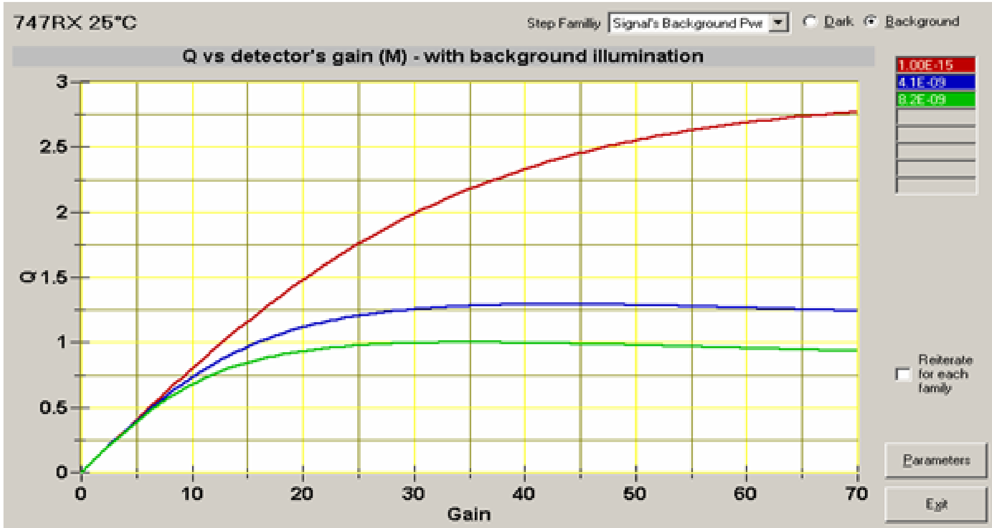

Figure 3: Optimal gain under different background conditions

WIDE TEMPERATURE RANGE

For these applications the avalanche photon diode must operate over a wide temperature range, usually from –45^{o}C to +125^{o}C. If the APD design structure and doping profile are not well defined the APD will breakdown at cold temperatures. This is illustrated in figure 4 below.

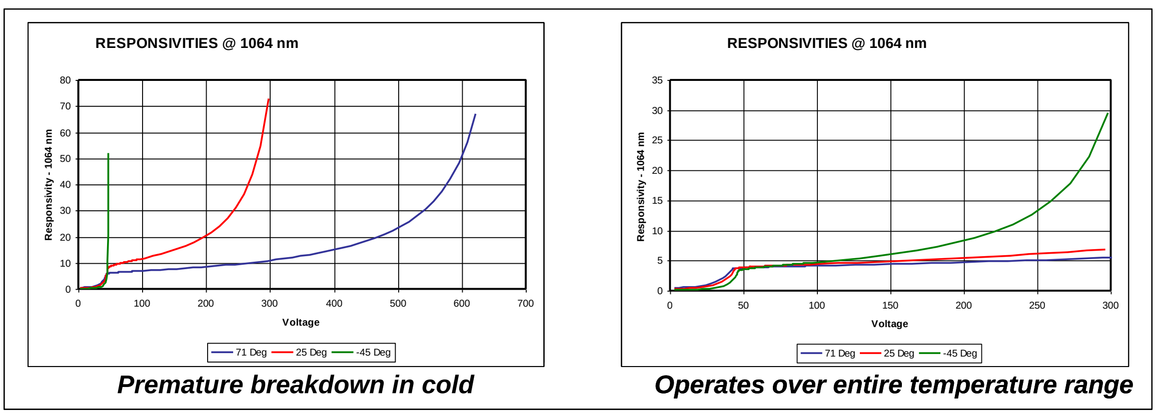

Figure 4: Premature breakdown – left, Operation over entire temperature range – right.

For some applications a heater can be incorporated but for others a heater cannot. If a heater is not used, then tremendous care must be taken to ensure that the APD will not go into breakdown at cold temperatures.

RECEIVER MODULE USING APDs – FAST RECOVERY

Under the right circumstances, Rx modules using APD's provide solid advantages to PIN's in terms of sensitivity. Also, with the right circuit design, the optimal gain can be automatically determined given the temperature and background. Figure 5, left, shows a module designed and produced by CMC Electronics that has the following characteristic's:

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- High voltage temperature compensation circuit to ensure the APD is operating at the same gain no matter what the temperature.

- Automatic background control. The module can sample the background and adjust the gain accordingly.

- Overload protection with fast recovery from overload, and without ringing/after-pulsing.

- Survivability to large power pulses.

While target distance and reflectivity varies, the return power may range from a nanowatt to nearly a kilowatt. The module should be able to recover very quickly when a high-energy pulse falls on the detector. CMC has tested this module to 10MW/cm^2 where catastrophic power level was reached. The module was able to withstand a couple of pulses with that energy before it was damaged. Failures at these power levels are caused by physical damage to the APD structure while the amplifier survives. In order to increase the APD's survivability, one method is to spread the focused beam onto a as large area as possible, thus, reducing the probability of damaging the material. CMC is currently exploring new packages that will transform the focused beam to a wider beam.

Overload to the electronic circuit is addressed by designing a robust module as shown in figure 5, left, that limits the current pulse and that quickly recovers from the overload. Figure 5, right shows an overload recovery to a pulse with peak power near to 1W, and the photo has a time scale of 50ns division. The output pulse (lower trace) shows smooth clamping of the low level followed by a recovery without any ringing, and a fast recovery APD.

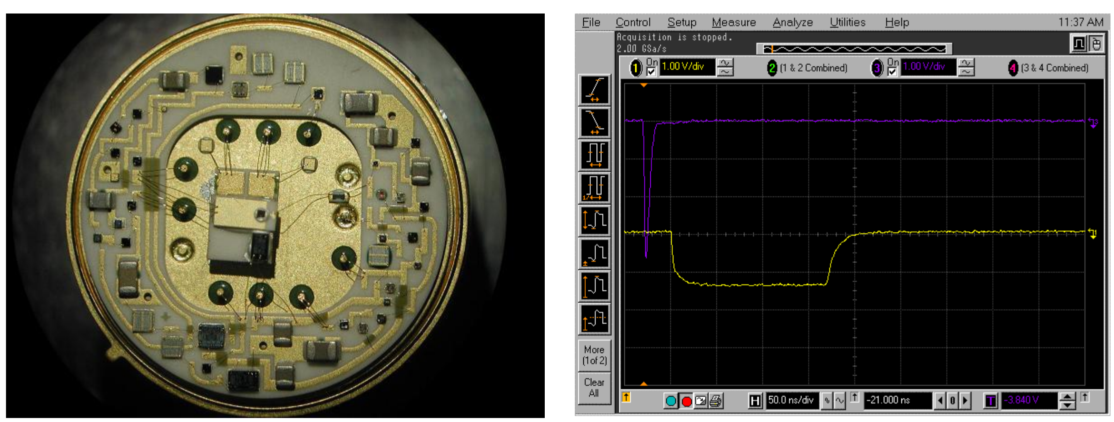


Figure 5: APD module with custom circuit design and recovery from overload

IMPORTANCE OF APD ON OVERLOAD RECOVERY

In these applications (Range finding, laser designation and laser warning), receiver module sensitivity is the most important parameter once the speed of the module is set by the laser pulse width that needs to be detected. In the applications that we are interested in, the laser pulsed that needs to be detected is usually 10 to 20ns and, therefore, speed or rise time is not a critical issue, but the following are:

- High QE (Thicker junction leads to higher QE and slower the response time)
- Low capacitance for lower noise receiver module performance.
- Low excess noise because of operation in high background environments.

When the APD itself gets overloaded and takes time to recover the problem is a little more difficult to address. Figure 6 shows the response tail of an InGaAs APD with different high power pulses. It is seen that depending on the power level, the recovery may be quite long. CMC has determined the cause of this phenomenon that is APD related, and is currently exploring APD designs to dramatically improve the recovery time.

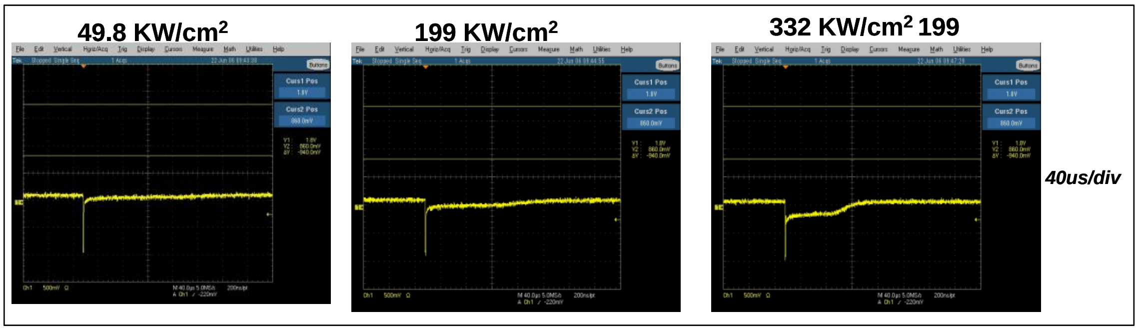
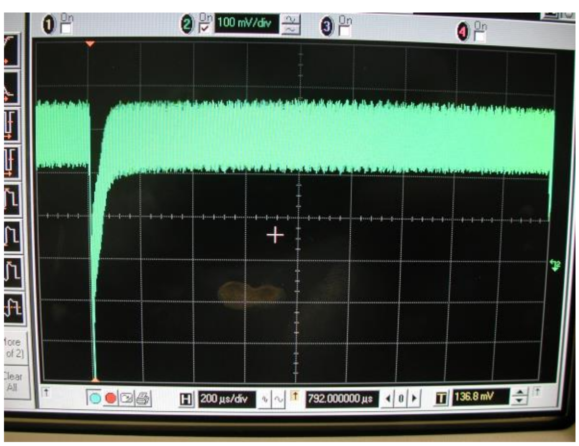


Figure 6: Recovery time for APD only at different power levels

The effect that is important for the APD to operate in this manner is the charge trapping. The charge traping distorts the internal electrical field of the APD, and causes the gain to increase after the overload pulse. A CW tone was injected in parallel with the overload pulse to obtain figure 7. We observe gain increase of nearly 30% at 199kW/cm^2 after overload pulse when compared to the gain in quiescent mode. The short-term impact on gain can also be observed on noise and in case of severe overload, the tail may cause false pulses detection causing systems errors.



(mV)	sn 0120	
	6kHz	1kHz
-10 us	92	86
10 us	110	109
Laser off	79	78

Figure 7: Effect of recovery tail on APD's gain

SUMMARY

We have shown that it is possible to have the desired performance from the optics and electronics. The performance from the electro-optics APD is achievable and we illustrated some of the effects seen on various APDs from different wafer and different source. The effect that is important for the APD to operate in this manner is the charge trapping. We showed measurement of their short term impact on gain and noise.

These modules can be done and optimized for 905nm pulsed laser diode, high power 1064nm lasers, 1550nm eye-safe laser range, or all of these wavelength at once with wideband detectors that can operate from 500nm to 1700nm or even higher. Operation temperature may range from –55^{0}C to 110^{0}C.

Infrared solid-state detectors are ideal for many high-end military and aerospace applications. When designing a module for a specific application start with choosing the detector that is best suited for the application or design one that is optimal for the application. Once that is accomplished, design the circuit that allows for all the specifications to be met. Since cost is always a factor do not over design the module to exceed all parameters if it will add cost. Finally, these modules, once qualified, will be used for a very-very long time and therefore it is important to minimize the design changes.

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