High efficiency 1.55 µm Geiger-mode single photon counting avalanche photodiodes operating near 0^{o}C

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ABSTRACT

Recent developments in three-dimension imaging, quantum cryptography, and time-resolved spectroscopy have stimulated interest in single-photon counting avalanche photodiodes (APD) operating in the short wavelength infrared region. For visible and near infrared wavelengths, Silicon Geiger-mode APDs have demonstrated excellent photon detection efficiency (PDE) and low dark current rate (DCR)[1]. Recently, MIT Lincoln Laboratories, Boeing Spectrolab, and Boeing SVS have demonstrated Geiger-mode (GM) APD focal plane arrays (FPA) operating at 1.06 µm. However for longer wavelength sensitivity around 1.55 µm, GM-APDs have to be cooled to 180~240 K to achieve a usable DCR. Power consumption, package weight and size and APD PDE all suffer with this cooling requirement.

In this paper we report the development of an InP/InGaAs GM-APD structure with high PDE and low DCR at 273K. The photon collection efficiency was optimized with a single step-graded quaternary layer and a 3.5 µm InGaAs absorption layer, which provides a broadband coverage from 0.95 µm to 1.62 µm. The InP multiplication layer and the charge layer are carefully tailored to minimize the DCR and maximize the PDE. Despite having a low bandgap absorber layer InGaAs, these APDs demonstrated excellent dark current, optical responsivity, and superior DCR and PDE at 1.55 µm. The DCR and PDE were evaluated on 25 µm diameter APDs at 273 K. DCRs as low as 20 kHz have been measured at a 2 V overbias, while PDEs at 1.55 µm exceed 30% at 2 V overbias.

Keywords: Avalanche photodiode, Geiger Mode, Photon counting, LIDAR, Focal plane array, 3D imaging, photodetector.

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1. INTRODUCTION

Recent developments in three-dimension imaging, quantum cryptography, and time-resolved spectroscopy have stimulated interest in single-photon counting avalanche photodiodes (APD) in the short wavelength infrared. Geiger mode avalanche photodiode focal plane arrays for short wavelength infrared applications have been reported by both MIT Lincoln Laboratories[2] and Boeing. However, most of the effort to date has been focused on photodiodes operating at 1.06 µm where high power emitters are available. For quantum cryptography in fiber optic communications and the eye-safe wavelength in LIDAR applications, there is considerable interest in Geiger mode avalanche photodiodes (GM-APDs) operating at 1.55 µm. The best 1.55µm GM-APDs reported today have demonstrated DCR in the range of 10 kHz with usable PDE about 40%[3] at temperatures in the range of 200-220K, but a higher operating temperature is highly desirable for system power consumption, package weight and size. One important figure-of-merit for GM-APDs is DCR, which establishes a noise and false event rate floor for the entire sensor system. In order to improve the GM-APD performance at higher temperatures, we optimized the epitaxial growth, process, and device design for the Geiger-mode operation, and achieved an excellent DCR and PDE at 0^oC.

2. DEVICE STRUCTURE

The device structure follows the traditional separate absorption and charge multiplication (SACM) design: using InGaAs as the absorber for 1.55 µm and InP as the multiplication layer. In order to minimize the tunneling and avalanche multiplication in the narrow-band absorber, a low electric field is applied throughout this layer near the breakdown voltage to drift carriers in the proper direction. The multiplication layer is exposed to a high internal field which promotes the impact ionization of photo-carriers. A precisely controlled charge layer separates these two layers.

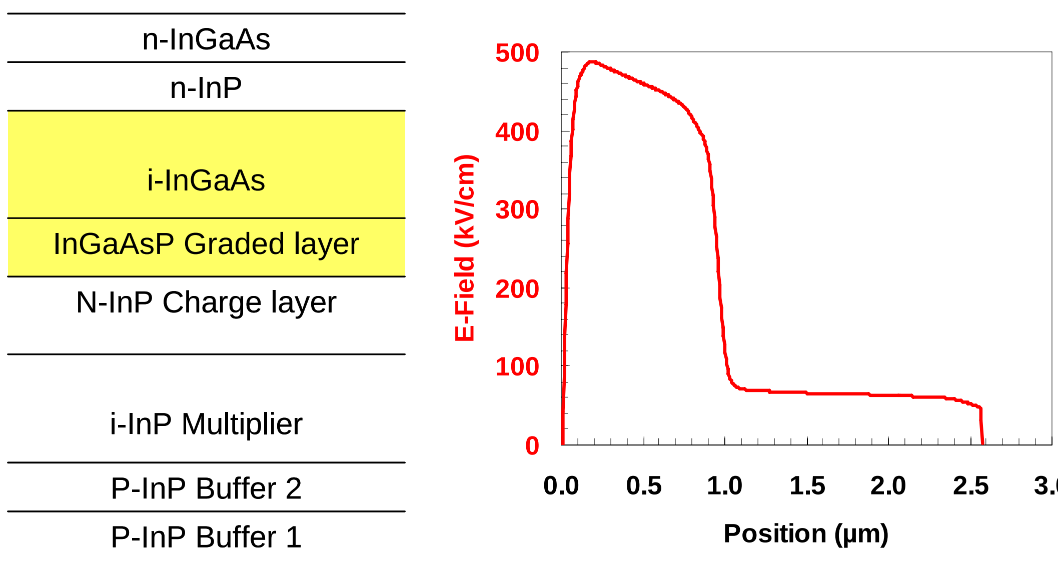

Figure 1 The cross section of the InP/InGaAs Geiger-Mode APD epitaxial stack and its typical electric field profile at operation. The position coordinate starts from the bottom p-i InP interface.

Figure 1 displays the InP/InGaAs APD cross section and the resultant electric field profile at the operating bias. The thin heavily doped InGaAs capping layer was grown for good ohmic contacts. Under this layer is an N-doped InP window layer, followed by an InGaAs absorber layer. The material quality and doping level of this narrow band material were closely monitored to minimize the thermal generation and avoid excess electric field and carrier traps. A thin InGaAsP quaternary layer (band gap ~ 0.96 eV) was incorporated as a transition layer to reduce the band discontinuity and carrier trapping between the InGaAs absorber and the InP charge and multiplication layers below.

The thickness and doping of the n-type charge layer were carefully controlled to create the electric field distribution between the multiplication region and the absorber so as to optimize the carrier collection and reduce the tunneling current in the absorber. Due to the charge layer, a high electric field is applied to the unintentionally doped InP, which serves as the multiplication layer. Below is a heavily doped p-type InP layer, followed by an InP buffer layer, also heavily doped.

3. GROWTH AND PROCESS

The APD structures were grown on two-inch n+ InP substrates in a multi-wafer MOVPE production reactor. Trimethylindium (TMIn), trimethylgallium (TMGa), arsine (AsH3) and phosphine (PH3) were used as sources for In, Ga, As, and P, respectively. Silicon and zinc were used as n- and p- type dopants, respectively. The growth parameters such as growth temperature, V/III ratio, and dopant concentration were optimized for the lattice-matched InP, InGaAsP, and InGaAs layers with the designed thicknesses and doping concentrations. The as-grown wafers were characterized by X-ray diffraction, Dektak, electrochemical-capacitance–voltage (ECV), photoluminescence, and SIMS techniques.

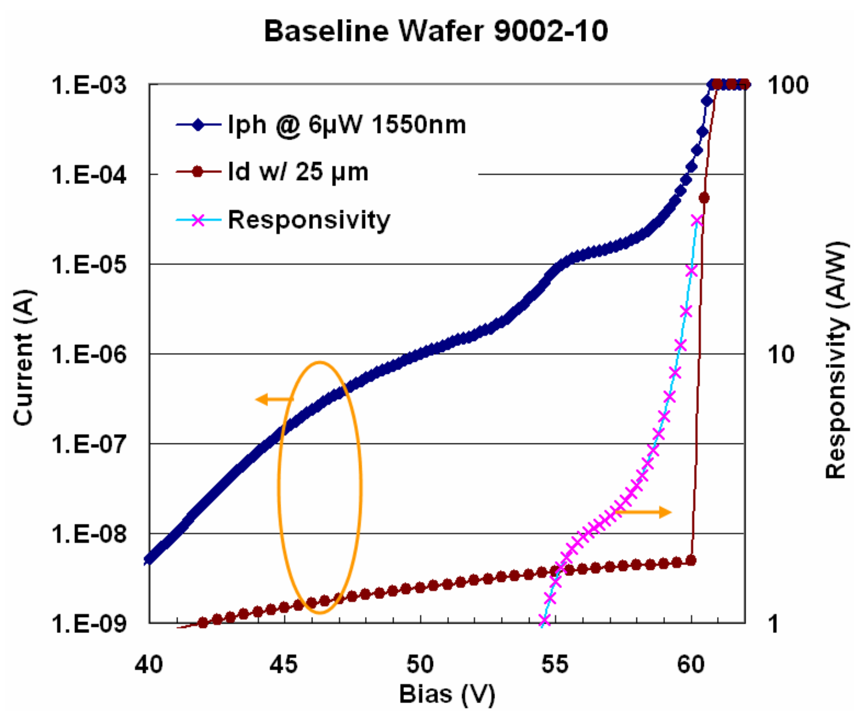

Figure 2 The DC current-voltage and responsivity-voltage characteristics of a Spectrolab 1.55 μm GM APD.

The device wafers were grown in large production MOVPE reactors that are also used to produce Spectrolab's high-efficiency multi-junction solar cells. The reactor is large enough to grow more than 40 2" substrates in a single run. Spectral efforts have been make to achieve the compositional and layer-thickness uniformity of better than +/- 2% over a single 2" wafer, which is an important parameter in the development of 32x32 or larger APD focal plane arrays. The charge layer doping uniformity is another important parameter to ensure a uniform performance across an array and between arrays.

A Bromine/Methanol solution was used to etch the device mesa. Polyimide and SiNx layers were deposited onto the sidewalls to cap and seal the devices. The typical Ti/Pt/Au and Au/Ge/Ni/Au metal stacks were deposited for p and n contacts, respectively. Backside processing was standard for making n type contacts. For the front-side illuminated devices, a more complex process sequence was needed for the front contact. Anti-reflection (AR) layers were typically single quarter wave stacks tuned to the desired wavelength.

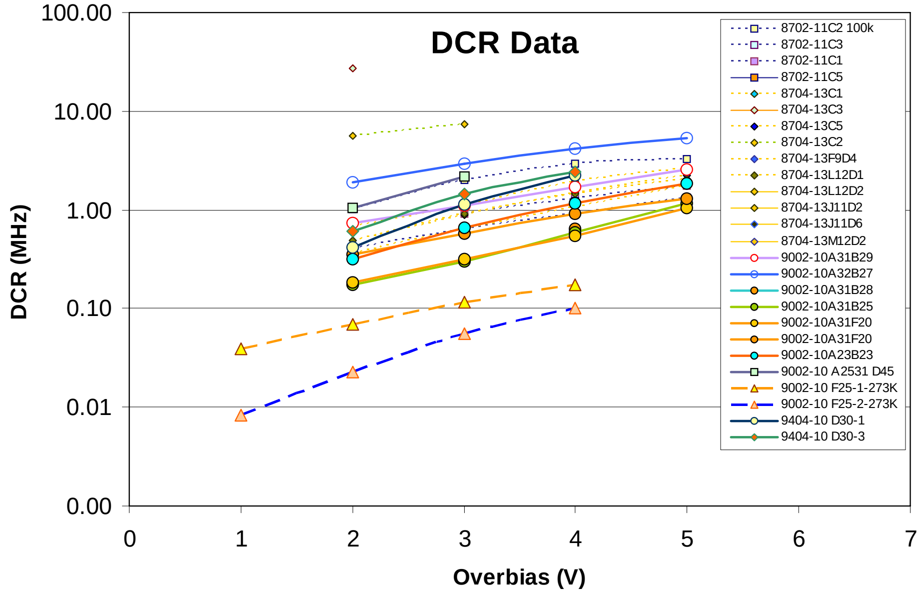

Figure 3 The DCR at room temperature and $0^{o}C$ versus overbias characteristics taken on two types of GM-APDs. The 8702 and 8704 APDs were InGaAsP/InP APDs optimized for 1.06 µm, and their curves are shown with dotted lines and smaller markers. The 9002 and 9404 series APDs are sensitive at 1.55 µm and yet display a very low DCR even at room temperature. They are illustrated with solid lines. The DCRs of the 9002 APDs at $0^{o}C$ are shown with dash lines.

4. RESULTS AND DISCUSSIONS

The dark current and photo response of the GM APDs were characterized with a computer-controlled Keithley 238 source meter. For simplicity and accuracy, the 1.55 µm laser beam in a single mode fiber was coupled through a lens and the AR coated surface of the front illuminated devices. Figure 2 illustrated the I-V curves of a 25-µm-diameter device measured at room temperature. The dark current stays below 10 nA before breakdown, which is essential for a low DCR. A clear punch-though can be observed in the photo response at about 55V, and above this bias the absorber is fully depleted, but it also provides a low field across the absorber even beyond breakdown. After normalized with the incident power, the responsivity curve shows some gain already at the punchthrough. An appreciable gain was measured before breakdown, and it implies a good PDE when the device is biased in the Geiger mode. In order to overcome some unintended doping in the absorber and keep a good PDE at low temperature, a reasonable separation before the punchthrough and breakdown has to be maintained.

In Geiger-mode operation, the APD is biased to just below the breakdown voltage, and an overbias pulse of a few volts is applied in a gate time of a few nanoseconds. The DCR performance of both 1.06 µm and 1.55 µm APDs fabricated at Spectrolab is shown in Figure 3. The device sizes are 30 µm for the 1.06 µm GM-APDs and 25 µm for the 1.55 µm APDs. Most of the 1.55 µm devices were measured at room temperature and their DCR-overbias curves are shown in solid lines. Compared with our previously developed GM-APDs for 1.06 µm shown in the dotted lines in the background, they demonstrated a significantly lower DCR even with a narrower-band absorber. As the temperature is reduced to 0^{o}C, the DCR of the 1.55 µm APDs decreases by about one decade and appears in the range of 10~100 KHz.

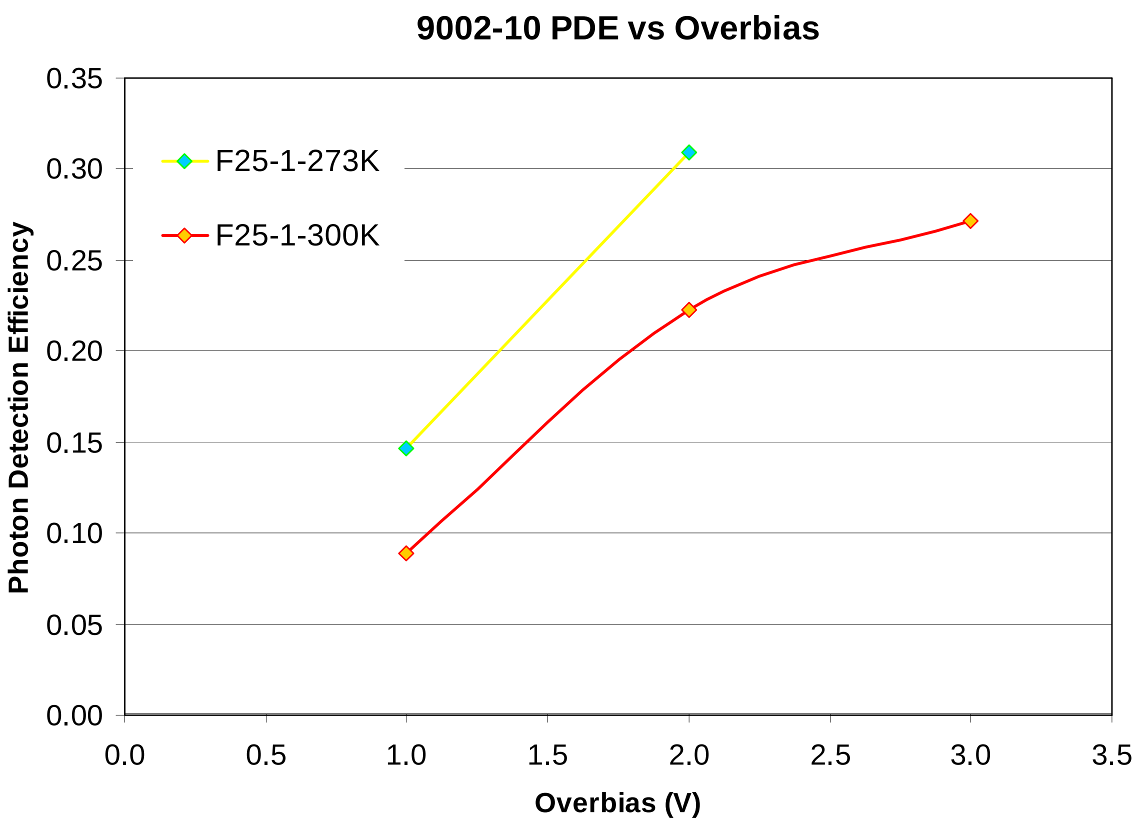

Figure 4 The PDE vs overbias at room temperature and 0^{o}C versus overbias. The PDE was measured at 1.55 µm.

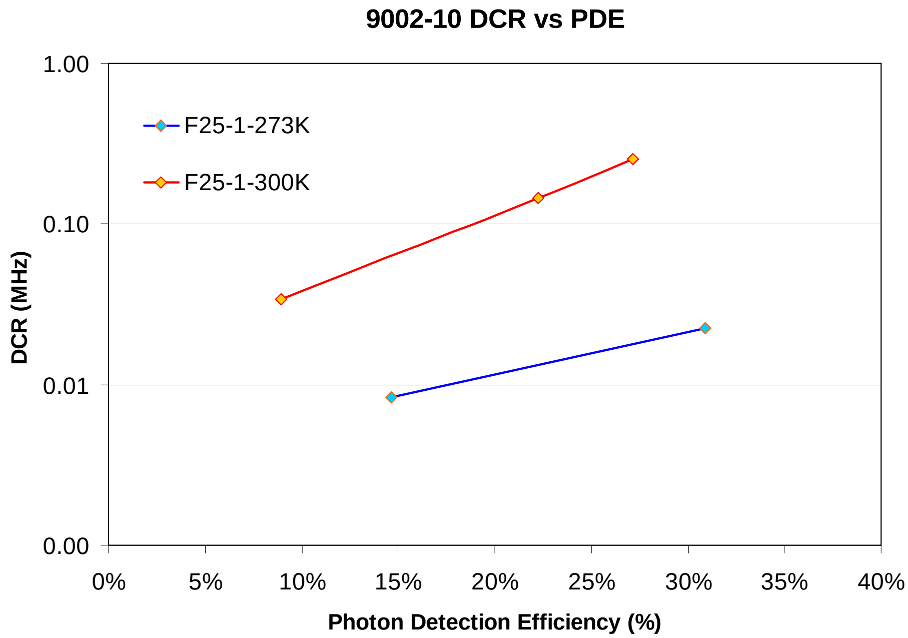

Figure 5 The PDE vs DCR at room temperature and $0^{o}C$ versus overbias. The PDE was measured at 1.55 µm.

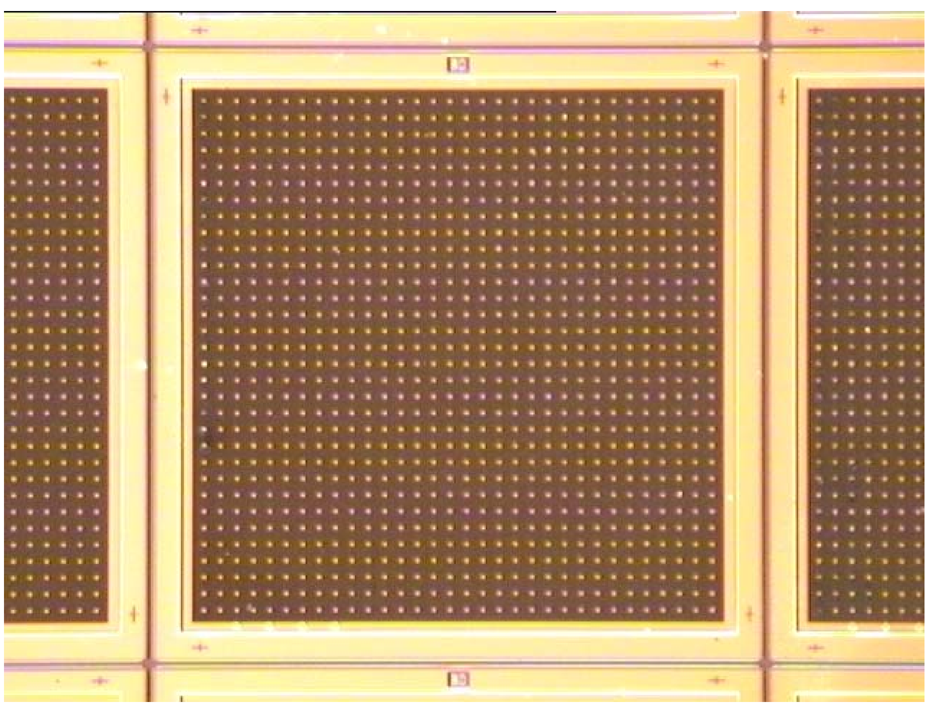

Figure 6 The fabricated 32x32 GM-APD arrays.

As is well known[4], both DCR and PDE decrease with overbias and temperature. For the best trade-off of the operation conditions for the GM-APDs, the photon detection efficiency (PDE) were measured as a function of overbias and plotted versus DCR as shown in Figures 4 and 5. The PDE data were measured with 1.55 µm laser pulses shorter than 1 nanosecond, and the overbias gate pulses were carefully synchronized with these laser pulses. 9002 series 1.55 µm GM-APDs demonstrated an efficiency greater than 30% with a DCR of about 20 kHz at 0^{o}C.

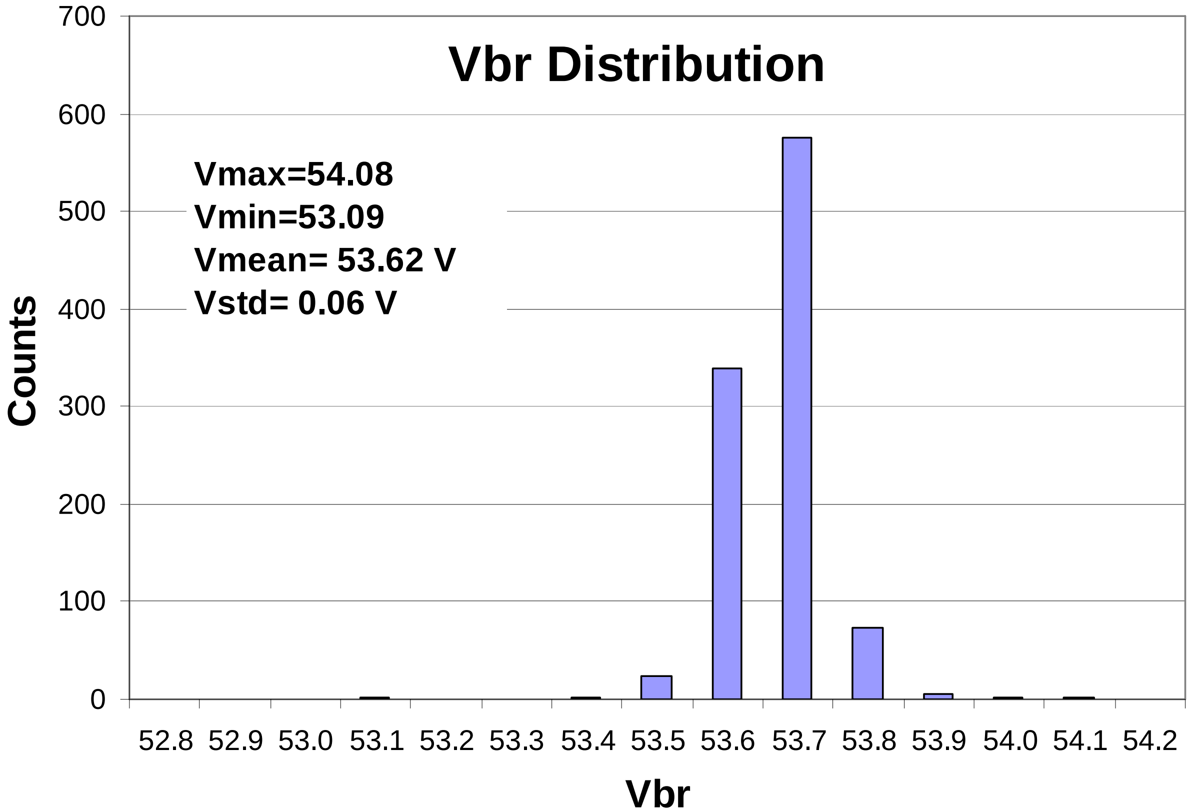

Figure 7 The histogram of the breakdown voltage of a 32x32 1.55 µm GM-APD at room temperature.

For the LADAR applications, 32x32 element 1.55 µm GM-APD arrays were fabricated at Spectrolab. Figure 6 shows a picture of finished 32x32 GM-APD arrays. The device mesa size is 25 µm with back-illuminated scheme, and the pixel pitch is 100 µm. Due to the efforts mentioned in the growth and process section, excellent device uniformity and yield were achieved in these arrays. The breakdown voltage and dark current just before breakdown were measured for each pixel. Figure 7 illustrates the tight distribution of the breakdown voltages among the 1024 devices in an array. With a span of 1V, the standard deviation is just 0.06 V, which ensures very uniform performance among the pixels under a single bias. The histogram of the dark current of the same array is shown in Figure 8. In the same narrow distribution, the dark current of each pixel is about 3 nA within a span of 2 nA.

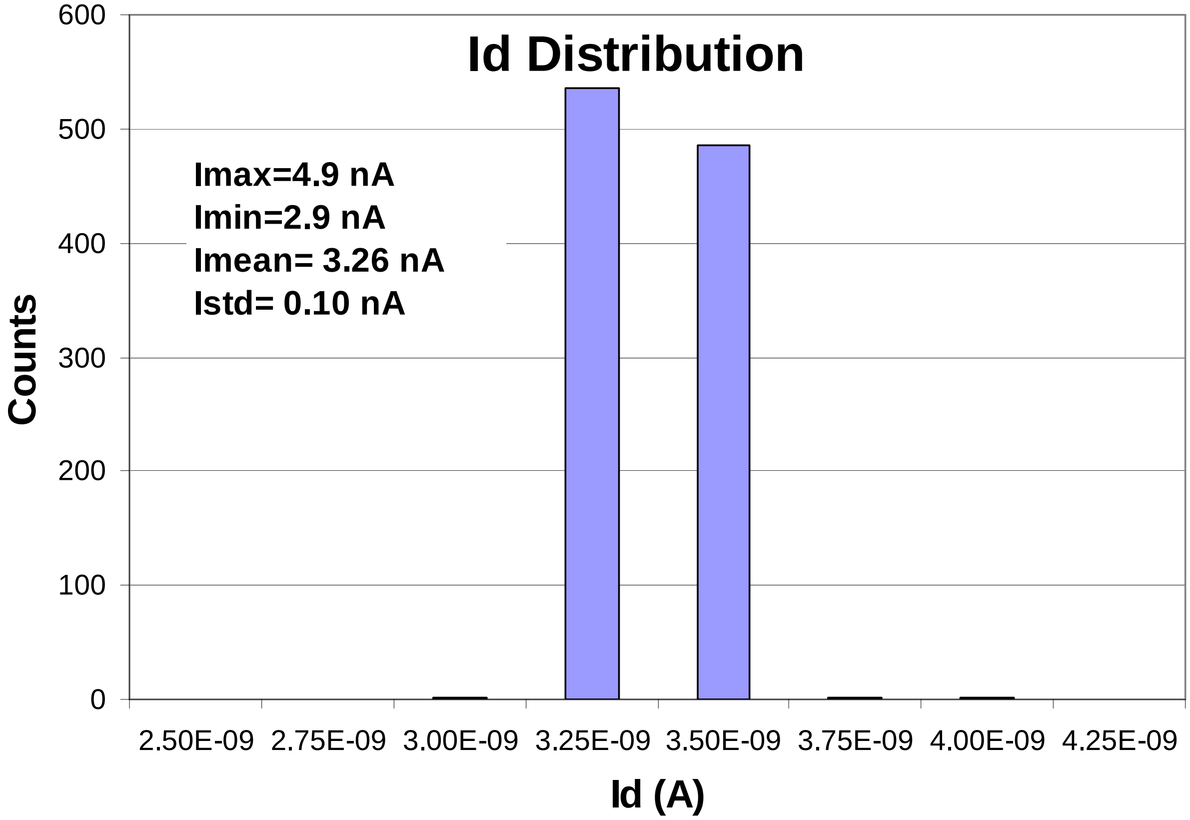

Figure 8 The histogram of the dark current before breakdown of a 32x32 1.55 μm GM-APD at room temperature.

5. CONCLUSIONS

1.55 μm GM-APD devices and arrays have been fabricated and characterized. Excellent DCR, PDE, and array uniformity have been achieved at room temperature and $0^{o}C$. Further improvement in the device stability and characterization are planned for the first quarter of 2008.

6. REFERENCE

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