GHz low noise short wavelength infrared (SWIR) photoreceivers

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ABSTRACT

Next generation LIDAR mapping systems require multiple channels of sensitive photoreceivers that operate in the wavelength region of 1.06 to 1.55 microns, with GHz bandwidth and sensitivity less than 300 fW/√Hz. Spectrolab has been developing high sensitivity photoreceivers using InAlAs impact ionization engineering (I^2E) avalanche photodiodes (APDs) structures for this application. APD structures were grown using metal organic vapor epitaxy (MOVPE) and mesa devices were fabricated using these structures. We have achieved low excess noise at high gain in these APD devices; an impact ionization parameter, k, of about 0.15 has been achieved at gains >20 using InAlAs/InGaAlAs as a multiplier layer. Electrical characterization data of these devices show dark current less than 2 nA at a gain of 20 at room temperature; and capacitance of 0.4 pF for a typical 75 micron diameter APD. Photoreceivers were built by integrating I^2E APDs with a low noise GHz transimpedance amplifier (TIA). The photoreceivers showed a bandwidth of 1 GHz and a noise equivalent power (NEP) of 150 fW/rt(Hz) at room temperature.

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

Silicon APD-based photoreceivers are widely used in NASA missions. Silicon APDs exhibit low excess noise factors, and low dark current. The state of art Si photoreceivers have an NEP of 40~50 fW/rt(Hz) over a bandwidth of 140 MHz [1]. Future NASA LIDAR missions require high bandwidth and low noise photoreceivers operating in the 1 – 1.6 µm wavelength region. Silicon photoreceivers do not meet these requirements since silicon photoreceivers have poor quantum efficiency for wavelengths greater than 1.1 µm and have low bandwidth, typically less than 500 MHz. At 1.06 µm, a very thick absorber (several tens of microns) is necessary to achieve reasonable absorption for these photoreceivers. The thick absorber thus limits the silicon APD bandwidth. On the other hand, III-V compound semiconductor-based APDs, like InGaAs APDs, show high quantum efficiency in the 1 to 1.6 µm wavelength region and a fast response [2]; bandwidths greater than several GHz are commonly achieved with these APDs. However, present InGaAs APDs have an NEP higher than 500 fW/√Hz due to the use of a relatively high excess noise InP multiplication layer.

2. LOW EXCESS NOISE APDS

APDs convert light signals into electrical signals with a gain from an avalanche process. Both photo-generated holes and electrons initiate avalanche processes. The excess noise is characterized by $k=\alpha/\beta$ or β/α ($k<1$ always), where α and β are electron and hole ionization coefficients. The APD excess noise and response speed (gain bandwidth product) are determined by the k value. For low noise and high speed applications, a small k value is critical. Common semiconductor material excess noise factors are summarized in Figure 1.

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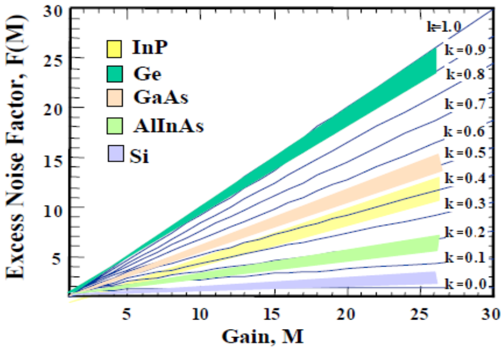


Noise power spectral density: $S = 2qI_o M^2 F(M) R(\omega)$

Excess noise factor: $F(M) = kM + (1-k)(2 - \frac{1}{M})$

Figure 1. Excess noise factors for commonly used semiconductor materials.

There are several approaches to reduce the k value in InGaAs APDs [3]. Spectrolab has been developing InGaAs APDs with InAlAs material as a multiplication layer. InAlAs has a lower k value (0.22) [2] than commonly used InP (0.5). The k-value can be further reduced by engineering the impact ionization region. These structures are called I^2E structures. In these approaches, the multiplier layers of the APD consist of two different semiconductors with different ionization threshold energies. The probability of avalanche events is higher in the semiconductor with lower ionization threshold energy. This preference translates into low noise because the avalanche events become less random. A k value of 0.1 has been demonstrated [4] in InAlAs I^2E.

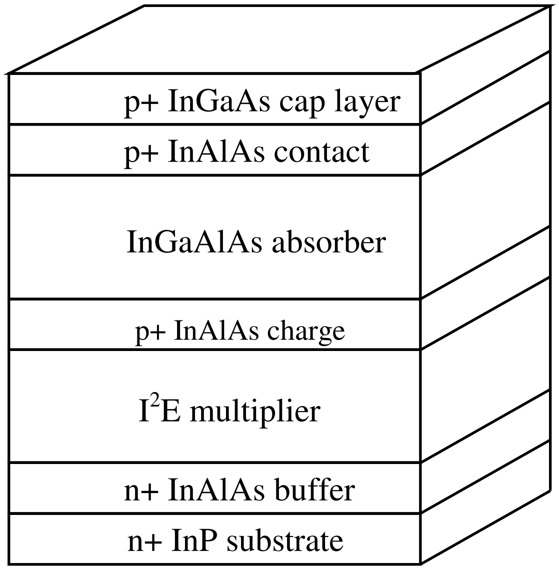


Figure 2. Spectrolab I^2E APD structure.

Figure 2 shows our I^2E APD design. The I^2E multiplier consists of InGaAlAs and InAlAs layers. A 100 nm InGaAlAs layer with a bandgap of approximately 1.2 eV was inserted into the conventional InAlAs multiplier. The absorber is an

InGaAlAs alloy with a bandgap of 1.05 eV for a 1.06 µm laser applications. The wafers are grown in an MOVPE reactor on 3 inch n+ doped InP substrate. All the layers are lattice matched with the InP substrate.

After growth, mesa devices were fabricated by photolithography and wet etching. Contacts were deposited on top of the mesa and the substrate. Current-voltage characteristics indicate very low dark currents and good optical gain. The excess noise factors of the I^2E APDs were determined from measurements made at the University of Virginia with an HP8970B noise figure meter. A UV Argon ion laser with wavelength 351/363 nm was used to illuminate the APDs from the top surface. The UV laser ensures pure electron injection into the multiplier and the measurement details were described in a previous publication [5].

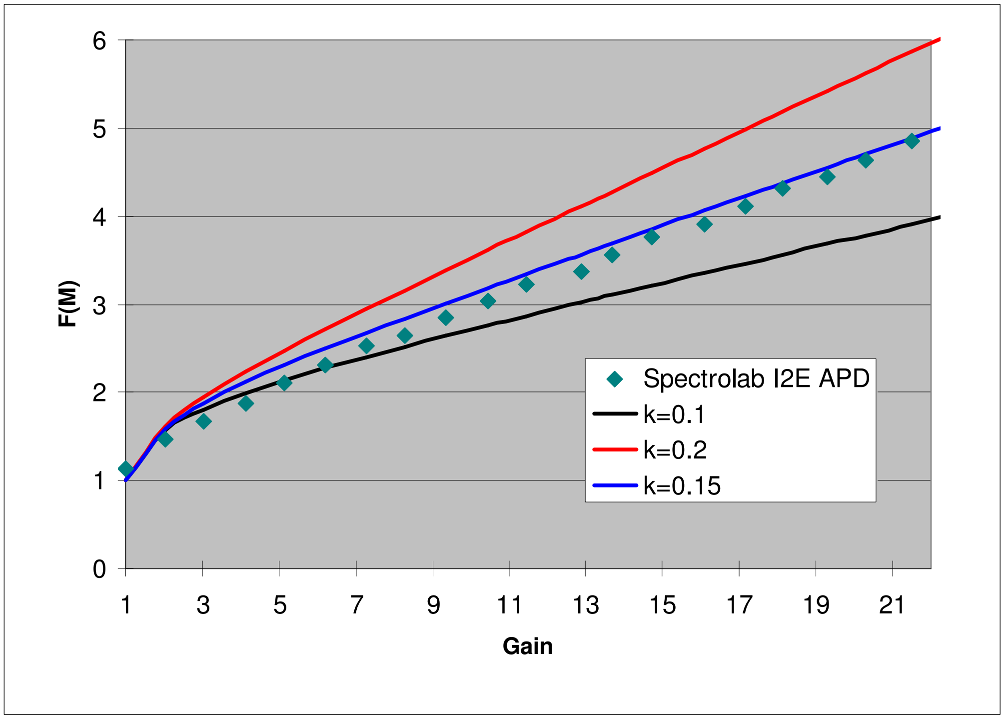


Figure 3. Excess noise data of I^2E APD devices.

Excess noise values were measured on I^2E APDs and the data are shown in figure 3. The solid lines correspond to k values of 0.1, 0.15, and 0.2. The Spectrolab I^2E APD shows a k value of less than 0.1 at a low gain regime due to the dead space effect[4]. In the high gain regime, the k value tends to fall on a value of 0.15, which is considerably lower than measured on InP (0.5) and the bulk InAlAs (0.22). One advantage of the I^2E method is that it does not rely on the dead space effect, which could yield a low k value with a multiplier less than 0.1 µm thick. These thin multiplier APDs tend to suffer from high tunneling dark current that is a source of increased noise. Also, it is difficult to grow uniform thin multiplier APD arrays. The Spectrolab I^2E APDs have a much thicker multiplier, resulting in very low dark current and good uniformity.

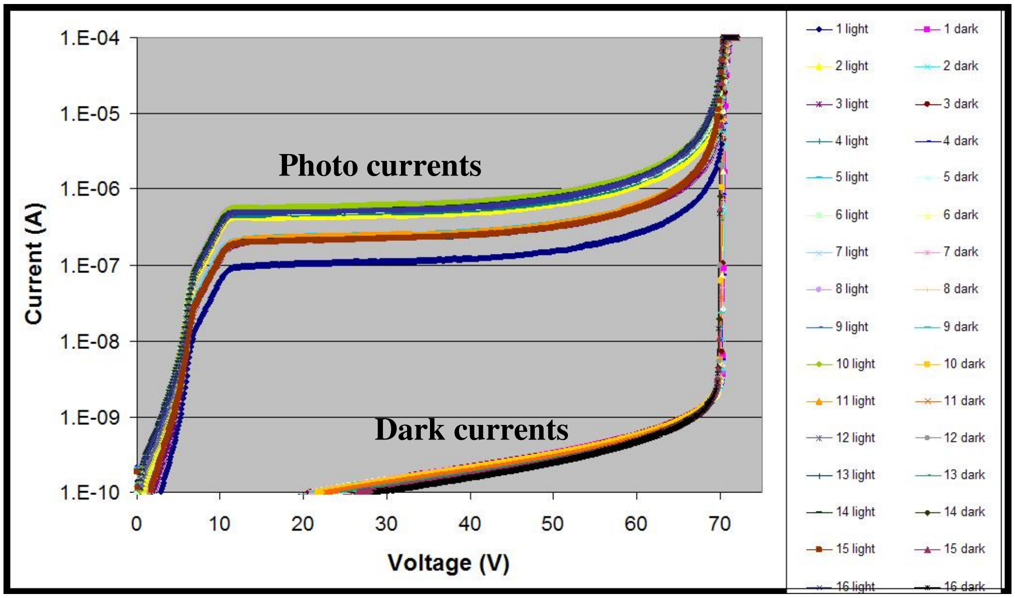


Figure 4. Spectrolab I^2E APD array current-voltage characteristics.

One dimensional APD arrays were fabricated to characterize the wafer uniformity. The arrays had a pitch of 250 µm and each individual APD had a mesa diameter of 75 µm. Figure 4 shows the dark current-voltage characteristics of one dimensional APD arrays; the dark current-voltage characteristic over the array is uniform. For 16 APDs, with a span of 4 mm, the breakdown voltage variation was less than 200 mV across the array. The variations on the photo current were the result of different incident light power on each APD during the measurement. The APDs showed low dark currents; at a gain of 10 the average dark current of the APD array was 1.34 nA with a standard deviation of 0.034 nA. Devices also demonstrated high optical gains over 50 with no premature breakdown.

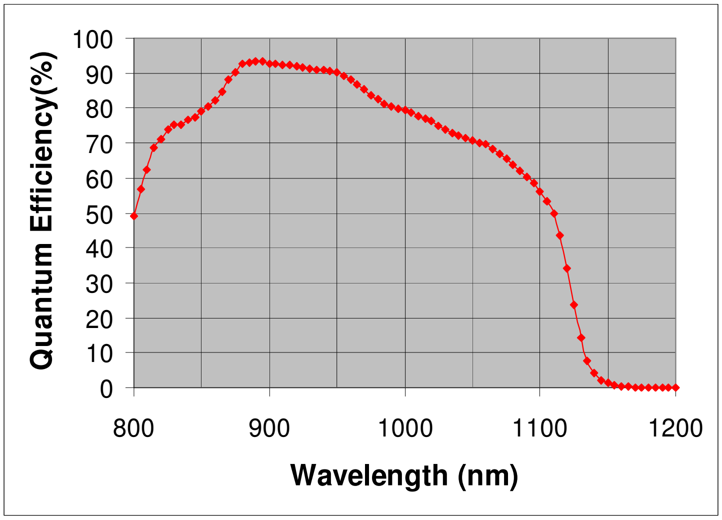


Figure 5. Quantum efficiency of a front-illuminated I^2E APD device.

Figure 5 shows the quantum efficiency of an I^2E APD device with the device illuminated from the front side. The APD bias voltage was 20 V which corresponds to an optical gain of unity. At 1.06 µm, the quantum efficiency is 70% and the quantum efficiency can be further improved by depositing a gold metal layer reflector on the backside of APDs. We estimate the quantum efficiency will increase to about 85% at 1.06 µm with the incorporation of this reflector.

In summary, Spectrolab developed low k (0.15) APDs using an InAlAs based I^2E multiplication layer. APD capacitance, another important parameter for low noise and high speed operaton, was less than 0.4 pF for a 75 μm APD. Combined with very low dark current and high quantum efficiency, these I^2E APDs can be assembled into very sensitive photoreceivers.

3. LOW NOISE GHZ PHOTORECEIVER

We designed and built a photoreceiver using a low noise I^2E APD device and a MAXIM low-noise transimpedance amplifier (TIA). The TIA has a noise current density of 6.6 pA/rt(Hz) over a bandwidth of 920 MHz. The I^2E APD was a front illuminated device with a mesa diameter of 75 μm. The details of the photoreceiver circuit were discussed in a previous publication [6]. The APD and TIA die were mounted on a 5 pin TO-46 header. The five pins correspond to ground, APD bias, TIA bias, and a differential output pair. A test board was built to test the operational characteristics of the photoreceiver. A photoreceiver mounted on a test board is shown in Figure 6. The differential outputs are AC coupled and are terminated with 50 Ω in test.

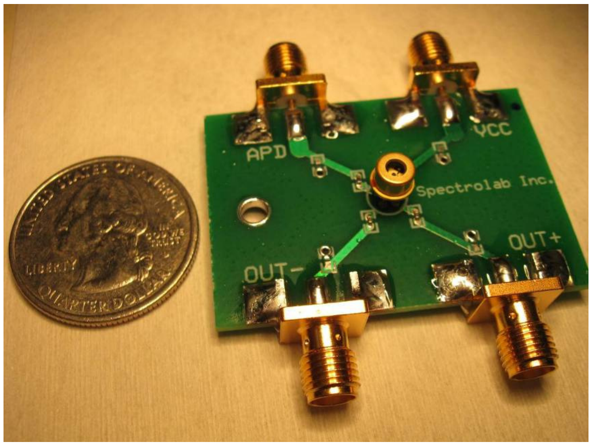


Figure 6. Picture of an I^2E photoreceiver on a test board.

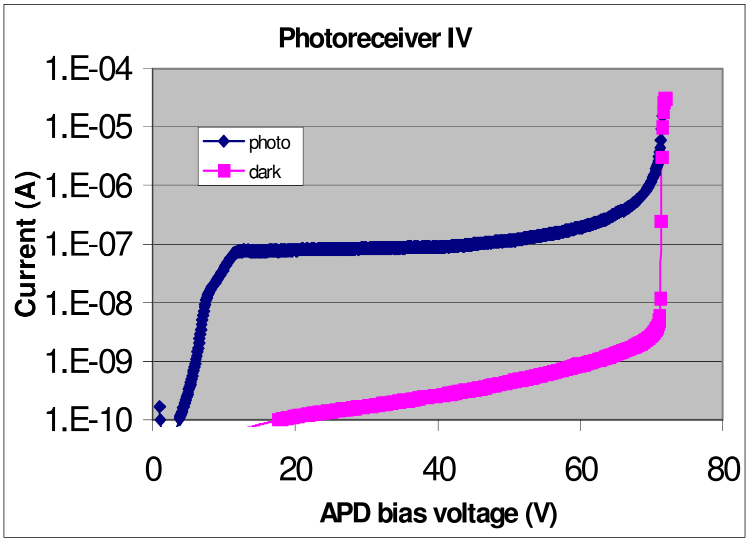
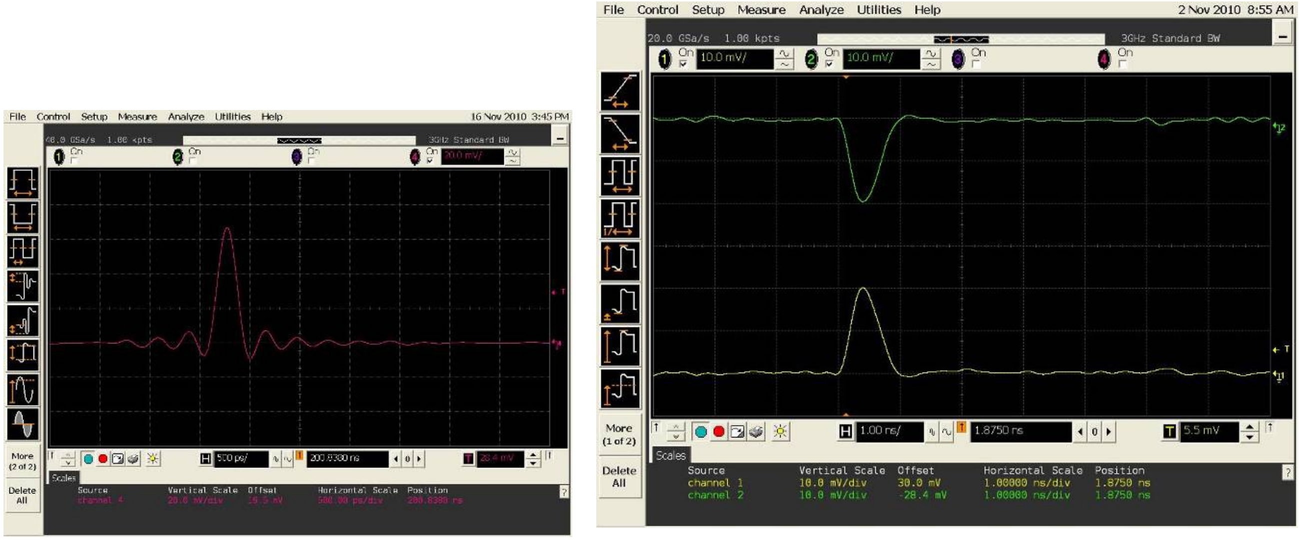


Figure 7. Current-voltage characteristics of an I^2E photoreceiver.

Figure 7 shows the APD current voltage characteristics of this I^{2}E photoreceiver. The data are very similar to the single APD die results; an optical gain over 50 before the APD breakdown. The bandwidth of the photoreceiver was measured using a 1.06 µm pulsed laser with a pulse width approximately 200 ps width the APD was biased to gain of 25. The photoreceiver outputs were fed into a high speed oscilloscope and the output pulses had a width well below 1 ns. The differential outputs were AC coupled. Figure 8 shows the output pulses from the photoreceiver. Based on these measurements the bandwidth of the photoreceiver was estimated to be about 900 MHz, which is consistent with the TIA bandwidth. Thus the TIA is the bandwidth limiting component in the photoreceiver.



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Source       Vertical Scale  Offset    Horizontal Scale  Position
channel 4    20.0 mV/div     19.5 mV   500.00 ps/div     200.8380 ns
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Source       Vertical Scale  Offset    Horizontal Scale  Position
channel 1    10.0 mV/div     30.0 mV   1.00000 ns/div    1.8750 ns
channel 2    10.0 mV/div     -28.4 mV  1.00000 ns/div    1.8750 ns
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Figure 8. I^{2}E photoreceiver response to a pulsed input laser beam.

Left: input laser pulse measured with a high speed PIN detector, Right: I^{2}E photoreceiver differential outputs

The photoreceiver was further tested at NASA Goddard Space Flight Center. The bandwidth about 900 MHz was confirmed at this facility using similar measurement techniques. The NASA measurement employed a laser pulse with a width of 98 ps. The measured photoreceiver outputs have a rise time of about 200 ps. The FWHM of the TIA output pulse is about 600 ps.

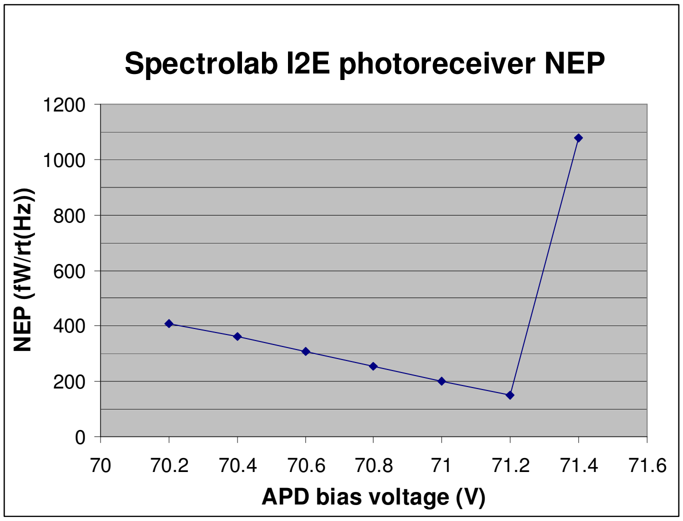

Figure 9. Noise equivalent power data of an I^{2}E photoreceiver.

The NEP of the photoreceiver as a function of the APD bias voltage was measured at NASA Goddard Space Flight Center. The testing procedures have been discussed in a previous publication [1]. The NEP data of an I^2E photoreceiver is shown in Figure 9. Initially the NEP decreases with increasing APD bias because when the APD gain is low, the TIA noise is much higher than the APD excess noise. By increasing the APD bias voltage (APD optical gain), the signal to noise ratio increases. At some point a further increase in APD bias raises the APD noise contribution above the TIA noise. Hence there is an optimum bias voltage where the NEP will have a minimum value. The Spectrolab I^2E photoreceiver's NEP has a minimum value of 150 fW/rt(Hz) at a bias voltage of 71.2 Volts. To the best of our knowledge, this is the lowest NEP achieved at 1GHz for a III-V compound based photoreceiver.

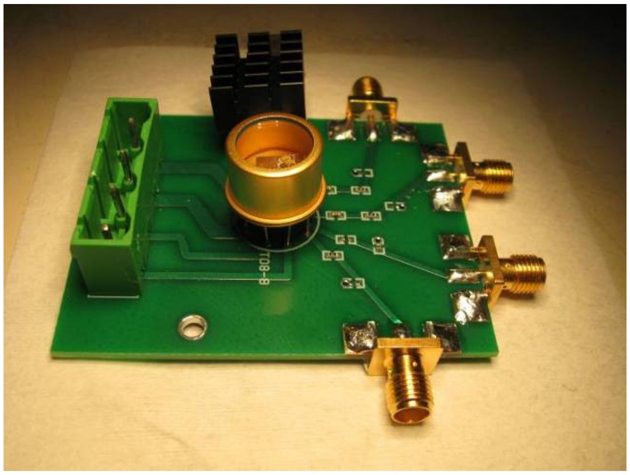

Figure 10. Spectrolab I^2E photoreceiver with built-in thermal electric cooler.

To further reduce the NEP, an I^2E photoreceiver was built with a thermal electric cooler (TEC). The TEC and photoreceiver were integrated packaged in a TO-8 header. The photoreceiver, mounted on a test board, is shown in Figure 10.

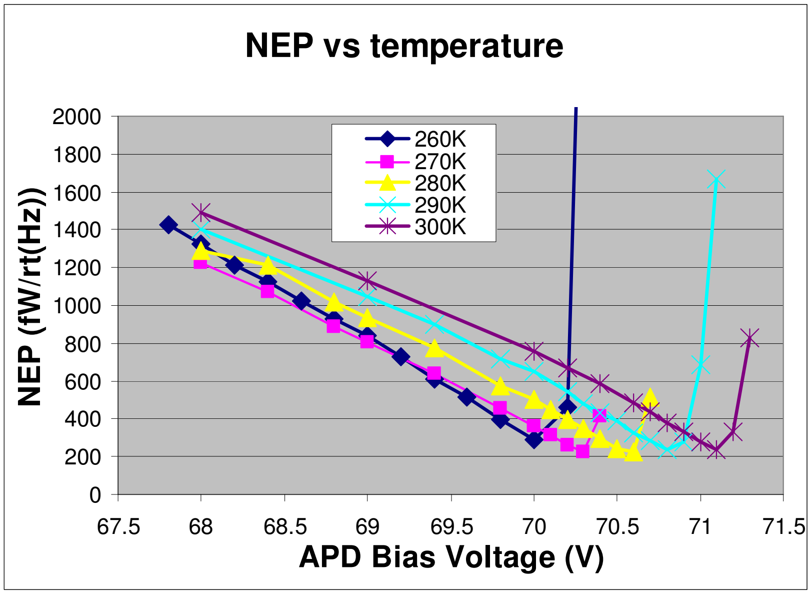

Figure 11. NEP versus temperature data of I^2E photoreceiver.

The I^2E photoreceiver NEP versus APD bias characteristic was measured at several different temperatures and the data are shown in figure 11. The bias voltages corresponding to the minimum NEP decreased as the temperature was lowered. Also, at lower temperatures, the dark current was reduced too. However, the minimum NEP does not change appreciably at different operating temperatures. The reason could be that the TIA noise dominates the photoreceiver noise performance. So as long as the TIA noise current does not change much with temperature, the minimum photoreceiver NEP will not display a significant temperature dependence.

4. SUMMARY

Spectrolab has developed a low noise InGaAlAs APD operating at 1.06 micron wavelength by impact ionization engineering design of the InAlAs multiplication layer. The effective k value achieved was about 0.15. One dimensional arrays were fabricated and characterized and good dark current uniformity across the array was achieved. A 1 GHz photoreceiver was built by integrating the low noise I^2E APD and a GHz TIA. The photoreceiver showed a NEP of 150 fW/rt(Hz) over a bandwidth of 900 MHz at room temperature and this is the lowest reported 1.06 micros photoreceiver NEP to date.

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