Development of Single Photon Counting Sensors Operating at Short Wavelength Infrared Wavelengths

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ABSTRACT

This paper will review the development of single photon counting sensors at Boeing Spectrolab. Future development over the next five years will be discussed in the context of sensor requirements that have been established and will be established. Greater sensitivity through lower false event rates, higher bandwidths, lower after-pulsing rates, higher operating temperatures, and better uniformity are figures-of-merit that will be discussed in this presentation. We will present performance of large format InP/InGaAs Geiger mode avalanche photodiode arrays operating at 1.06 µm and 1.55 µm.

1. INTRODUCTION AND BACKGROUND

Recent developments in three-dimension imaging have stimulated interest in single-photon counting avalanche photodiodes (APD) in the short wavelength infrared region. Geiger mode avalanche photodiode focal plane arrays (GM-FPAs) for short wavelength infrared applications have been reported by both MIT Lincoln Laboratories[1] and Boeing Spectrolab.[2] Most of the effort to date has been focused on photodiodes operating at 1.06 µm where high power emitters are available. For eye-safe Laser Detection And Ranging (LADAR) applications, there is also considerable interest in Geiger mode avalanche photodiodes (GM-APDs) operating at 1.55 µm.

2. SENSOR FLOWDOWN REQUIREMENTS

Important figures-of-merit for GM-APDs are dark count rate (DCR) and photon detection efficiency (PDE) which together establish an upper limit on the signal-to-noise for the entire sensor system. For active 3-D imaging sensors FPA timing jitter is also a critical parameter as this sets an upper limit on range resolution. Other figures-of-merit of importance to the sensor system designer include afterpulsing and maximum frame rate. Afterpulsing, or temporal crosstalk between range gates, ultimately limits sensor efficiency. Frame rate limits sensor update time which in some applications is a critical performance parameter. Finally, spatial resolution is limited by pixel pitch and spatial crosstalk between pixels on the FPA.

Together these parameters must be optimized to realize optimal sensor performance. In practice these parameters are not decoupled and often trade off against one another. A robust FPA read out integrated circuit (ROIC) can improve sensor performance by mitigating APD deficiencies. However, as is almost always the case, the FPA design is fundamentally limited by detector performance. Table 1 details the most important FPA figures of merit that impact single photon counting sensor systems.

Parameter	Spec	Test conditions
Wavelength	1.06 µm	
Format	32x32	
Pixel Pitch	100 µm	
PDE	40%	240K, 4V overbias
Fill Factor	70%	
DCR	20 kHz	240K, 4V overbias
Cross talk	2%	Optimized overbias for SCA
Pixel operability	95%	
RMS timing jitter	0.5 ns	

Table 1. **Single photon counting focal plane array figures-of-merit for a 32x32 GM-APD array presently fabricated at Spectrolab**

3. GM-APD FPA FUNDAMENTALS

In Geiger mode operation the avalanche photodiodes are biased above the breakdown voltage, ~2 - 4 V, for a short period of time, typically a few nanoseconds gate time. Without any photon falling on the detector array, the noise in the detector array during the nanoseconds gate time operation is the dark count rate (DCR) and DCR increases with increasing overbias. Not all photons that fall onto the APD during this period of overbias are absorbed and converted into digital pulses that can be measured by the readout circuit. The fraction that is converted into signal is a figure-of-merit called the photon detection efficiency. Figure 1 details the general concepts of Geiger mode operation.

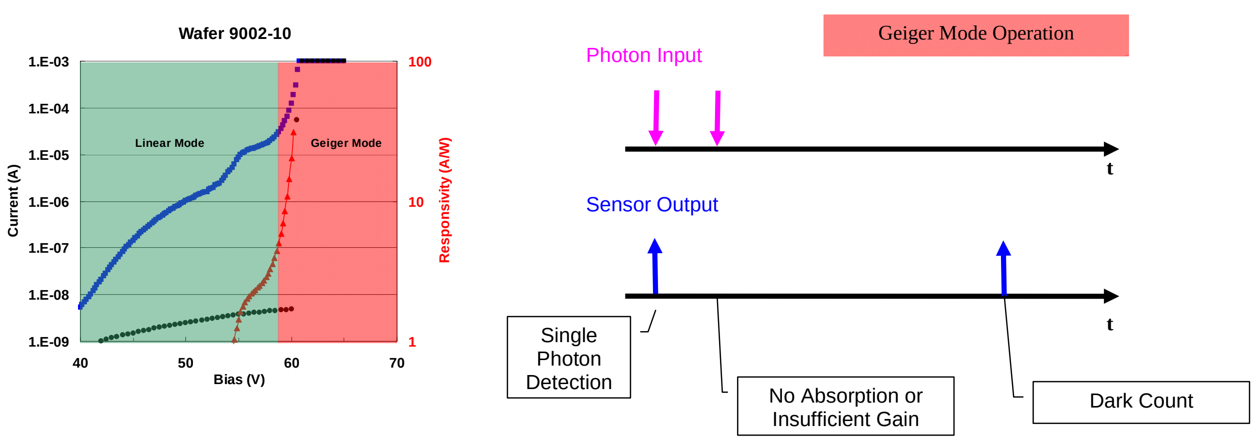
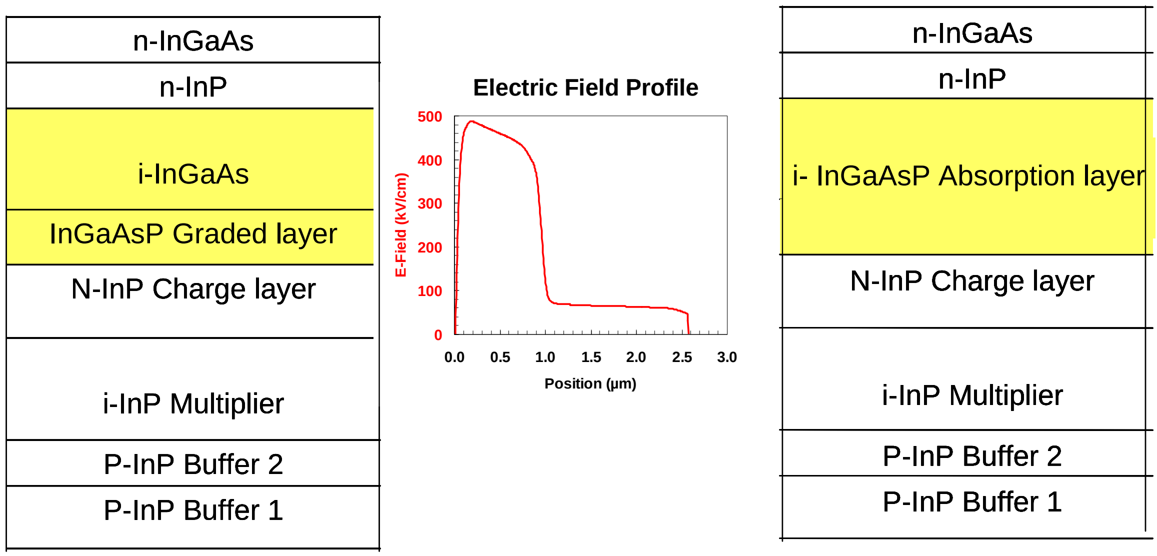


Figure 1. **Geiger mode operation of an avalanche photodiode.**



1.5 µm Gm-APD device design 1.06 µm Gm-APD device design

Figure 2. Gm-APD device designs and the electric field profile of the designs

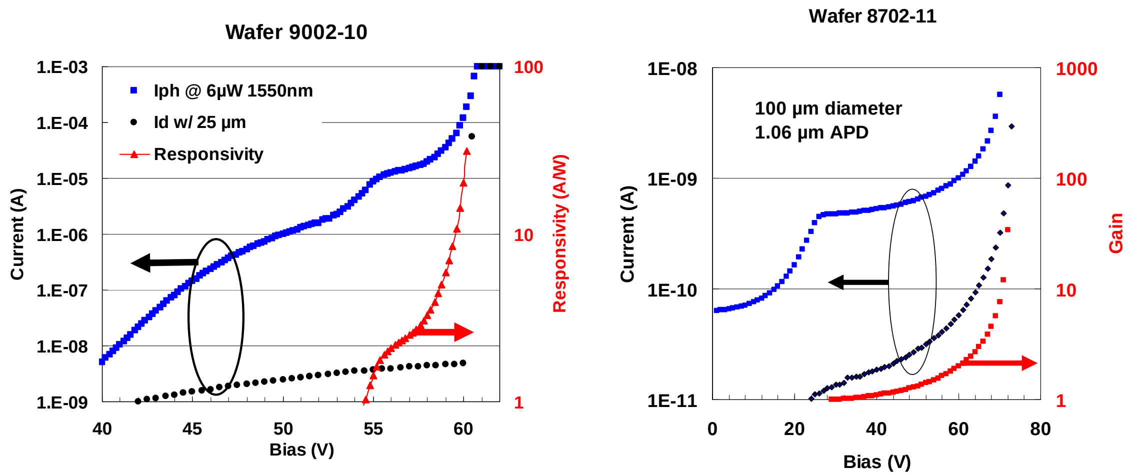
Device Structure

Figure 2 shows the 1.06 µm and 1.5 µm Gm-APD separate absorption and gain and multiplication (SAGM) device structures. For both structures InP layer is the multiplication layer and silicon doped InP layer is the charge layer. InGaAsP layer and InGaAs layers are used as the absorption layers for 1.06 µm and 1.5 µm device structures, respectively. Figure 2 also shows the electric field profile in these device structures. The device structure was designed in such a way that the electric field is maximum at the InP multiplication layer for high avalanche gain and it is minimum across the absorption layers so that the dark current will be low in these devices. In the case of 1.5 µm Gm-APD design, a thin InGaAsP layer was introduced between n-InP charge and InGaAs absorption layers to reduce the trapping of carriers due to the valence band discontinuity between InP and InGaAs. An N^+ InGaAs layer was used as a contact layer for the both designs. The nominal thickness of both InGaAs and InGaAsP absorption layers was 1.5 µm in order to have good quantum efficiency. The separate absorption and multiplication avalanche photodiode device growth and characterization details have been described elsewhere.[2]

4. STATE OF THE ART AT SPECTROLAB

Single Element Device Fabrication And Testing Results

Single element mesa devices with different mesa diameters are typically fabricated using photolithography and the fabrication details were described earlier.[2] Devices with various diameters, from 20 µm to 200 µm, are fabricated to evaluate the quality of epitaxial wafers and also to optimize the device designs for improved device performance. Initial I-V testing of devices is done at room temperature to determine breakdown voltage, punch through voltage, and leakage current. Device optical gain and responsivity were measured by illuminating with 1.5 µm and 1.06 µm wavelength lasers. Figure 3 shows the I-V data of 1.5 µm and 1.06 µm devices with 25 µm and 50 µm diameter devices respectively. Both devices clearly exhibit low dark current and high gain near the breakdown voltages. The dark currents near breakdown voltage for the 1.5 µm and 1.06 µm devices are below 10 nA and 50 pA, respectively. As expected for the small bandgap (1.5 µm) device the dark current is higher than the wider bandgap (1.06 µm) device.



a) 1.5 μm Gm-APD device

b) 1.06 μm Gm-APD device

Figure 3. **Room temperature I-V data of; a) 1.5 μm and b) 1.06 μm devices**

Figure 4 shows the DCR measured at room and at low temperatures as a function of overbias, multiplication layer thicknesses, and pixel size for both 1.5 μm and 1.06 μm single element devices. As expected, DCR increases with increasing overbias for both 1.5 μm and 1.06 μm devices and decreases with decreasing pixel size, increasing multiplication layer thickness, and at reduced temperatures. The devices labeled as 8702 and 8704 had thin multiplication layer thickness (<1 μm) and they show DCR greater than 1 MHz at room temperature. Upon increasing the multiplication layer thickness to 1.5 μm DCR values decreased to less than 500 KHz for both 1.5 μm and 1.06 μm devices due to reduced electric field in the multiplication layer. A reduction in dark count rate with increasing multiplication layer thickness has been reported by Lincoln Laboratory.[3]

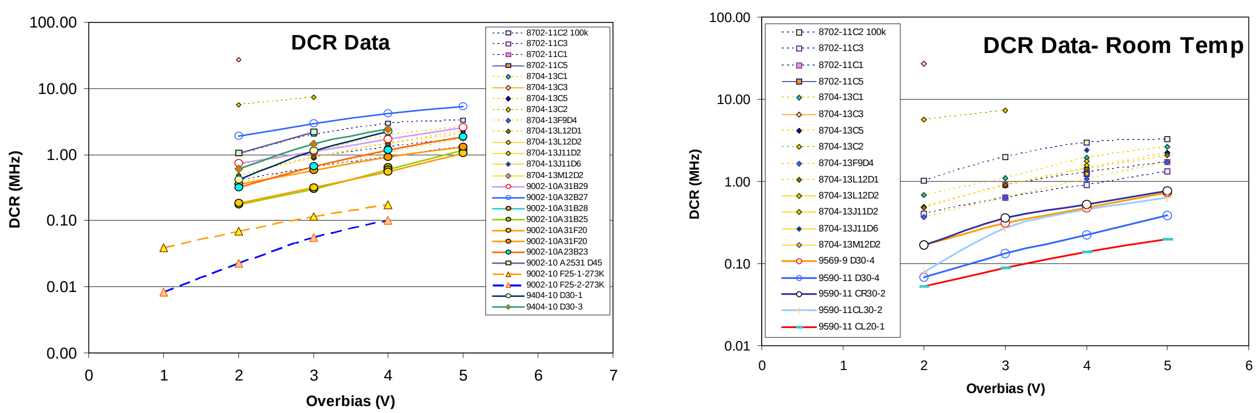


Figure 4. **The DCR at room temperature and 0°C versus overbias characteristics taken on two types of GM-APDs. The 8702 and 8704 APDs were InGaAsP/InP APDs optimized for 1.06 μm, and their curves are shown with dotted lines and smaller markers. The 9002 and 9404 series APDs are sensitive at 1.55 μm and yet display a very low DCR even at room temperature. They are illustrated with solid lines. The DCRs of the 9002 APDs at 0°C are shown with dash lines.**

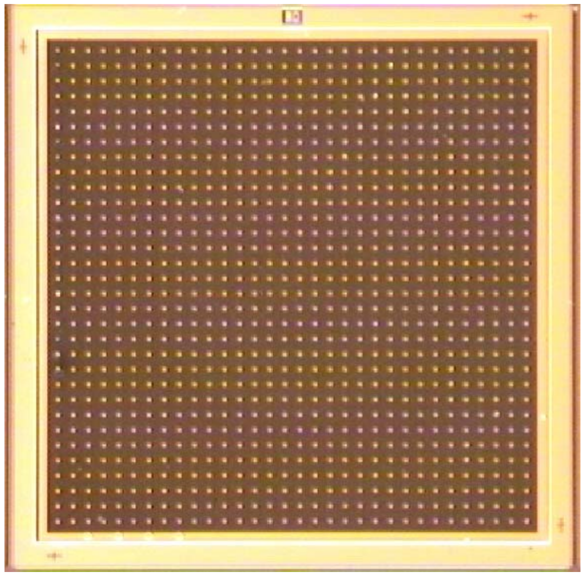


Figure 5. Photograph of a 32 x 32 Gm-APD detector array

<u>32x32 GM-APD Array Fabrication And Testing Results</u>

A 32x32 element GM-APD array is shown in Figure 5. These detector arrays have been integrated with MIT-LL CMOS2002 ROICs and packaged into hermetically-sealed modules that include thermoelectric cooling. In order to improve the GM-APD performance temperatures, we have optimized the epitaxial growth, process, and device design for the Geiger-mode operation, and achieved an excellent DCR and greater than 40% PDE at operational temperatures. DCR data collected on recent APD arrays is shown in Figure 6. Optical crosstalk has been an issue with these GM-APD FPAs to date. Spectrolab has developed device designs to minimize crosstalk across these arrays. Crosstalk across the GM-APD arrays is shown in Figure 7 and has been demonstrated to be less than 2%.

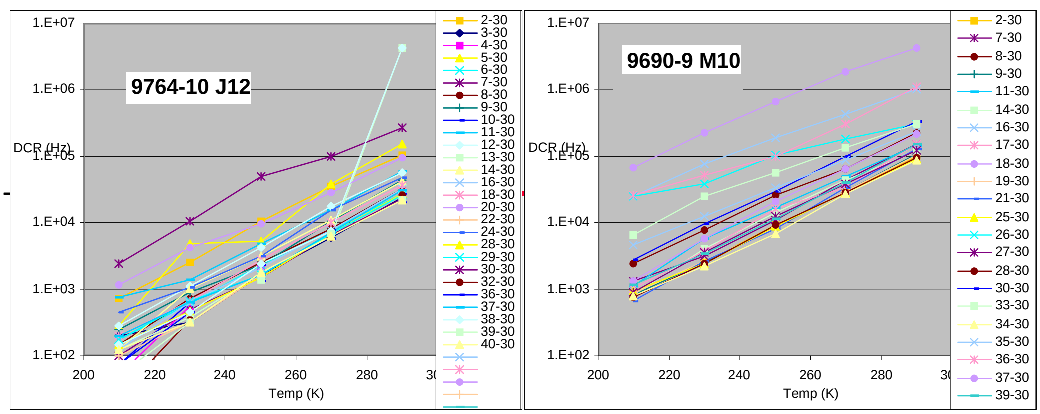
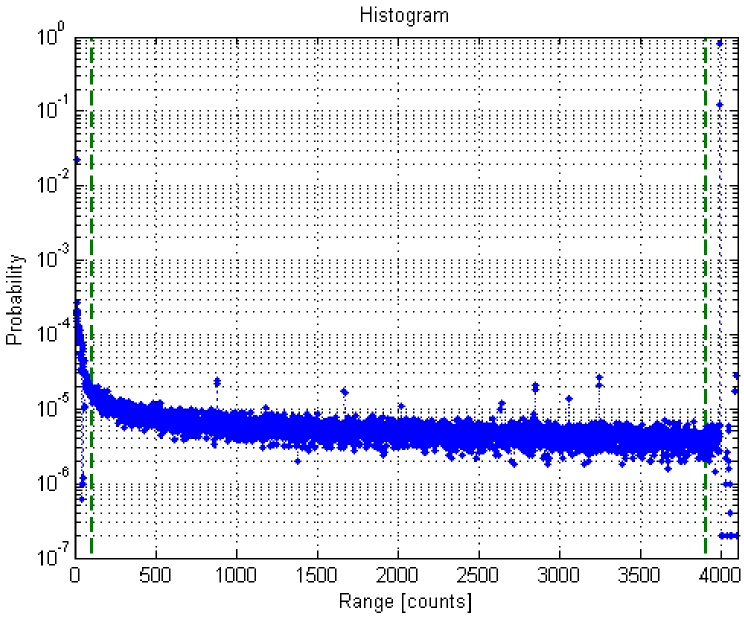


Figure 6. Dark count rate data collected on two recent Spectrolab 32x32 focal plane arrays. All data are taken with a 4 volt overbias on 30 µm diameter pixels.



9764-10 J9	
Average Dark Count Rate (kHz)	11.1
Crosstalk (%)	1.4

Figure 7. **The measured cross talk data histogram and corresponding DCR on a recent Spectrolab 1.06 µm GM-APD focal plane array module. These data were collected at Boeing SVS.**

Timing jitter is a particularly important figure-of-merit for FPAs because this temporal noise establishes an upper limit on range resolution. Recent data collected at Boeing SVS on Spectrolab GM-APD arrays is shown in Figure 8. In these measurements a 1.06 µm laser was pulsed using an internal trigger from an MIT Lincoln Laboratory CM2002 ROIC. The laser pulse width was 660 ps and the system jitter was 600 ps. An FPA jitter of 500 ps would result in a measured jitter of greater than 1.5 ns. The data shown in Figure 8 show a FWHM of less than 2 bins indicating that the FPA has less than 500 ps of jitter.

Not every parameter can be measured across all 1024 elements of a 32x32 FPA. However it is possible to measure breakdown characteristics across an array to insure that an optimized biasing condition can be applied to all elements to achieve optimal array performance. Figure 9 shows breakdown voltage characteristics across a typical Spectrolab 32x32 APD detector array. These data demonstrate excellent materials uniformity and control that result in uniform device characteristics.

5. SUMMARY AND PATH FORWARD

Spectrolab, together with MIT Lincoln Laboratory, has been developing GM-APD sensor technology for SWIR applications. Continuous improvement in materials and device design has resulted in excellent FPA performance in a single photon counting technology that finds application in LADAR sensors. Dark count rate, photon detection efficiency, jitter, crosstalk and array uniformity continue to improve.

While 32x32 arrays find applications in many sensor systems, development of 128x32 and 256x64 arrays have been reported by MIT Lincoln Laboratory.[3] In the near term Spectrolab will be developing these larger format arrays for emerging single photon counting sensor systems. These FPA modules will cover both 1.06 µm and 1.55 µm wavelengths and utilize Spectrolab's internal materials growth and characterization infrastructure. In addition, Spectrolab is developing a compact LADAR camera using these FPAs for many airborne applications.

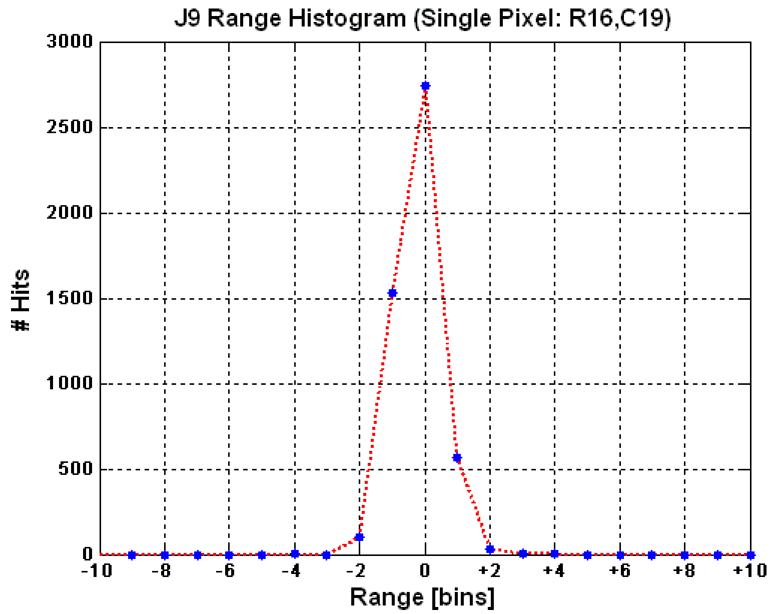


Figure 8. **Jitter data collected on a single pixel of a Spectrolab 1.06 µm GM-APD module. Each bin corresponds to 500 ps. After accounting for system jitter, a FWHM of less than 3 bins corresponds to a jitter less than 500 ps.**

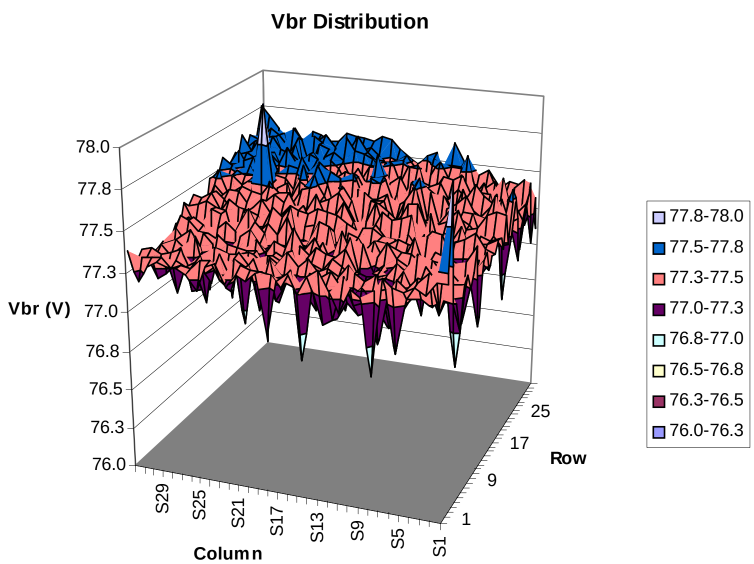


Figure 9. **The breakdown voltage characteristics across a Spectrolab 1.06 µm GM-APD array measured at 20 °C.**

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