640x512 InGaAs focal plane array camera for visible and SWIR imaging

Tara Martin*, Robert Brubaker, Peter Dixon, Mari-Anne Gagliardi, Tom Sudol
Sensors Unlimited Inc., 3490 U.S. Route 1, Bldg 12, Princeton, NJ 08540

ABSTRACT

We report on our 640x512 pixel InGaAs/InP focal plane array camera for visible and short-wavelength infrared imaging. For this camera, we have fabricated a 640x512 element substrate-removed backside-illuminated InGaAs/InP photodiode array (PDA) with a 25 µm pixel pitch. The PDA is indium bump bonded to a silicon read out integrated circuit. Removing the InP substrate from the focal plane array allows visible wavelengths, which would otherwise be absorbed by the InP substrate due to its 920 nm wavelength cut-off, to reach the pixels' active region. The quantum efficiency is approximately 15% at 500 nm, 70% at 850 nm, 85% at 1310 nm, and 80% at 1550 nm.

Features incorporated into this video-rate, 14-bit output camera include external triggering, windowing, individual pixel correction, 8 operational settings of gain and exposure time, and gamma correction. The readout circuit uses a gate-modulated pixel for high sensitivity imaging over a wide illumination range. This camera is useable for visible imaging as well as imaging eye-safe lasers and is of particular interest seeing laser designators and night vision as well as hyperspectral imaging.

Keywords: focal plane array, InGaAs, visible imaging, near infrared, SWIR

1. INTRODUCTION

The ability of indium gallium arsenide (InGaAs) photodiodes to operate at room temperature with high quantum efficiency for wavelengths from 920 nm to 1700 nm makes InGaAs an optimal material choice for short wavelength infrared (SWIR) imaging applications. These applications span such commercial and industrial opportunities as semiconductor-wafer inspection, wavefront sensing, astronomy, spectroscopy, and machine vision. In the military, applications range from covert surveillance to active pointing and tracking and laser radar. Recently, $In_{0.53}Ga_{0.47}As$ photodiode arrays (PDAs) capable of simultaneously detecting visible (400 nm – 750 nm), near-IR (750 nm – 1000 nm), and SWIR (1000 nm – 1700 nm) wavelengths have been developed. We will refer to these InGaAs arrays that image from 400nm to 1700nm as "Visible InGaAs™" from this point forward. This technology enables a single array to do a job previously requiring two arrays and complex system integration including beam splitters and specialized optics. The dual-wavelength-band InGaAs arrays achieve the same low dark current as commercial SWIR InGaAs arrays.

Traditional SWIR InGaAs PDAs as well as the newly developed Visible InGaAs™ PDAs are hybridized to CMOS readout integrated circuits (ROICs). The resulting focal-plane arrays (FPAs) are then integrated into cameras for video-rate output to a monitor or for use with a frame grabber in a computer for quantitative measurements and machine vision. Popular InGaAs FPA geometries include 320 × 240 pixels on a 40 µm pitch, and 320 × 256, and 640 × 512 element arrays both on a 25 µm pixel pitch. Sensors Unlimited's (SUI) Visible InGaAs™ focal plane arrays are currently available in all these formats.

The traditional epitaxial structure for InGaAs *p-i-n* photodiodes consists of an *n*-type indium phosphide (InP) substrate, followed by an intrinsic InGaAs absorption region, and topped off with an InP cap. InGaAs photodiodes can be either front- or backside illuminated. Single-element photodiodes and 1-D arrays are most often frontside illuminated, while 2-D arrays are backside illuminated because of the indium-bump-bonding process used to integrate the arrays with a CMOS readout circuit. In the case of backside-illuminated arrays, a "planar/mesa" process is used in which the individual photodiodes are planar with all the processing done through holes in a passivating silicon nitride coating. The entire photodiode array is isolated on a mesa that allows frontside electrical contact to the common-cathode substrate.[1, 2]

* tmartin@sensorsinc.com; phone 609-524-0345; www.sensorsinc.com

Infrared Technology and Applications XXXI, edited by Bjørn F. Andresen, Gabor F. Fulop, Proc. of SPIE Vol. 5783 (SPIE, Bellingham, WA, 2005)
0277-786X/05/$15 · doi: 10.1117/12.603406

In a frontside-illuminated format, light must pass through the InP cap to reach the InGaAs absorption region, while in a backside-illuminated format light must pass though the InP substrate to reach the absorption region. Typically, the InP cap is on the order of 1 μm thick while the InP substrate is hundreds of microns thick. The quantum efficiency of front- and backside-illuminated photodiodes is the same for wavelengths greater than 1100 nm for both diodes, but the quantum efficiency of the frontside-illuminated diode is greater for wavelengths below 1100 nm (see Fig. 1). This higher quantum efficiency is due to the thinner InP layer that the light passes through before reaching the active InGaAs region in the frontside-illuminated format. In fact, the ability to vary the thickness of the InP window layer previously enabled InGaAs linear arrays to be used within the visible spectrum.[3]

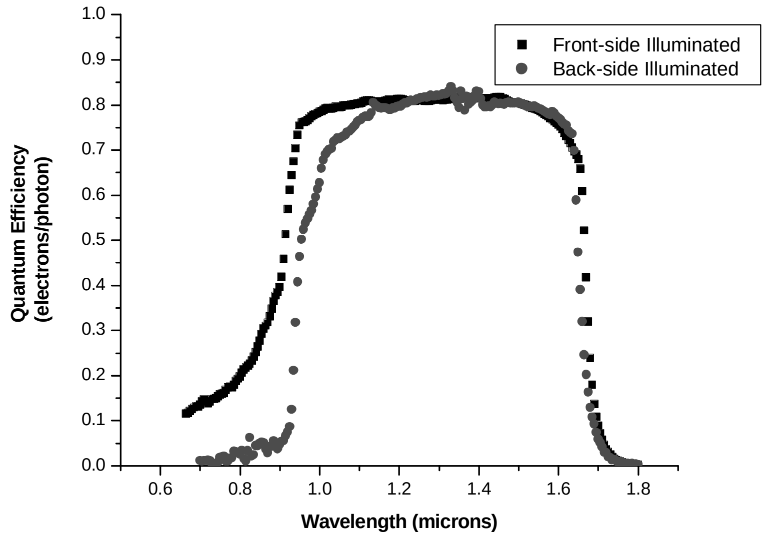

Figure 1. Quantum efficiency of frontside InGaAs *p-i-n* photodiodes is greater than that for backside-illuminated devices for wavelengths shorter than 1100 nm.

The bandgap of InP is 1.35 eV, corresponding to a cutoff wavelength of 920 nm. The bandgap of lattice-matched InGaAs is 0.75 eV, corresponding to a cutoff wavelength of approximately 1700 nm. While the InGaAs on its own responds to both visible and SWIR wavelengths below 1700 nm, the InP cap (for frontside-illuminated devices) or substrate (for backside-illuminated devices) absorbs the wavelengths below 920 nm, resulting in only wavelengths greater than 920 nm reaching the InGaAs active region. The InP is necessary to passivate the InGaAs surface, but it is the InP absorption below 920 nm, not the capabilities of InGaAs itself, which until recently has limited InGaAs FPAs for visible imaging.

2. METHODOLOGY

The objective in our development of all Visible InGaAs™ products has been to maximize quantum efficiency in the visible wavelength range while maintaining the excellent performance and reliability seen in SWIR InGaAs FPAs. The fabrication process for Visible InGaAs PDAs is largely the same as that for SWIR InGaAs PDAs. In our PDA process, the individual photodiodes are planar with all the processing done through holes in the passivating SiN_x coating. The entire photodiode array is isolated on a mesa allowing front-side electrical contact to the common-cathode contact layer or substrate. The photodiode arrays are then flip-chip bonded to a ROIC.

Because it is the InP substrate that prevents visible light from reaching the InGaAs active region in InGaAs FPAs, thinning or removing the InP substrate results in more visible light reaching the InGaAs active region, and therefore in increased quantum efficiency in the visible wavelength band.[4] For a backside-illuminated FPA, just enough InP to passivate the InGaAs surface and provide a contact layer for the front-side common-cathode contact is needed. The substrate removal process and epitaxial growth are the most critical fabrication steps for achieving consistent visible response performance

We achieve visible response by removing the InP substrate after flip-chip bonding. Once the PDA and ROIC have been pressed together, an epoxy is wicked between them. This epoxy holds the hybridized device together and provides critical support to the PDA during and after the substrate removal process. Any voids in this epoxy will result in cracks and holes in the thinned PDA. After the substrate removal process, the FPA consists of just the epitaxial layers of the PDA bump bonded to a CMOS ROIC.

So that the substrate removal results are consistent, an etch stop layer is added to the standard InGaAs p-i-n structure. The resulting epitaxial structure is shown in Figure 2. The epitaxial wafers were grown at Sensors Unlimited in an Emcore LDM-180 MOCVD reactor. The substrate is removed from the hybridized PDAs using a combination of mechanical and wet chemical etching techniques and is highly reproducible. Because of the very high selectively of the wet etches and excellent control of the epitaxial growth, the remaining InP contact layer thickness, and therefore the visible response is highly reproducible. The thin contact layer achieved with wet etching and mechanical thinning is thinner than that achieved by mechanical thinning alone. The remaining InP contact layer thickness must be controlled to within 10 nm for consistent visible quantum efficiency. Layer thickness can only be controlled to within a couple of microns at best using purely mechanical removal techniques. Thicker InP layers lead to lower quantum efficiency in the visible spectrum, as well as to image retention.[5] The image retention most likely arises from photoluminescence from the InP, which absorbs visible light and re-emits photons near the InP bandgap; this process is slow, with a time scale on the order of video-rate imaging.

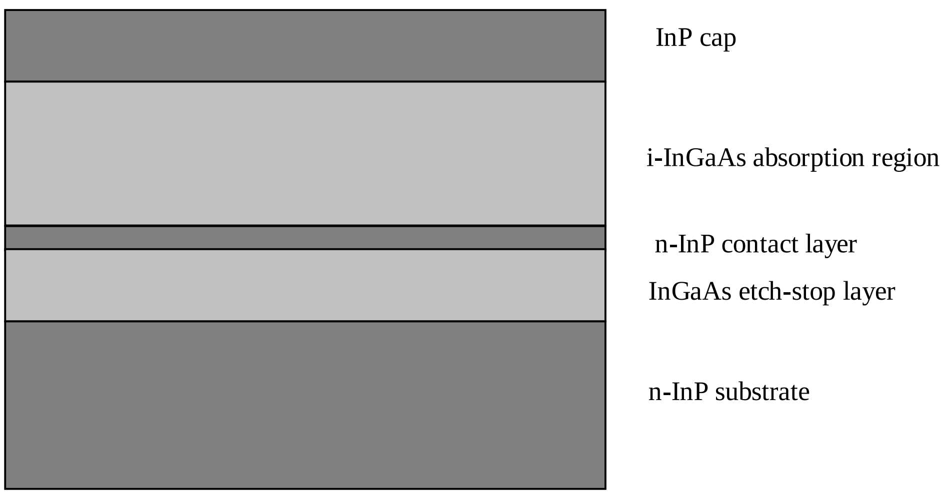

Figure 2. Visible InGaAs™ Epitaxial Wafer Structure.

3. DATA

We were successful in increasing quantum efficiency in the visible wavelength band while also achieving the same low dark current, high pixel operability, high quantum efficiency in the SWIR wavelength band, and excellent reliability exhibited by SWIR FPAs. At the FPA operating bias voltage of 300 mV the pixel dark current is less than 1 pA (see Figure 3). Pixel operability, the percentage of pixels with responsivity deviation less than 30% from the mean, is greater than 99%.

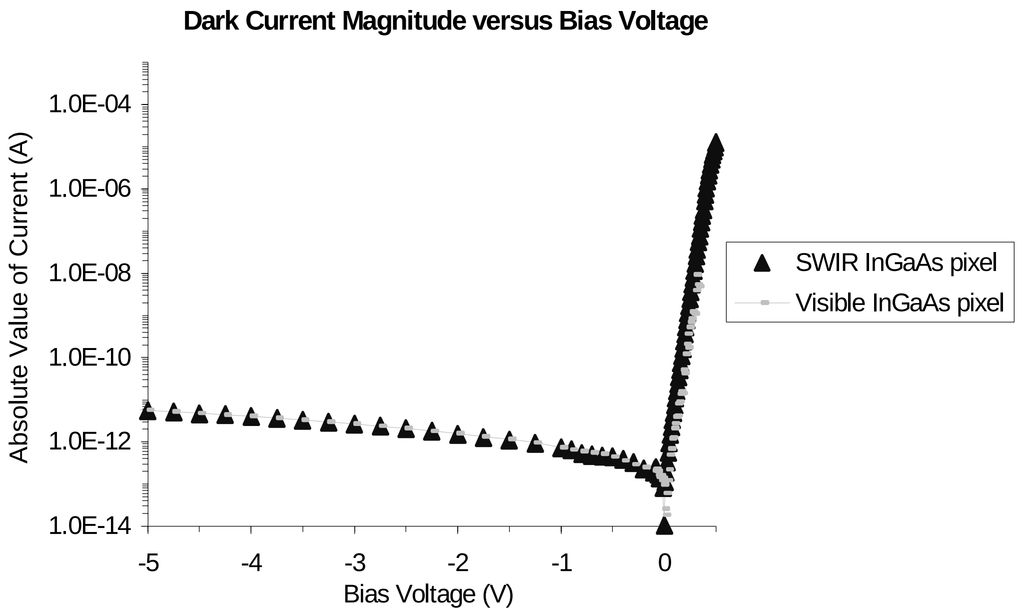

Figure 3. Dark current magnitude versus bias voltage of a pixel from a SWIR InGaAs array and a pixel from a Visible InGaAs™ array. The change in epitaxial structure and the substrate removal process do not impact pixel dark current.

At the time of the writing of this paper, 2000 hours of reliability burn-in had been completed on our Visible InGaAs™ FPAs. The FPAs were biased at their operating voltage of 300 mV and run continuously in an 85˚C oven. After 2000 hours there was no statistically significant change in mean dark current or pixel operability in either the FPA population undergoing the burn-in or the control populations. Figure 4 shows the change in the number of bad pixels over 2000 hours for Visible InGaAs™ arrays that have undergone burn-in at 85˚C for 2000 hours, Visible InGaAs™ arrays that have not gone through burn-in, and for standard InGaAs arrays that were added to the population at 1000 hours. Bad pixels were defined as those that had very high dark current (> 3800 dark counts), had no response (< 500 counts under flat field conditions), or whose responsivity was not within +/- 25% of the mean. The maximum increase in bad pixels at the end of 2000 hours was 1 pixel, the maximum decrease was 11 pixels.

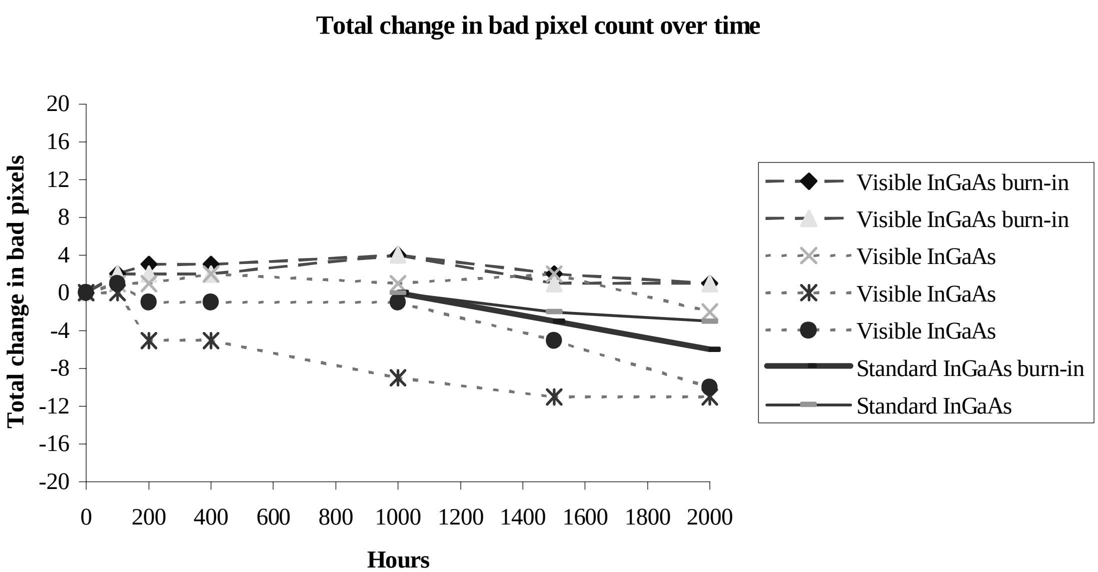

Figure 4. Change in the number of bad pixels in Visible InGaAs™ and Standard Focal Plane arrays over 2000 hours.

Figure 5 shows the quantum efficiency for a Visible InGaAs™ FPA and a SWIR InGaAs FPA. The quantum efficiency for the Visible InGaAs™ at 700 nm is now 50%. This is almost a factor-of-five improvement over even that for a frontside-illuminated detector and far more when compared to that of typical backside illuminated detector such as that shown in Figure 4. At 500 nm, quantum efficiency is approximately 15% versus less than 1% typically seen for standard front- or backside-illuminated photodiodes at 500 nm. The backside anti-reflective coating used on the visible arrays is centered around 1000 nm versus approximately 1300 nm for the SWIR only FPA. This contributes to some of the increased response around 1000 nm and decreased response beyond 1500 nm. The window on the Visible InGaAs™ FPA package has a broadband anti-reflective coating, which minimizes reflections from 600 nm to 1700 nm. This does cause a decrease in quantum efficiency below 600 nm compared to that measured on the same array without the antireflective window coating.

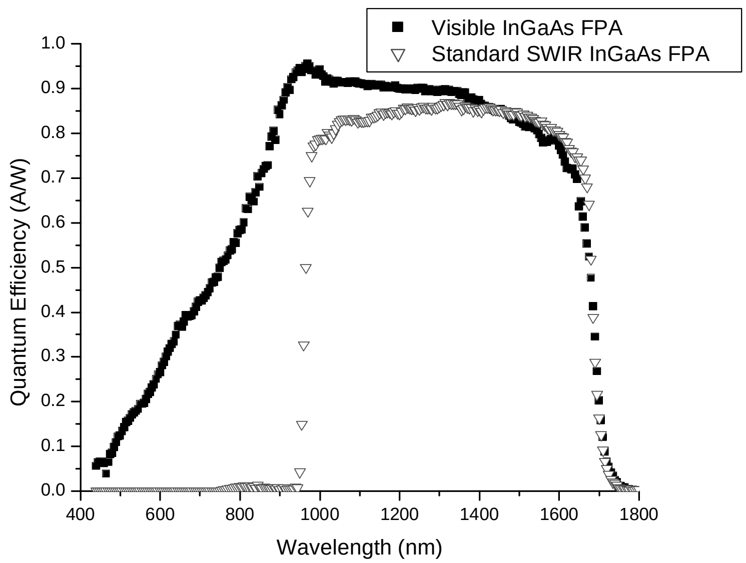

Figure 5. Quantum efficiency for the Visible InGaAs™ array is much higher than that of the standard SWIR InGaAs array in the visible and near infrared wavelengths bands.

4. RESULTS

Since the Visible InGaAs™ FPA uses the same multiplexer and package as our SWIR InGaAs FPAs, it can be dropped into a standard SUI camera for direct performance comparisons. We also compared the Visible InGaAs™ imagery to that of a visible camera. Several applications where SWIR cameras excel include night vision, imaging eye safe lasers, seeing through fog, and camouflage detection. On the other hand, SWIR cameras cannot image computer or television screens since the imagery consists only of visible light and SWIR only cameras cannot image some painted or printed details on signs, fabrics, and vehicles. Figure 6 shows images of the same scene imaged with a visible camera, an SUI™ SWIR camera and an SUI™ Visible InGaAs™ Camera. The visible camera can see the details on the colored poster, and images the red laser pointer and the white LED source. It cannot see 1550 nm LED flashlight and the heat from the soldering iron. The SWIR only camera can see the heat from the soldering and the 1550 nm LED flashlight, but cannot see the red laser pointer or the graphics on the color poster. The Visible InGaAs™ images can see all the light sources, the hot soldering iron, and the color graphics in the scene.

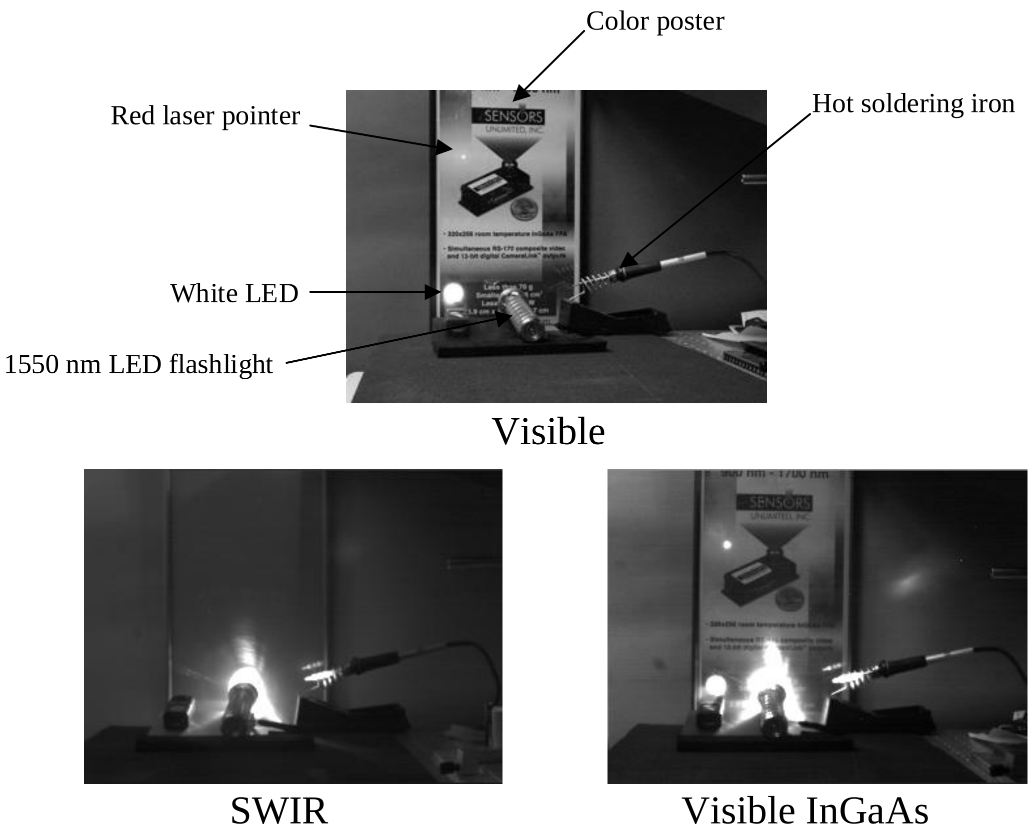

Figure 6. Pictures of the same scene taken with a visible camera (top), an InGaAs SWIR camera (bottom left), a Visible InGaAs™ (visible and SWIR) camera (bottom right).

Figure 7 shows images taken at night along a dark road with the same three cameras. The top left image is SWIR only, the top right is SWIR and visible, and the bottom is visible only. In visible only image, the road sign in the foreground can be seen, but nothing else can be seen at night. In addition to the SWIR and visible emission of artificial sources and moon light, there is near-infrared sky glow even on a moonless night.[6] The SWIR camera can see the nightglow and shows the tree line and power lines, the road sign can be seen, but the writing on it is not visible. The Visible InGaAs™ camera can see the tree line and power lines as well as see the printing on the sign. The Visible InGaAs™ image is also brighter than the SWIR only image because this camera responds to both visible and SWIR light present so it can detect more photons.

Figure 7. Pictures taken at night along a dark road. Top left taken with SWIR InGaAs camera. Top right taken with Visible InGaAs™ camera (SWIR + visible). Bottom taken with visible camera.

The 640x512 Visible InGaAs™ array has the same geometry and package as the Sensors Unlimited (SUI) SWIR 640x512 InGaAs array. The same SUI housing and camera electronics are used with both arrays (see Figure 8). The Visible InGaAs™ camera weighs approximately 1 Kg without a lens and its outer dimensions are 18.1 cm x 7.6 cm x 7.6 cm (l x w x h). The camera operates from 0 ˚C to 40 ˚C. Factory set exposure times are variable from 250 µs to 33.8 ms with 8 steps, and programmable exposure times greater than 10 µs are possible with an external trigger. Two-point (offset and gain) pixel-by-pixel image correction is selectable by the user at all 8 integration times. The maximum frame rate for full resolution is approximately 30 Hz. Digital output is 14-bit Camera Link® compatible and analog output is RS-170 compatible.

Figure 8. SUI™ 640x512 camera

Further improvements to Visible InGaAs™ arrays are expected over the next couple of months and years. One such improvement will include optimizing the epitaxial wafer structure to increase quantum efficiency throughout the visible-wavelength band. The optimization will mostly include improvements to the contact layer. By decreasing the layer thickness, and experimenting with different contact layer materials such as InAlAs, visible response can be improved. The substrate removal technology will be applied to larger area as well as smaller pitch focal plane arrays. Recently, we applied the substrate removal technique to our 320x256 snap shot arrays, which allowed us to introduce a Visible InGaAs™ camera in our smaller micro camera package. The smaller package opens up UAV and covert surveillance applications.

5. CONCLUSIONS

Visible InGaAs™ FPAs perform as well as SWIR InGaAs FPAs that have not undergone the substrate removal process, but the Visible InGaAs™ FPAs can detect visible as well as SWIR light. The newly developed Visible InGaAs™ arrays sense light over a wavelength range of 400 to 1700 nm, making them a prime choice for applications such as night vision, imaging all commonly used military lasers, inspection, and agricultural sorting. Having a single FPA that can image both in the visible and SWIR wavelength bands is of interest for applications that currently require two separate cameras to image the two wavelength bands. Having a single camera simplifies image-fusion systems and decreases payload size and weight. Focal-plane arrays made with InGaAs are widely used for night-vision applications because of the SWIR light available at night. Indium gallium arsenide performs far better than image-intensified CCDs at night, but standard InGaAs arrays are not able to see some standard laser designators used by the military. The new Visible InGaAs™ arrays can see all commonly used laser designators (800- to 900-nm lasers, as well as 1310-nm communications lasers and eye-safe 1550-nm lasers). Combined visible-SWIR capabilities are also of interest for hyperspectral-imaging applications. The visible response should also assist the nighttime imaging capability of InGaAs by detecting more of the available photons--that is, visible and SWIR instead of one or the other.

SWIR only cameras provide high-contrast daytime images, but because they cannot see visible light, they cannot image details that are painted or printed for use in the visible, such as signs, paintings, fabric patterns, and vehicle lettering. In addition, SWIR cameras cannot view television or computer monitors because the imagery consists of only visible light. In some applications, and in particular for military-surveillance applications, having the ability to see details on signs, fabrics, and computer monitors, as well as to see all laser-designator wavelengths and perform nighttime imaging is important

In commercial applications, visible-SWIR cameras can assist in machine vision as well in hyperspectral imaging. The same array can allow multiple "colors" across two wavelength bands to be imaged by one camera. This simplifies the optical system necessary as well as the processing power required to analyze and compare two camera images. Areas of interest are in agricultural sorting, for which defects are not necessarily apparent in the visible spectrum; and inspection applications, in which visible attributes need to be simultaneously observed with hidden nonvisible attributes. One example of the latter is pharmaceutical bottles, where labels need to be read by users but tamper-resistant protections meant to stay hidden are written in ink that is detectable in the near-IR and SWIR bands only.

ACKNOWLEDGEMENTS

We would like to acknowledge the Air Force Research Laboratories, which has funded and continues to support much of our Visible InGaAs™ development through the Small Business Innovative Research (SBIR) Program.

REFERENCES

1. Ettenburg, M. H., Cohen, M. J., Brubaker, R. M., Lange, M. J., O'Grady M., Olsen, G. H., "Indium Gallium Arsenide Imaging with Smaller Cameras, High Resolution Arrays and Greater Material Sensitivity", *Proceedings of SPIE*, *Aerosense* (2002).

2. Ettenburg, M. H., Lange, M. J., O'Grady M., Vermaak, J., Cohen, M. J., Olsen, G. H, "A Room Temperature 640x512 Near-Infrared InGaAs Focal Plane Array", *Proceedings of SPIE*, *Aerosense* (2000).

3. Williamson, J. B., Carey K. W., et al. "High-Density, Planar Zn-Diffused IngaAs/InP Photodetector Arrays with Extended Short-Wavelength Response." IEEE Transactions on Electron Devices **38** (12): 2707-2707 (1991).

4. Ettenberg, M. H., Cohen, M. J., Lange, M. J., Dixon, P., Olsen, G. H., "A Thin Film Indium Gallium Arsenide Focal Plane Array for Visible and Near-Infrared Hyperspectral Imaging," *LEOS '99*. IEEE Lasers and Electro-Optics Society 1999 12th Annual Meeting (1999).

5. Hoelter, T. R., Barton, B. B., "Extended short wavelength spectral response from InGaAs focal plane arrays." *Proceedings of SPIE* (5074): 481-490 (2003).

6. Vatsia ML, Stich UK, Dunlap D. Night Sky Radian Sterance from 450 to 2000 Nanometers. (U.S. Army Technical Report ECOM7022). Fort Belvoir, VA: Army Electronics Command Night Vision Lab; 1972.