Ultra Low Dark Current InGaAs Technology for Focal Plane Arrays for Low-Light Level Visible-Shortwave Infrared Imaging

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ABSTRACT

Under the DARPA Photon Counting Arrays (PCAR) program we have investigated technologies to reduce the overall noise level in InGaAs based imagers for identifying a man at 100m under low-light level imaging conditions. We report the results of our experiments comprising of 15 InGaAs wafers that were utilized to investigate lowering dark current in photodiode arrays. As a result of these experiments, we have achieved an ultra low dark current of 2nA/cm^2 through technological advances in InGaAs detector design, epitaxial growth, and processing at a temperature of +12.3°C. The InGaAs photodiode array was hybridized to a low noise readout integrated circuit, also developed under this program. The focal plane array (FPA) achieves very high sensitivity in the shortwave infrared bands in addition to the visible response added via substrate removal process post hybridization. Based on our current room-temperature stabilized SWIR camera platform, these imagers enable a full day-night imaging capability and are responsive to currently fielded covert laser designators, illuminators, and rangefinders. In addition, improved haze penetration in the SWIR compared to the visible provides enhanced clarity in the imagery of a scene. In this paper we show the results of our dark current studies as well as FPA characterization of the camera built under this program.

Keywords: InGaAs, dark current, Shortwave infrared, imaging, focal plane array, FPA.

1. INTRODUCTION

We present the results of the first phase of the DARPA Photon Counting Arrays (PCAR) program aimed at enhancing current night vision capability. InGaAs based image sensors which detect in the shortwave infrared (SWIR) (0.9 μm to 1.7 μm wavelengths) are better matched to the nightglow spectrum[1] than Si or GaAs based imagers. Our calculations show that identification of man (friend or foe determination) from 100m under low light level conditions can be achieved through lower dark current, large imager format, smaller detector pitch, and lower readout noise. The noise of SWIR imagers can be reduced by decreasing the dark current of InGaAs photodiode arrays and by designing extremely low noise read out integrated circuits (ROICs).

During Phase I of the program, we have developed a 640x512 (20 μm pitch) focal plane array (FPA) with extremely low noise. The readout integrated circuit was designed to exhibit read out noise less than 10 e^- rms, and the photodiode array dark current density to be less than 2 nA/cm^2. With the capability of InP substrate removal, the InGaAs FPA has sensitivity from 400 nm to 1700 nm and can detect all laser sources and designators in the SWIR, near infrared, as well as the visible wavelength range. In Phase II, we will design and deliver a camera with a 1280x1024 InGaAs FPA on a 15 μm pitch with extremely low noise. This high resolution, low noise camera will permit man identification from 100m under low light level imaging conditions.

Based upon the match of the visible-SWIR InGaAs absorption spectrum to the night sky spectrum, we had conducted detailed modeling[2] using a noise limited resolution analysis. The analysis reported previously illustrated the results of utilizing different cutoff wavelengths for InGaAsP based absorption regions with 1280 x 1024 format, 15 μm pitch FPAs with 10e- read out noise. The dark current density of 2nA/cm^2 was used for lattice matched InGaAs (1.7 μm cutoff wavelength), and the dark current was scaled for the InGaAsP alloys based on their cut off wavelengths as a function of exp(-Eg/2kT) (Eg is the band gap in eV). Extended wavelength InGaAs with cutoff wavelengths of 1.86 μm and 1.93 μm were also considered in the calculations. Out of the different InGaAsP based materials, it was reported that

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lattice matched InGaAs provided the highest noise limited resolution capability in man identification 100 m with less than 2 mlux scene illumination. This outperforms an Omni V imager that can identify a man at 100 m at 20 mLux scene illumination.

As illustrated in Figure 1, an InGaAs 640 x 512 focal plane array developed under Phase I with a 20 µm pitch exhibiting a read out noise of 10 e- is capable of *recognizing* a man from 100 m at 0.5 mlux. This assumes that the PDA exhibits a dark current density of 2nA/cm^2. However, due to limited resolution of the imager it is not possible to identify the object even under full moon scene illumination. Achieving the 100 m man identification goal requires a larger format imager, as proposed for Phase II of the PCAR program, a 1280 x 1024 format on a 15 µm pitch array. This imager will be able to recognize *and* identify a man from 100 m with 0.3 mlux and 1 mlux scene illumination respectively as shown in Figure 1. The Omni V image intensified CCD (I^{2}CCD) by comparison requires more than 1 mlux scene illumination for recognition and 20 mlux for identification.

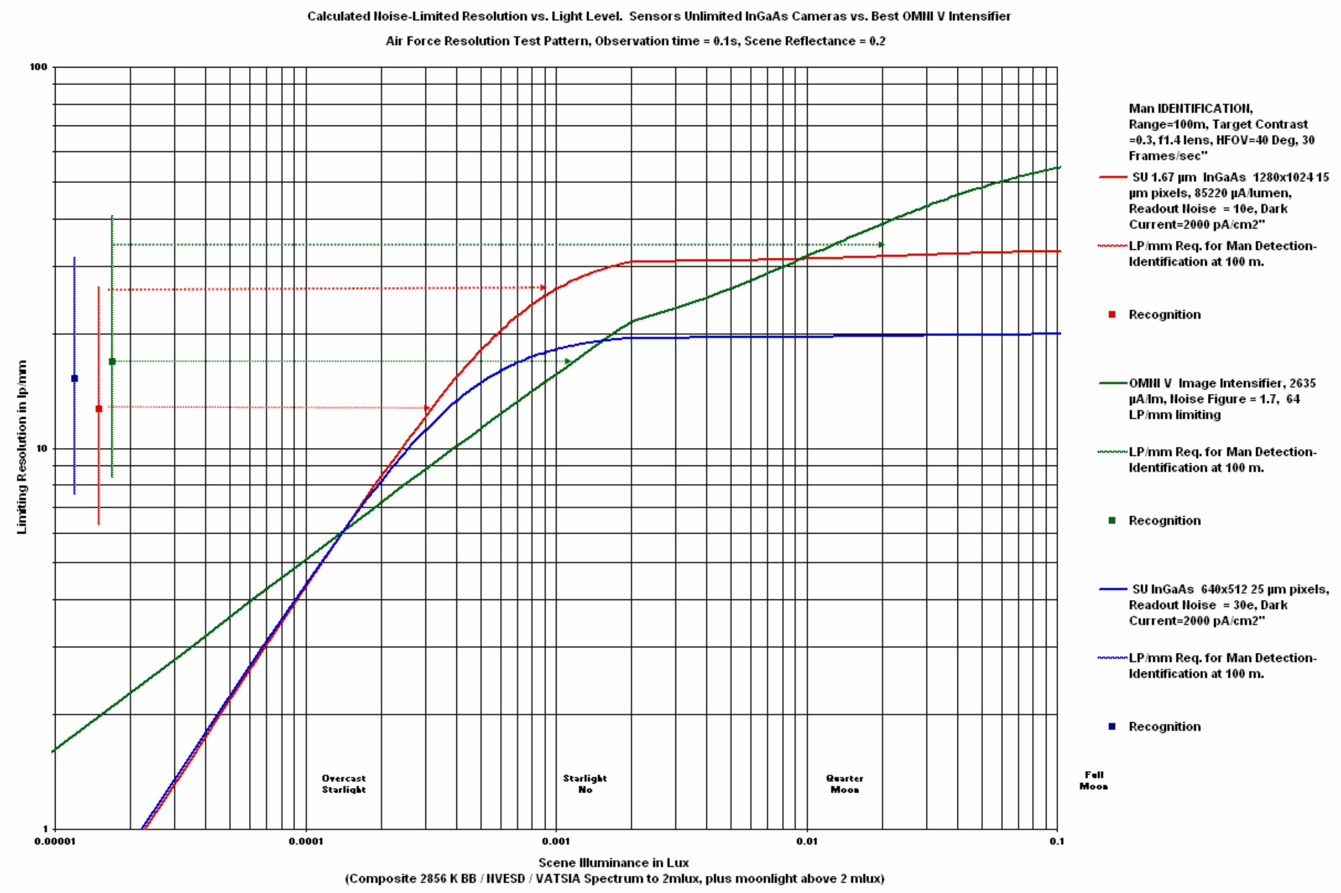

Figure 1. Modeled performance of a Visible-SWIR InGaAs Photodiode array 1280 x 1024on a 15 um pitch, Visible-SWIR InGaAs Photodiode array 640 x 512 on a 20 um pitch compared to an OMNI V imager

Under Phase I of the PCAR program, SUI has achieved the read out noise goal of 10 e$^-$ rms and these results will be reported separately[3]. In this paper we report the dark current density reduction that has accomplished 2 nA/cm^2 at a temperature of 12.3^{o}C. Currently, imagers that are used in SUI's commercial cameras, which employ the industry's lowest dark current InGaAs photodiode arrays, achieve the dark current density of 2 nA/cm^2 at a temperature of 0^{o}C.

2. REDUCTION IN DARK CURRENT

The impact of the dark current reduction on SWIR imaging is two fold: 1) In commercial cameras, such that the InGaAs FPA is room temperature stabilized via a thermoelectric cooler (TEC), the imaging system will benefit from higher sensitivity, due to the noise reduction. 2) In applications such as man portable systems where high sensitivity, low power operation may be desirable, the same dark current can be achieved at a higher TEC set temperature (e.g. such as 12.3°C vs. 0°C). Therefore the TEC will consume less power at high ambient temperatures while maintaining identical sensitivity. Figure 2 depicts the TEC power consumption as a function of set temperature at an ambient temperature of 25°C. Setting the temperature of the FPA to 12.3°C as opposed to 0°C reduces system power dissipation by approximately 1.5 Watts.

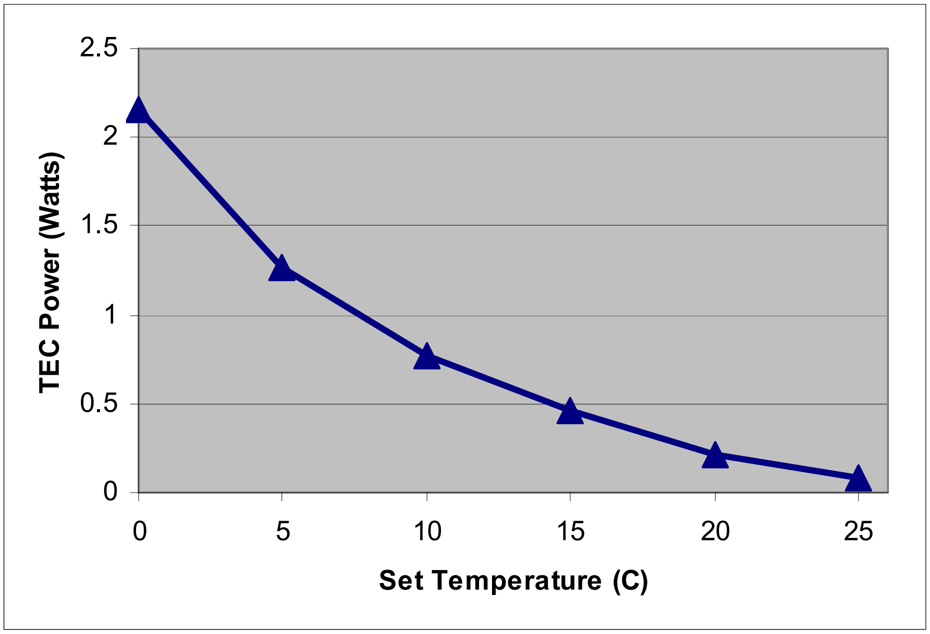

Figure 2. TEC power consumption for a 640 x 512 PDA as a function of set temperature at an ambient temperature of 25°C.

In the operating conditions of our photodiodes (TEC temperature stabilized, V < 300mV), the dark current is made up of a diffusion component, due to thermal generation in the n and p regions, and a generation-recombination component, the result of carrier generation inside the depletion region. The reverse saturation current due to the diffusion term is given by[4]:

$$I_s = qn_i^2 \frac{\pi}{\tau_d^{1/2}} \left(\frac{D_n^{1/2}}{N_A}\left(\frac{d^2}{4}\right) + \frac{D_p^{1/2}}{N_D}\left(\frac{d^2}{4}\right) + \frac{D_p^{1/2}}{N_D}(Wd) \right)$$

where n_i is the intrinsic carrier concentration; D_n, D_p are the carrier diffusion constants; N_A, N_D are the acceptor and donor concentrations; W is the depletion width; d is the detector diameter; and τ_d is the minority carrier diffusion lifetime. The generation recombination term is given by[3]:

$$I_{gr} = qn_i \frac{A \cdot W}{\tau_{eff}} \left(e^{(qV/2kt)} - 1 \right)$$

where A is the detector area and τ_{eff} is the effective carrier lifetime. For an abrupt p-n junction, the depletion width

W is proportional to the square root of the applied voltage, and inversely proportional to the square root of the donor concentration (in a p+-n device).

The two equations above highlight factors that we exploited to minimize the dark current of our photodiode arrays. Both the diffusion and generation recombination terms are reduced by moving to a smaller pixel, finer pitch device. The optimization of the InGaAs absorption layer thickness also plays a role, wherein reducing its thickness reduces the diffusion component in the n region at the expense of quantum efficiency. The volume effect of both the diffusion and generation-recombination terms can be traded against the modest reduction in quantum efficiency through the reduction in absorption layer thickness from 3.5 µm to 2.0 µm.

We utilize a novel technique to add visible response to shortwave-infrared wavelength response of InGaAs based photodiode arrays[5]. One of the critical components of this technique is the substrate removal epitaxial structure illustrated in Figure 3a. Using a thin n+ doped InP contact layer and InGaAs etch stop layer facilitates removal of the InP substrate after FPA hybridization. Figure 3b illustrates a comparison of the quantum efficiency obtained with standard InGaAs and substrate removed Visible InGaAs. No degradation in the dark current from the photodiode arrays is observed when the substrate is removed. The uniformity of the spectral response across the array (better than 0.5%) is guaranteed by the accuracy of the MOCVD epitaxial growth method, as we have already demonstrated the validity of excellent chemical etches for selectively removing InGaAs over InP. We have successfully applied this technique to our production 640 x 512 (25 µm pitch), 320x256 (25 µm pitch) and 320x240 (40µm pitch) FPAs and are currently commercially available.

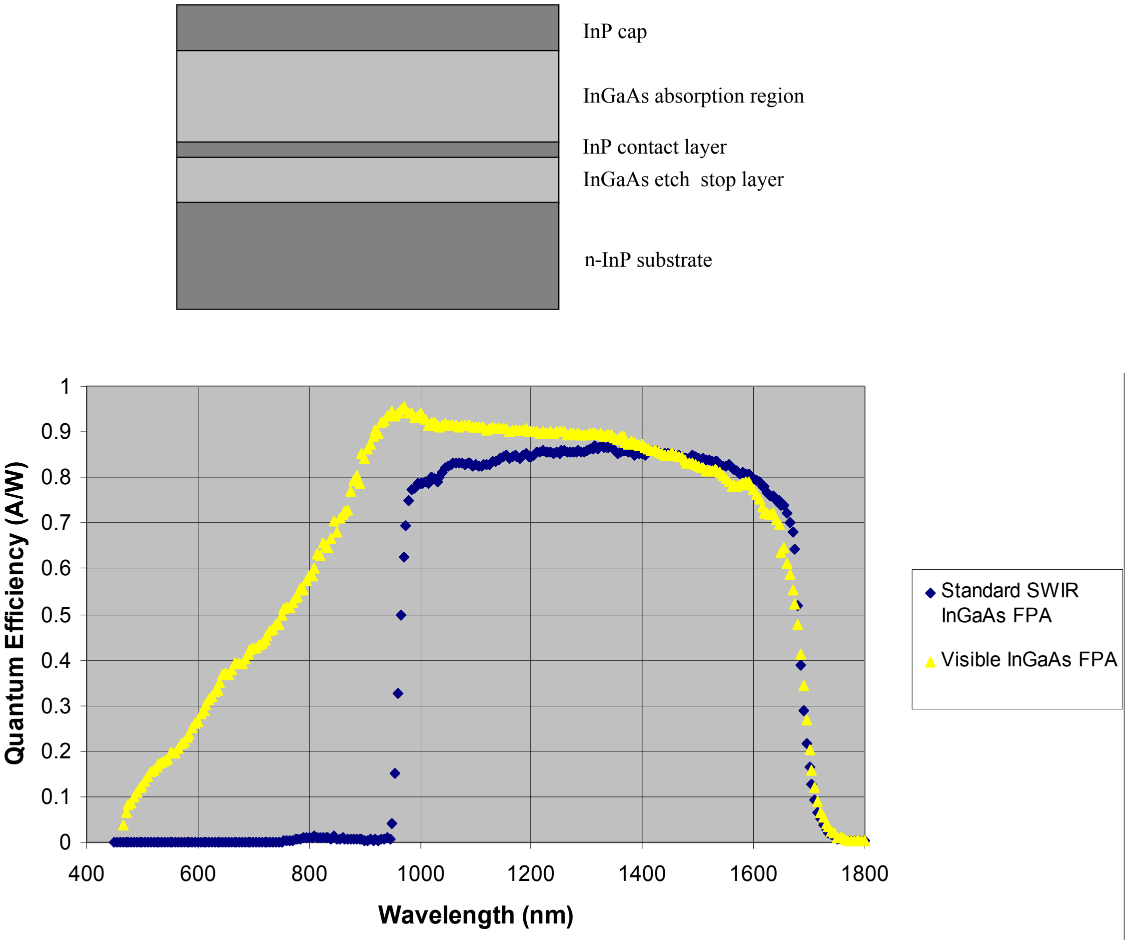

Figure 3. a) Epitaxial wafer structure with InP contact layer. b) Resulting quantum efficiency improvement.

Wafer Processing: A total of 15 InGaAs wafers were grown on 3" InP wafers and were processed at our facility. The controlled experiments included variations in epitaxy design, growth techniques, processing and photodiode design. All other aspects of the photodiode array processing was performed through our standard processing conditions used in production. Post processing, all wafers were I-V tested on a semiautomatic probe station.

Each of the 15 wafers grown were processed in our fab utilizing a new mask set designed for this program. The goal of this new mask design was to utilize test structures that will yield the necessary information of the bulk vs. perimeter origination of dark current. Therefore photodiodes with different perimeter to area ratios (circles, rectangles and squares) with different sizes and shapes were designed. In addition, we designed a "pixel bias test" structure such that a an array of photodiodes were designed with pitches ranging from 15 μm to 25 μm. In this test, a center photodiode (pixel) dark current is measured while the surrounding photodiodes of the array are biased identically.

Low Dark Current Characterization Setup: Goodrich Corporation, SUI has utilized an Alessi semiautomatic wafer prober with integrated temperature controlled chuck. The upgraded prober is able to perform very low noise current voltage measurements at a temperature range from -65°C to 200°C. The prober has been integrated with an Agilent 4156C precision semiconductor parameter analyzer. Very low noise current measurement capability is achieved by use of triax cable connections and Kelvin measurement probes.

3. CHARACTERIZATION RESULTS

Figure 4 illustrates typical I-V measurement results of the pixel bias test taken at room temperature. The dark current shown as a 'dotted' line is the current state of the art pixel I-V characteristic for a photodiode in an array of photodiodes on a 25um pitch. At the beginning of the PCAR program, the minimum bias applied by the ROIC to the photodiode array was -350mV reverse bias. This yielded in a dark current density of 22 nA/cm^2. During the PCAR program, the dark current was reduced to 7.2 nA/cm^2 at -350 mV reverse bias measured at room temperature.

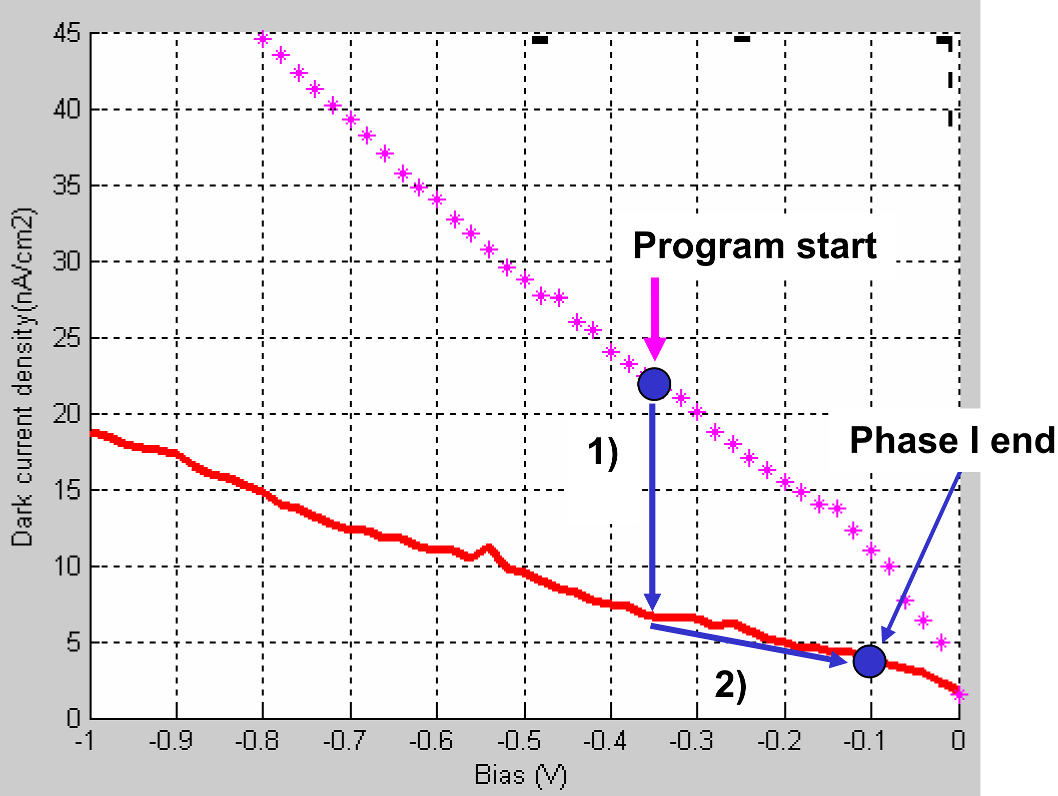

Figure 4. Dark current characteristics of different photodiode pixels at room temperature.

The new ROIC designed[4] under this program also permits applying lower bias across the photodiode array. This is due to the selection of a capacitive transimpedance amplifier (CTIA) read out circuit. Therefore, an additional decrease of photodiode dark current can be obtained by the reverse bias reduction to -100mV. For the new photodiode process, the pixel on a 20 μm pitch at 100mV reverse bias will yield a dark current of 12 fA or dark current density of 3 nA/cm^2.

Direct Pixel Tests: Figure 5 illustrates the results of the pixel bias dark current measurement of the same wafers shown in Figure 4 as a function of temperature. At each temperature, 5 photodiodes were measured and the median value was used in the chart to extract the temperature dependence. The dark current density of the top curve is our standard photodiode process pixel on a 25um pitch. The bottom curve represents the improvements developed under the PCAR program, at a given temperature. The bias of the dark current shown for the two wafers was kept identical for comparison. The dark current reduction from the start of the program to the end of Phase I is a factor of **3**. By a moderate TEC cooling of 12.3^{o}C as opposed to the 10^{o}C reported in the earlier section. The program goal of 2 nA/cm^2 is achieved at a temperature of +12.3 degree C.

There are two interesting observations deduced from the chart shown in Figure 5.

1) The temperature dependency of both photodiode designs are similar, the slope of both curves yielding a band gap dependence of Eg/kT, Eg being the band gap of InGaAs of 0.75eV. This temperature dependence represents that the diffusion current is the major contributor of dark current.
2) There is a substantial difference in dark current from a free standing 12 μm photodiode and the dark current of a 12 μm photodiode in an array. The free standing photodiode dark current of our standard process is approximately 100 fA, while a 12 μm active diffusion diameter pixel dark current in 20 μm pitch array from the same wafer is 44 fA at room temperature.

These results suggest that pixels in an array exhibit lower dark current due to the surrounding pixels collecting peripheral diffusion current originating from InGaAs.

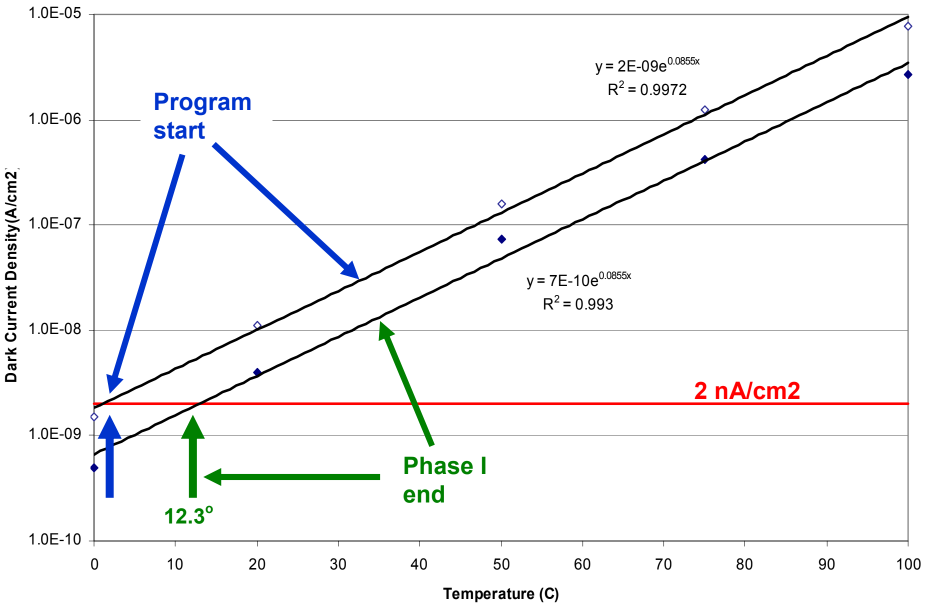

Figure 5. Pixel bias dark current density results at -100mV reverse bias as a function of temperature.

4. FOCAL PLANE ARRAYS

The InGaAs photodiode arrays were hybridized to the low noise ROIC designed for the PCAR program that exhibited 9.2 e^- read out noise and is described in detail in Ref 3. A test camera was built to operate and characterize the FPAs with the test electronics providing the necessary power, analog biases, clock signals and addresses to drive the FPAs, and digitize the output signals. The test electronics supported multiple sampling techniques such as correlated double sampling (CDS) for FPA noise reduction. The imagery taken with CDS demonstrated that it is a sufficient technique to produce the desired noise goal.

FPA Dark current: Dark current was measured on the hybridized FPA. The detector was reverse biased to 100 mV, and the dark current measured by differencing a signal and reference frame using CDS for a given exposure time. The measurement was repeated at two different temperatures and results are shown in Table 1.

0°C	1.85 fA
25°C	30.8 fA

Table 1. FPA mean array dark current at 100 mV reverse detector bias.

The dark currents listed in Table 1 are consistent with our findings in Figure 5. However, the photodiode arrays that were hybridized with the ROICs were not able to benefit the latest design, processing, and epitaxial growth techniques that were developed under the PCAR program. This is due to time constraints such that the two efforts had to be accomplished in parallel.

Imagery: Imagery was taken under low light level conditions in a laboratory environment comparing the PCAR camera to the previous generation 640SDX developed under the DARPA MANTIS program. Both images were acquired simultaneously with identical 25mm f/2.8 lenses. An integration time of 16 ms was used while the digital gain was set to 1 for both cameras. The PCAR camera had a TEC set temperature of 0^oC to reduce the dark current below 2 nA/cm^2. In addition the ROIC was operated in CDS mode for low readout noise capability. The 640SDX camera utilized a TEC set point temperature of 18^oC and used a single background subtraction. Figure 6 illustrates the difference between the two cameras with indirect (reflected) tungsten lamp illumination only. The PCAR camera image shows higher contrast compared to the SU640SDX.

Figure 6. Images from the camera designed for PCAR (left) and 640SDX camera (right) in low light level laboratory environment with Tungsten lamp illumination only.

Figure 7 illustrates the difference between the two cameras with 1550nm LED illumination only. The PCAR camera image shows higher contrast compared to the SU640SDX. Figure 8 illustrates the difference between the two cameras with 850nm LED illumination only. The PCAR camera image displays the scene with 850nm light since it has added visible response since its substrate is removed, as opposed to the SU640SDX, where the InP substrate blocks the 850nm light.

Figure 7. Images from the camera designed for PCAR (left) and 640SDX camera (right) in low light level laboratory environment with 1550 nm LED illumination only.

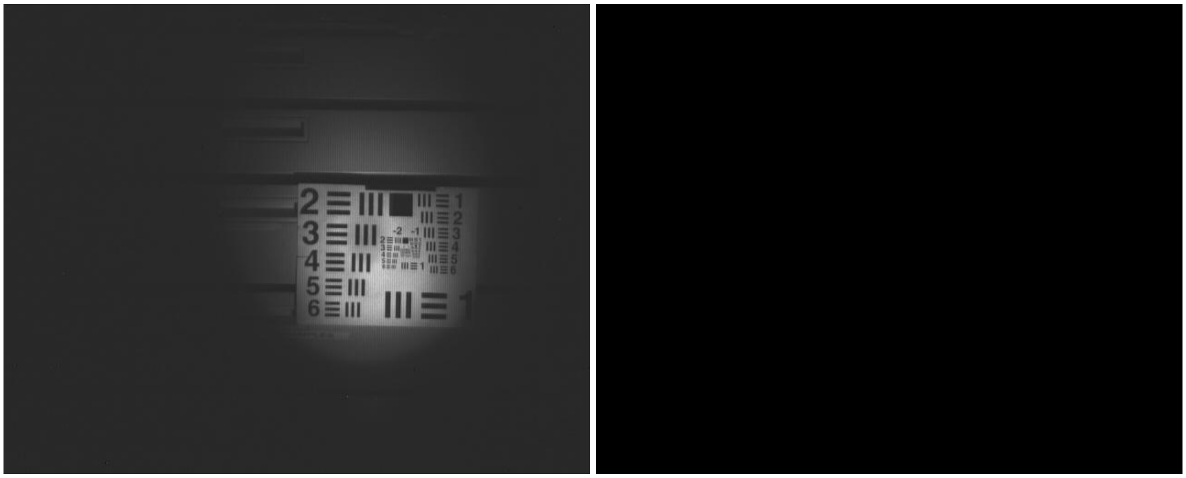

Figure 8. Images from the camera designed for PCAR (left) and 640SDX camera (right) in low light level laboratory environment with 850 nm LED illumination only.

5. CONCLUSIONS

In Phase I of the PCAR program, Goodrich SUI has developed and demonstrated a 640 x 512 (20 µm pitch) focal plane array (FPA) with extremely low noise. We achieved the milestones of demonstrating a ROIC read out noise less than 10 e^- rms, and photodiode array dark current density less than 2 nA/cm^2. We have reduced our already low dark current InGaAs photodiode arrays by a factor of 3 at a given bias of -100mV. These dark current improvements will be integrated into our production cameras and will be available for foundry orders within the next year. We will also leverage the results in the Phase II of the program to design and deliver a camera with a 1280x1024 InGaAs FPA on a 15 µm pitch. If successful, the deliverable camera with high resolution, low noise will permit man identification from 100m under low light level imaging conditions that can outperform current I^{2}CCD technologies.

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