Development of High Sensitivity SWIR APD Receivers

Xiaogang Bai*[a], Ping Yuan[a], James Chang[a], Rengarajan Sudharsanan[a],
Michael Krainak[b], Guangning Yang[b], Xiaoli Sun[b], Wei Lu[b],

[a]Spectrolab Inc., A Boeing Company, 12500 Gladstone Ave, Sylmar, CA 91342, USA;
[b]NASA Goddard Space Flight Center, Code 554/694, MD, 20771, USA;

ABSTRACT

Emerging short wavelength infrared (SWIR) LIght Detection And Ranging (LIDAR) and long range laser rangefinder systems, require large optical aperture avalanche photodiodes (APDs) receivers with high sensitivity and high bandwidth. A large optical aperture is critical to increase the optical coupling efficiency and extend the LIDAR sensing range of the above systems. Both APD excess noise and transimpedance amplifier (TIA) noise need to be reduced in order to achieve high receiver sensitivity. The dark current and capacitance of large area APDs increase with APD aperture and thus limit the sensitivity and bandwidth of receivers. Spectrolab has been developing low excess noise InAlAs/InGaAs APDs with impact ionization engineering (I^2E) designs for many years and has demonstrated APDs with optical gain over 100 utilizing multiple period I^2E structures in the APD multiplier. These high gain I^2E APDs have an excess noise factor less than 0.15. With an optical aperture of 200 μm, low excess noise multiple periods I^2E APDs have capacitances about 1.7 pF. In addition, optical gains of InAlAs based APDs show very little temperature dependence and will enable APD photoreceivers without thermal electric cooling.

Keywords: avalanche photodiode, low excess noise, photoreceiver, LIDAR, impact ionization engineering, short wavelength infrared detector, laser ranging, Indium Phosphide (InP), Indium Aluminum Arsenide (InAlAs)

1. INTRODUCTION

In recent years, LIDAR systems show great successes in numerous missions, like humanity rescue mission in 2010 Haiti earthquake [1] and military surveillances in Afghanistan, and provide valuable information with unprecedented accuracy and speed. Now LIDAR systems have been integrated into various platforms in the space, in the air, and on the ground vehicles and robotic platforms [2].

The sensitivity of the LIDAR system is the most important figure of merit and depends on the laser source power, target reflectivity, weather conditions, receiver optical design, photodetector quantum efficiency, and electronic amplifiers noise. The sensitivity not only defines the maximum sensing range of the LIDAR system, but also is an important factor in the laser source selection, which typically is the most expensive component of the LIDAR. Advances in the LIDAR photoreceiver sensitivity allow the use of low power lasers to reduce power consumption and LIDAR system cost. Photoreceiver bandwidth is another important figure of merit of a LIDAR receiver. The resolution of the LIDAR system is the minimum distinguishable distance of two adjacent objects by the receiver. A photodetector with a large aperture increases the receiver signal to noise ratio by collecting more returned laser light. At the same time, the photodetector dark currents and capacitance also increases with the aperture and have adverse effect on receiver sensitivity and bandwidth. Current commercial LIDAR systems have bandwidths in the range of several MHz to 100 MHz. The demands on higher resolution and ranging accuracy are pushing the LIDAR bandwidth higher, in some cases, even beyond GHz. The photodetector bandwidth is limited by the RC effect in large aperture APDs. Special efforts are needed to reduce APD capacitance while maintains the same optical aperture.

Spectrolab has been developing high sensitivity SWIR APD receivers for many years. Low excess noise, large optical aperture, and high speed APDs have been developed to improve receiver sensitivity. Spectrolab InAlAs based APDs also show very low temperature dependence on optical gain and could operate without thermal electric coolers (TECs), which

*xiaogang.bai@boeing.com; phone 1-818-898-7563;

are used in photo-receivers to maintain stable operation and consumes a significant amount of power in the LIDAR system. A TEC-less APD photoreceiver offers small weight and power consumption and is important to reduce LIDAR system cost and size. It is possible to integrate the TEC-less LIDARs into handheld systems in the near future.

2. HIGH GAIN AND LOW EXCESS NOISE APD

In the photoreceivers, APDs convert the incoming light into electric current, amplify the current through internal impact ionization avalanche processes, and feed the amplified current into the following electric amplifier. The additional amplification, i.e. APD gain M, increases the input signal level and the receiver sensitivity. However, the amplified APD currents come with an increase in intrinsic noise, which is the uncertainty of the avalanche process. In the visible spectrum, silicon APDs show very little excess noise with a gain in the range of a few hundred (k~0.01). The benchmark of the APD receivers is silicon APD receivers widely used in NASA missions [3]. These receivers have mm size aperture, proven performance in space environment, very low dark current, very low capacitance due to its over 100 µm thick depletion region, and noise equivalent power (NEP) as low as 40 fW/rt(Hz). However, silicon becomes transparent in SWIR spectrum. Current state-of-the art APDs in the SWIR spectrum are based on InGaAs APDs with either InP or InAlAs as the multiplication layer. InP APDs are widely used in Geiger mode 3D LIDAR cameras, which provide single photon detection sensitivity [4]; however, InP APDs show high excess noise in linear mode operation. On the other hand, InAlAs has much lower excess noise than InP, with a k value of 0.22 compared to 0.5 of InP. In order to reach sensitivity similar to silicon APD receiver, the SWIR APD excess noise must be reduced further than InAlAs.

APD based photoreceiver consists of an APD and a following transimpedance amplifier (TIA). The NEP of the photoreceiver can be expressed as:

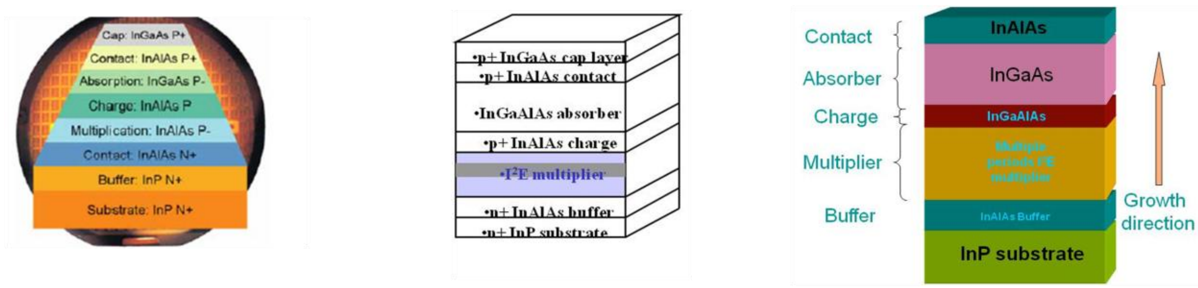
$$NEP = \frac{1}{Rsp}\left[2qI_d F + \frac{\alpha^2}{M^2}\right]^{1/2} \qquad \text{Eq. 1}$$

$$F = kM + (2 - \frac{1}{M})(1-k) \qquad \text{Eq. 2}$$

where, R_{sp} is the APD responsivity at unity gain, q is the electron charge, I_d is the APD dark current, F is the APD excess noise factor, α is the TIA input noise current, M is the APD gain, and k=α/β or β/α (k<1 always), where α and β are electron and hole ionization coefficients.

Spectrolab builds APD photoreceivers with off-the-shelf commercial available TIAs, which have acceptable higher noise than customer designed TIAs for specific LIDAR applications for certain applications. In this paper, Spectrolab will focus solely on APD development to increase receiver sensitivity. The TIA noise α actually has implicit dependence on receiver bandwidth and increase with TIA bandwidth fast. For example, MAXIM has a series of TIAs: MAX3658 has a noise current of 2.1 pA/rt(Hz) with 580 MHz bandwidth, and MAX3266 has a noise current of 6.6 pA/rt(Hz) with a bandwidth of 920 MHz. Once the TIA is selected based on application requirements, From Eq. 1, an APD should have high quantum efficiency R_{sp}, low excess noise F, and high gain M to reach a low receiver NEP.

Spectrolab has been improving excess noise of InAlAs/InGaAs APDs for many years and three generations of low excess noise APDs developed by us are shown in Figure 1. All these APDs are separated absorption, charge, and multiplification (SACM) APDs. In SACM APDs, an intentionally doped charge layer is used to control the electric fields in the multiplier and the absorber independently. In each generation, the multipliers are studied to lower the excess noise and the absorbers are kept similar. The first generation is InGaAs/InAlAs APDs, which has an InGaAs absorber and an InAlAs multiplier with k of 0.22. In the second generation, we implemented I^2E InAlAs/InGaAlAs heterostructure in the multiplier layer to reduce the APD excess noise to 0.15 and improved the APD photoreceiver sensitivity to 150 fW/rt(Hz) at 1.06 µm wavelength [5, 6]. In the third generation, multiple periods of I^2E structures were integrated into the multiplier and these APDs showed gain over 100 before breakdown.



Gen 1 design
Baseline InAlAs APD
k=0.22
Optical gain: 10~20

Gen 2 design
Baseline I^{2}E APD
k=0.15
Optical gain: 10~20

Gen 3 design
Multiple I^{2}E APD
k<0.15
Optical gain: 10~100

Figure 1 Three generations low noise APDs developed at Spectrolab.

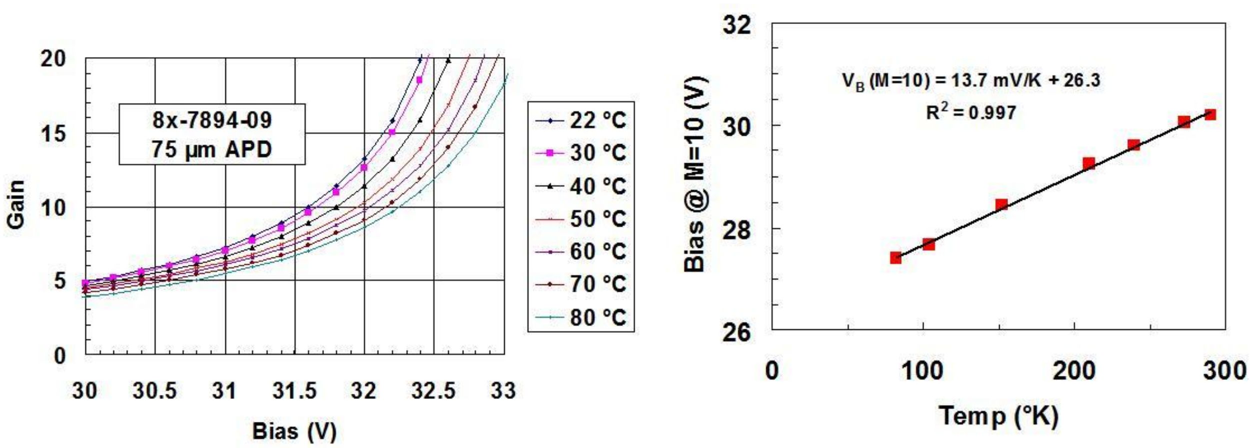


Figure 2 Left: Gain vs. bias voltage of Spectrolab baseline InAlAs APDs. Right: bias voltage@gain=10 vs. temperatures.

In Figure 2, the Gen 1 InGaAs/InAlAs APDs current-voltage characteristics are measured under different temperatures and the bias voltage at gain of 10 are linearly fitted into the temperature. A small coefficient about 13mV/°C was measured in a wide range of operating temperature. For the InP APD, the coefficient is about 300 mV/°C. The Spectrolab Gen 2 and Gen 3 APDs are also based on InAlAs multiplier and similar temperature dependences are expected.

Spectrolab implemented I^{2}E design to reduce APD excess noise, which is a design consisting of two or more semiconductor materials with different impact ionization threshold energies in the APD mulitiplier layer [7]. When properly biased, the carriers are accelerated by the high electric field in the multiplier and excite new electron-hole pairs through impact ionization. In the region with lower impact ionization threshold energy, the carriers show high probability to initiate an impact ionization avalanche event; in the region with higher impact ionization threshold energy, the carriers show low probability to initiate an avalanche event. Compared with a multiple consist of only one material, I^{2}E multiplier has region with more avalanche events than rest of the multiplier. It translates into lower excess noise.

The Spectrolab Gen 1 APDs have InAlAs multipliers, which exhibit a k value of 0.22. With a single material in the multiplier, the avalanche events have uniform probability across the multiplier. In the Gen 2 single I^{2}E APDs, the multiplier consists of InAlAs and InGaAlAs. The InGaAlAs layer has lower impact ionization threshold energy than the InAlAs layer. The carriers are more likely to initiate an impact ionization event in the InGaAlAs layer. In other words, the random avalanche events show some preference in part of the I^{2}E region and the preference results in a low excess noise. The Gen 2 APDs have an effective k value of 0.15, which is less than k values of both bulk InAlAs and InGaAlAs.

A photoreceiver was built with a Gen 2 APD and a GHz TIA from MAXIM (MAX3266) and shows a record low NEP of 150 fW/rt(Hz) at 1.06 µm [5].

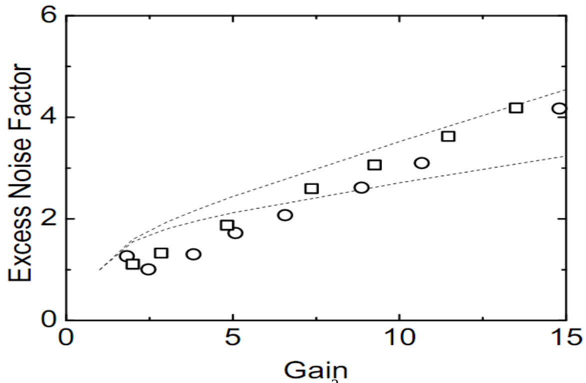


Figure 3 Excess noise of an APD with 5 periods of I^2E. The dot line corresponds to k=0.1 and k=0.15.

In Spectrolab Gen 3 APDs, multiple periods I^2E structures are integrated into the multiplier to further reduce excess noise. The Spectrolab Gen 3 APDs not only have low excess noise, shown in Figure 3, but also show very high optical gain. Gains over 100 are achieved in APDs with 3, 5, and 7 periods I^2E multiplier. It is worth to point out that the APD gain also relates to its excess noise. Silicon APDs have very little excess noise with k~0.01 and have optical gain as high as 1000 before APD breakdown. InP/InAlAs APDs typically have a maximum gain around 50 before breakdown because of their much higher k values. The achieved high optical gain in Gen 3 APDs indicate the excess noises are further suppressed in the multiple I^2E APD. The preliminary direct experiment results show a k value between 0.1 and 0.15 for a 5 periods I^2E APD, shown in Figure 3.

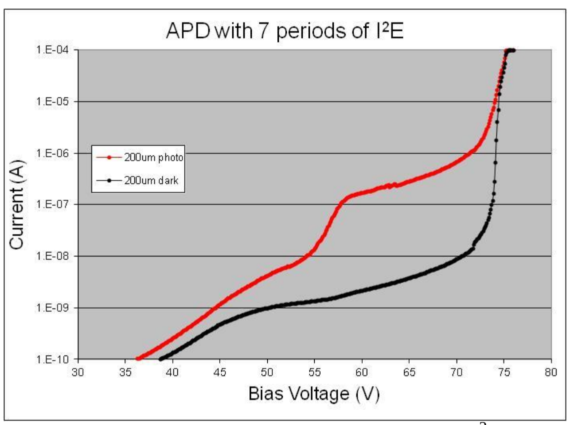


Figure 4 Current voltage characteristics of an APD with 7 periods of I^2E and 200µm diameter.

In Figure 4, an APD current voltage characteristic is shown. This APD has 7 periods I^2E structures in its multiplier and a diameter of 200 µm. The APD shows low dark currents at room temperature and gain over 100 before breakdown. At a gain of 50, the APD has a dark current less than 100 nA. The nominal optical gains, calculated by assuming unity gain at punch through around 57 Volts, are well above 100 before breakdown. However, right after the punch through, the photo currents show a fast rising trend instead of a plateau, which indicates the actual gain at punch through is larger than unity assumed in the gain calculation. Thus, the actual APD gains should be higher than the nominal gain. The exact value of the gain at punch through is difficult to extract based on the current-voltage characteristics alone.

In Figure 5, the optical gain from Spectrolab Gen 1, Gen 2, and Gen 3 APDs with 3, 5, 7 periods of I^2E structures are compared. All these APDs have different punch through voltages and breakdown voltages. The bias voltages are normalized between 0 and 1 to compare all these different APDs on one graph, where 0 corresponds to punch through voltage and 1 corresponds to breakdown voltage. For each APD, unity gain is assumed at the punch through voltage. The optical gain then is calculated referenced to the unity gain. The Gen 3 multiple periods I^2E APDs have higher gain than Gen 1 and Gen 2 APDs at the same bias point, and the gain increases with number of I^2E periods in Gen3 APDs. At a fixed gain value, Gen 3 APDs are operated at bias point much lower than Gen 1 and Gen 2 APDs. Typically APDs are vulnerable to unstable operation from temperature variation and supply bias voltage fluctuations. Gen 3 APDs provide operating bias points show less dependence on the fluctuations, which is favorable for a receiver without TEC to maintain a constant temperature.

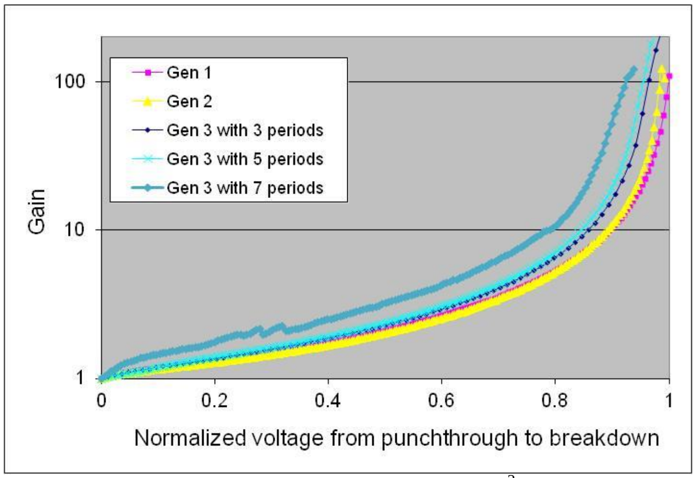


Figure 5 Gain vs. normalized bias of multiple I^2E APDs.

Two photoreceiver were built with same GHz TIA (MAX3266) and a Gen 2 APD and a Gen 3 APD with 5 periods I^2E. In Figure 6, the photoreceiver NEPs are shown. On the left, the photoreceiver shows a minimum NEP about 150 fW/rt(Hz) around 71.15V and increases sharply afterwards. The APD must be operated in a tight range, 71 V to 71.2 V, to maintain the NEP less than 200 fW/rt(Hz). The photoreceiver built with Gen 3 APD also has a minimum NEP about 150 fW/rt(Hz). However, the photoreceiver NEP is less than 200 fW/rt(Hz) in a much wide range, from gain of 50 to 80. Together with the low temperature dependence on the gain, Spectrolab Gen 3 APDs are capable to operate in a wide range of temperature and provide near minimum NEPs over the range. Such capability is very important and will allow the APD receivers operate without a TEC to stabilize the temperature but also guarantees the high sensitivity at the same time.

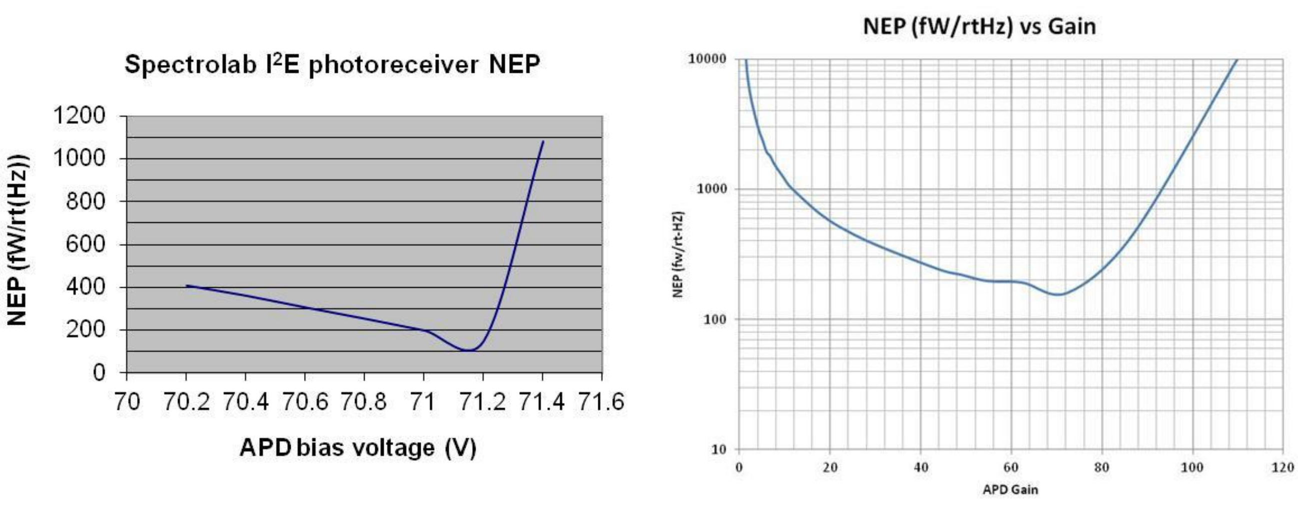


Figure 6 NEPs of photoreceivers build with same GHz TIA and: left, a Gen 2 APD; right, a Gen 3 5 periods I^2E APDs.

All Spectrolab Gen 1, Gen 2, and Gen 3 APDs share similar charge layer and absorber design. Zinc is the dopant of the charge layer and is notorious for its diffusion into absorber during the epitaxy growth. Before breakdown, the APD absorbers are only partially depleted due to the Zinc diffused into the absorber. A partial depletion in the absorber first reduces the APD quantum efficiency. Photo-excited electron-hole pairs reach multiplier through slow diffusion instead of drift and some carriers are recombined before reach the multiplier. The second drawback of the partial depleted absorber is the high capacitance, which limit the bandwidth of the large area APDs.

3. LARGE AREA AND LOW CAPACITANCE APDS

Another important figure of merit of the APD photoreceiver is the bandwidth. Most of the LIDAR systems have pulsed laser sources. A fast receiver is essential to distinguish the return laser pulses from two adjacent objects, in other words, the resolution of the LIDAR system. LIDAR systems always prefer optical aperture as large as possible. A large optical aperture not only collect more light, but also relax the requirements on receiver optics, which leads to lower cost on the LIDAR system. For large area APDs, the intrinsic bandwidth is limited by their capacitance instead of the carrier transit time through the multiplier. The APDs also work as the input capacitive loads to then following TIAs. For GHz applications, typical TIA input capacitances are limited to less than 1 pF, which in turn limits the optical aperture of the APD.

In Figure 7, capacitance voltage characterizes from Gen 1 baseline InAlAs APDs and Gen 3 APDs with 5 periods I^2E are shown. Both APDs have a diameter of 200 µm and are doped with Zinc in the charge layer. The baseline InAlAs APD has a capacitance about 4 pF before breakdown and the 5 periods I^2E APD has a capacitance about 1.7 pF. The depletion widths in the absorber of both APD are similar. The reduction on capacitance in Gen 3 APD is the result of a thicker multiplier in the 5 periods I^2E APDs, which is more than double thick than the Gen 1 InAlAs APD. However, it is difficult to further reduce capacitance through thick multiplier. As the multiplier thickness increase, carriers transit time through the multiplier also increase and the bandwidth of the APD starts to reduce.

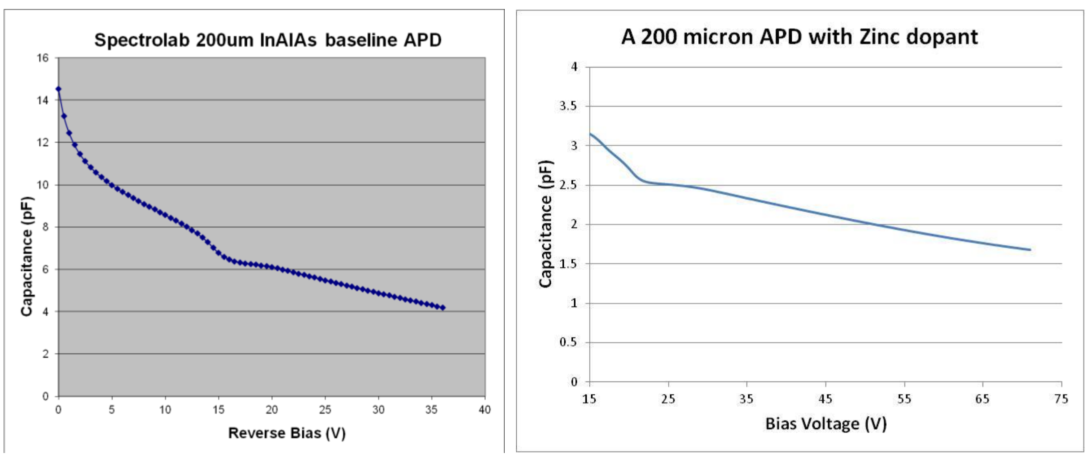


Figure 7 Capacitance voltage characteristics of: left, Gen 1 APD; right, Gen 3 5 periods I^2E APD with 200 µm diameter.

APDs with fully depleted absorber will not only provide much lower capacitance, but also increase the APD quantum efficiency. Carbon is an alternative p-type dopant. Unlike Zinc, Carbon shows very slow diffusion and provides a well defined doping profile. There are also reports on reducing dark current with Carbon doping in InAlAs APDs [8]. A Gen 1 InAlAs APD was grown with Carbon as the charge dopant. The APD current-voltage and capacitance-voltage characteristics are shown in Figure 8. The APD shows very low dark current and very good photo response. The APD has a capacitance about 2.7 pF before breakdown, which is less than the 4pF realized with Zinc doping in the identical structure. However, the absorber is still partially depleted because of a very low level Zinc doping in the absorber. Spectrolab now is developing Carbon doped Gen 2 and Gen 3 APDs. For Gen 3 APD with 200 µm diameter, a capacitance less than 1 pF is feasible with a fully depleted absorber.

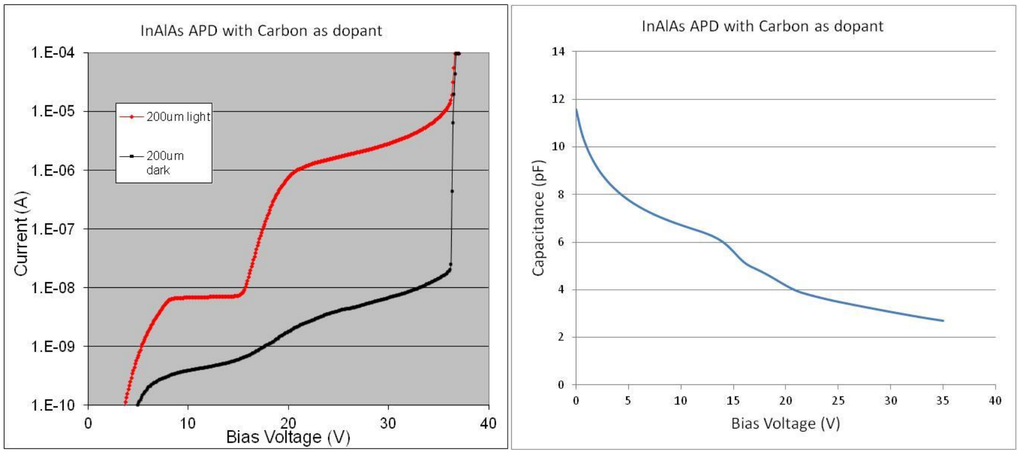


Figure 8 Current voltage characteristics and capacitance voltage characteristics of an InAlAs APD with Carbon as dopant and 200 µm diameter.

4. SUMMARY

The next generation LIDAR systems require high performance and low cost photoreceivers. Spectrolab developed multiple periods I^2E APDs with low excess noise, high optical gain, and low capacitance. Photoreceiver built with these APDs show NEP less than 200 fW/rt(Hz) in a wide range of gain to enable stable operation and possible of TEC-less LIDAR system. Spectrolab are continuing to optimize the APDs to increase quantum efficiency, reduce capacitance, and demonstrate a TEC-less photorecievers with low NEP.

REFERENCES

[1] Amy L. Neuenschwander, Melba M. Crawford, etc., “Terrain classification of ladar data over Haitian urban environments using a lower envelop follower and adaptive gradient operator”, Proc. SPIE 7684, 768408 (2010)

[2] Robert Moss, Ping Yuan, Xiaogang Bai, etc., “Low-cost compact MEMS scanning ladar system for robotic applications”, Proc. SPIE 8379, Laser Radar Technology and Applications XVII, 837903 (2012)

[3] Michael A. Krainak, Xiaoli Sun, Guangning Yang, and Wei Lu, “Comparison of linear-mode avalanche photodiode lidar receivers for use at one micron wavelength”, SPIE 7681-34, 2010

[4] Ping Yuan, Rengarajan Sudharsanan, Xiaogang Bai, etc., “Three-dimensional imaging with 1.06 µm Geiger-mode LADAR camera”, Proc. 8379, 837902 (2012)

[5] Xiaogang Bai, Ping Yuan, etc.; “GHz low noise short wavelength infrared (SWIR) photoreceivers” Proc. SPIE Laser Radar Technology and Applications XVI, 803717-1 (2011).

[6] Xiaogang Bai, Ping Yuan, etc., “16 channel GHz low noise SWIR photoreceivers”, Proc. Of SPIE Vol. 83532E (2012).

[7] J. Campbell, “Recent advances in telecommunications avalanche photodiodes”, Journal of Lightwave Technology, Vol. 25, No. 1, 109 (2007)

[8] Anne Rouvie, etc., “Low noise and high gain-bandwidth product AlInAs avalanche photodiodes”, Indium Phosphide and Related Materials, 2008