

## Keynote

# Advanced Imaging Research and Development at DARPA

Nibir K. Dhar

Defense Advanced Research Project Agency, Microsystems Technology Office  
675 North Randolph Street  
Arlington, VA 22203

Ravi Dat

Booz Allen Hamilton  
3811 N. Fairfax Drive  
Arlington, VA 22203

## ABSTRACT

Advances in imaging technology have huge impact on our daily lives. Innovations in optics, focal plane arrays (FPA), microelectronics and computation have revolutionized camera design. As a result, new approaches to camera design and low cost manufacturing is now possible. These advances are clearly evident in visible wavelength band due to pixel scaling, improvements in silicon material and CMOS technology. CMOS cameras are available in cell phones and many other consumer products. Advances in infrared imaging technology have been slow due to market volume and many technological barriers in detector materials, optics and fundamental limits imposed by the scaling laws of optics. There is of course much room for improvements in both, visible and infrared imaging technology. This paper highlights various technology development projects at DARPA to advance the imaging technology for both, visible and infrared. Challenges and potentials solutions are highlighted in areas related to wide field-of-view camera design, small pitch pixel, broadband and multiband detectors and focal plane arrays.

Keywords: Imaging, FPA, SWIR, MWIR, LWIR, ROIC, Multicolor, Broadband.

## 1. INTRODUCTION

Further advancement in imaging systems requires solution for many fundamental and technological issues related to wide field of view (FOV), resolution, pixel pitch, optics, multicolor, form-factor, etc. This paper highlights a few projects currently fielded through the Microsystems Technology Office (MTO) of the Defense Advanced Project Agency (DARPA). These projects are aggregated under an umbrella program called, "Advanced Wide Field of View Architectures for Image Reconstruction and Exploitation (AWARE)", and address many of the fundamental limits to push the technological edge towards advanced imaging capability for the warfighters. The aim of the AWARE program is to develop several enabling technologies to provide advanced capabilities in the electro-optics and infrared (EO/IR) field. These projects span a very wide range of wavelengths to cover optical imaging research from 500 nm to 14  $\mu$ m. Specific challenges and solutions to achieve wide field-of-view, pixel scaling, broadband and multiband are briefly described. This paper discusses four challenges and offer solutions and results obtained by the DARPA R&D performers. These challenges are:

1. Fundamental limits in FOV and resolution: novel camera architecture.
2. Pixel/unit cell scaling for high density FPAs.
3. Broadband image sensors for multi-band and high operating temperature.
4. Multi-band detectors

The advances in imaging technology require innovation in camera design, focal plane arrays, electronics and computation. These innovations, however, must be guided by pragmatic approaches that lead to affordable and relevant products necessary for the current military environment. A set of generalized metrics are defined to evaluate the efficacy of the final imaging system in the program.

$$M = \frac{\text{Target Information}}{\text{SWaP} \times \text{Cost} \times \text{Time}} \quad (1)$$

$$N = \frac{\pi^2}{(2\lambda F/\#)^2} D^2 \quad (2)$$

$$P = \frac{\text{Features}}{\text{Measurement set}} \quad (3)$$

M is the optimized design space, N is the optimized number of measurement channels and P is the number of features. SWaP is size, weight and power of the system,  $\lambda$  is the wavelength, F/# is the optics parameter and D is the aperture. In the design space, target information is maximized for the lowest possible SWaP, cost and time to acquire the image. Measurement channels, N represents maximum possible pixels for a design space governed by the aperture, wavelength and F/#. The parameter P represents maximum features, for instance number of wavelength bands, for the minimum set of measurements. The above metrics provide a guide to optimize the design of an imaging system.

The DARPA-MTO has a long history of supporting the development of novel infrared sensor technologies and components. Continuing in this tradition, the DARPA-MTO AWARE program is providing unique solutions to address the scaling limitations of conventional camera designs with innovative camera architecture, focal plane arrays, computation and optics. Brief descriptions of each of the above challenges are described in the following sections.

## 2. CAMERA SCALING

In an imaging system, the number of degrees of freedom is approximately equivalent to the number of independent measurements required to fully characterize the scene being imaged. Typically this corresponds to the number of pixels that can be mapped from a continuous scene with physical objects therein; thus characterized by the space bandwidth product (SBP), which is the number of pixels required to achieve the maximum information capacity, N, defined in equation 2 above. The analysis presented by Lohmann [1] clearly shows that the actual SBP does not scale linearly with the aperture area. Therefore, the relevant scene information saturates as the aperture size increases, thus presenting a fundamental scaling challenge for wide field-of-view lens design. The scaling challenge for an imager is illustrated in Figure 1.

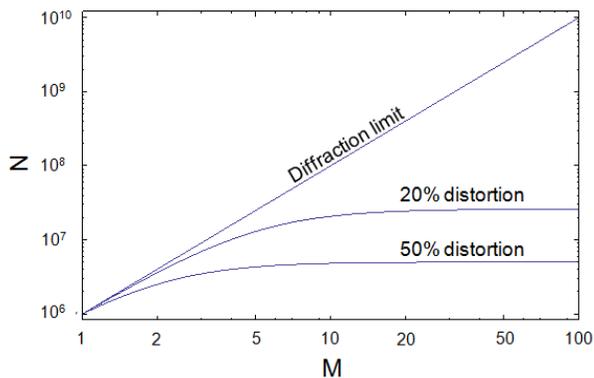
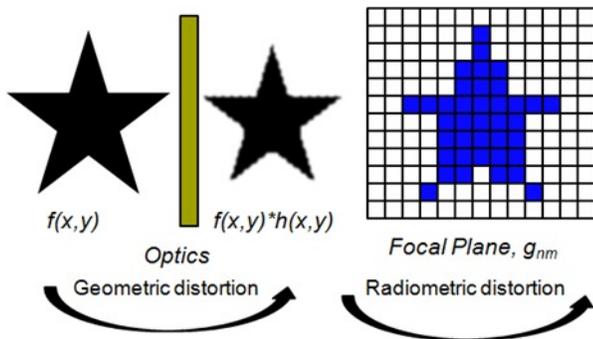


Figure 1. Space bandwidth product (N) as a function of imager scale (M) illustrating that traditional imager designs are limited by lens distortions.

In general, imaging process is a methodology that implements mapping of a continuous object field to a discrete set of measurements. The process therefore introduces geometric distortions at the image plane, due to various optical aberrations and radiometric distortions at the focal plane due to imperfections in the detector array. This is illustrated in Figure 2. Scaling up the optics and the detector array does not scale information linearly, as might be expected from the diffraction limited line in Figure 1. Therefore, to achieve very wide field-of-view and, correspondingly, large number of pixels would require many optical elements to correct aberrations making the system very large and expensive.



Furthermore, increasing the number of detectors would increase the detector array size leading to significant non-uniformity and a corresponding degradation in the image quality.

Figure 2. Illustration of two primary distortions in a typical imaging system.

The DARPA AWARE-WFOV program provides a unique solution to the above stated scaling challenge. The program objective is to design a new architecture to solve the scaling problem by demonstrating tens of Giga pixel class visible cameras with nearly 120 degree of field of view. The camera uses a novel multi-scale optical design with micro optical field processors to correct the spatial aberrations and to seamlessly stitch a very large panoramic scene. In this architecture, a mono-centric objective lens captures the wide field scene. The subsequent image plane is further measured and corrected by an array of micro cameras. The micro cameras are designed for overlapping image fields and can be seen as optical processors, much like a parallel computer using an array of microprocessors. The concept is illustrated in Figure 3a. The objective lens and micro-cameras used for the first prototype system is shown in Figures 3b and 3c, respectively. The raw image taken from this 2-Giga pixel camera is shown in Figure 3d, where the uncorrected edges of the micro cameras are evident.

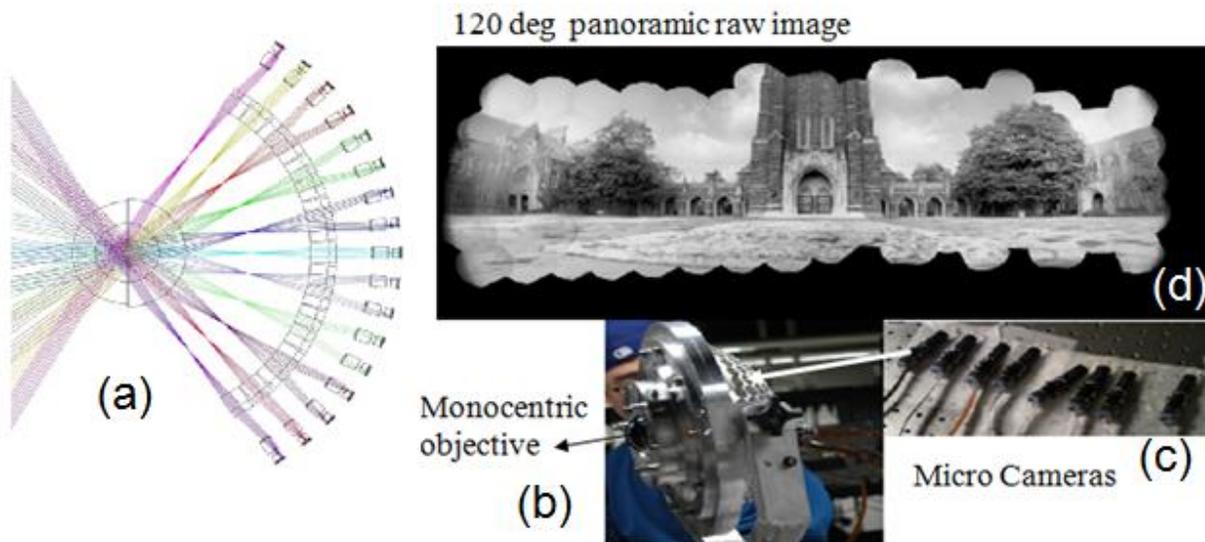


Figure 3. Illustration of the optical design (3a), the objective lens and camera mount for micro-cameras (3b), individual micro-cameras (3c) and a representative 2-Giga pixel 120 degree panoramic image (3d).

### 3. BROADBAND FOCAL PLANE ARRAYS (0.5-5.0 microns)

Traditional detector arrays are typically designed for a narrow band of wavelengths due to inadequate absorption and charge collection from photons with varying wavelengths. Broadband absorption is usually inadequate due to quantum efficiency (QE) roll-off. To design a detector with high QE across a very broad band of wavelengths, say visible to 5  $\mu\text{m}$  range, traditional detector design would be less than optimum. The concept of using photonic crystals is relatively well understood and has been demonstrated for applications like VCSELs, which have a very similar device structure to a photovoltaic detector [2]. Krishna et al. [3] have shown application of photonic structures to IR detectors. Sub-wavelength size semiconductor pillar arrays within a single detector can be designed and structured as an ensemble of photon trapping units to significantly increase absorption and QE for a wide band of wavelengths. Each sub-element in each pixel can be a 3D photonic structure fabricated using either a top-down or bottom-up process scheme. The sub-element architecture can be of different shapes such as pyramidal, sinusoidal or rectangular. Additionally, the sub-elements themselves can have p/n junctions. The motivation for this design is to significantly increase photon trapping, and their subsequent absorption and generation of electron-hole pairs in the absorber material. Such a design also leads to a reduction in the material volume and, thus, a decrease in the dark current. The sub-wavelength photonic trap allows for high absorption and increases the signal-to-noise ratio. This design strategy allows for a higher temperature of operation.

The goal of the broadband FPA architecture is to develop a versatile infrared detector technology that will improve performance at a higher temperature (200 K) and offer design flexibility for uniform quantum efficiency (QE) across the full 0.5 to 5.0  $\mu\text{m}$  band. Using unique pyramidal and pillar topologies etched into the photon absorbing layer, the performers have demonstrated 3D photon trapping, achieved significant reduction in dark current and established uniform QE. This is the first demonstration of broadband performance in a single infrared detector using a pillared microstructure in a semiconducting material. The broadband technology has been demonstrated independently in II-VI and III-V based epitaxial materials. This achievement paves the way to replace multiple cameras with one. It also gives the ability for hyper spectral sensing that will enable better target discrimination compared to a single narrow band camera. The high performance at 200 K compared to traditional 80 K operation allows for a smaller SWaP design, since high power and large cryogenic coolers can be replaced by low power miniature coolers. Such cameras would have significant impact on aerial surveillance in shadow class UAVs and many other smaller platforms.

One of the most successful broadband detector designs is based on a dry-etched, pyramidal photon trapping (PT) InAsSb structure (see Figure 4(a)), in conjunction with a compound barrier-based device architecture (nCBn) to further suppress dark current through absorber volume reduction. Based on optical simulation, the pyramidal structures minimize the reflection and provide  $> 90\%$  absorption over the entire 0.5  $\mu\text{m}$  to 5.0  $\mu\text{m}$  spectral range (Figure 4(b)), while providing up to 3x reduction in absorber volume. InAs<sub>0.91</sub>Sb<sub>0.09</sub> absorbing layers with 4.3  $\mu\text{m}$  cut off as well as InAs<sub>0.82</sub>Sb<sub>0.18</sub> with 5.25  $\mu\text{m}$  cutoff at 200 K are grown by Molecular Beam Epitaxy (MBE) on GaSb and GaAs substrates, respectively. The measured dark current on these nCBn detectors (cutoff = 5.25  $\mu\text{m}$ ) fabricated FPAs are presented in Figure 4 (c).

The dark current density in the pyramidal structured diodes is reduced by a factor of 2-3, which is consistent with the volume reduction due to pyramid formation. The detectivity ( $D^*$ ) of  $> 1.0 \times 10^{10} \text{ cm}^2 \sqrt{\text{Hz/W}}$  is achieved at longer cut-off, and a quantum efficiency of  $> 80\%$  is maintained over the entire 0.5 to 5  $\mu\text{m}$  spectral band at 200 K. Figure 4(c) is the measured dark current data as a function of detector bias of 64X64 detectors tied in parallel sampled from a 18  $\mu\text{m}$  pitch detector array of 1024x1024 FPA. The data also implies that detectors have high operability and uniformity.

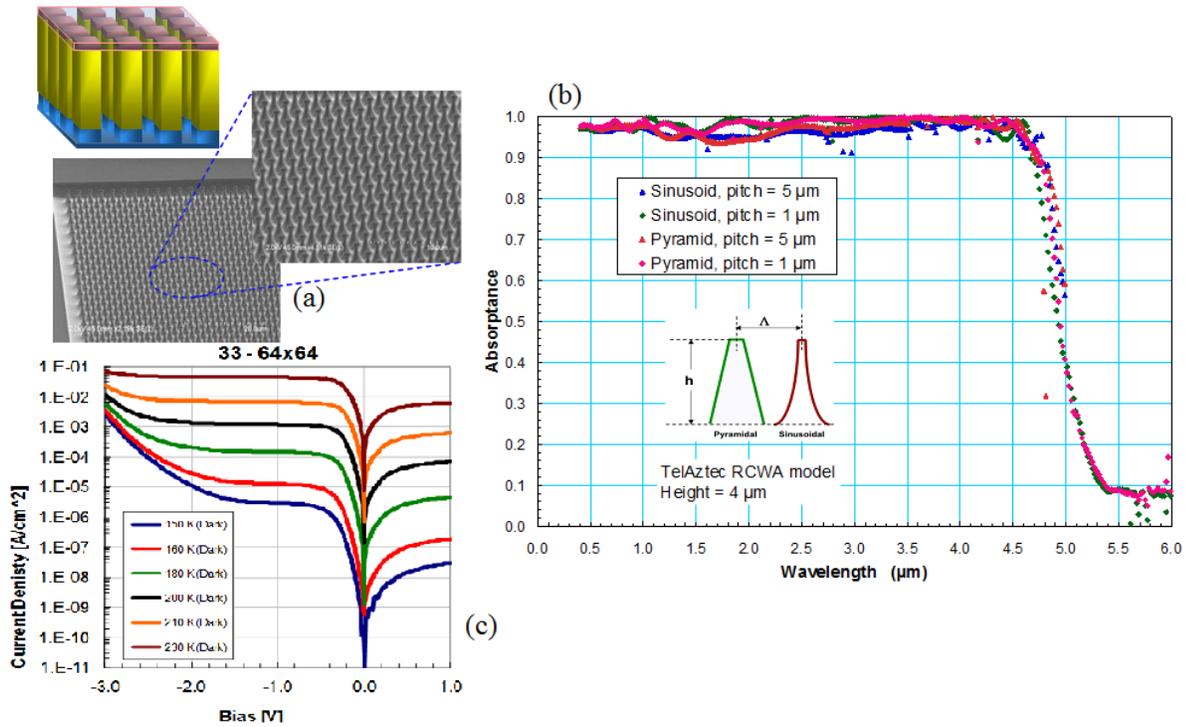


Figure 4. Micrograph of pyramidal PT structure fabricated in epitaxial InAsSb 4(a) with illustration of pillared structure; broadband absorption model 4(b) and;  $J_d$ - $V_d$  characteristics of nCBn detectors 4(c).

Other PT design approach uses a photonic crystal architecture with holes as well as pillars in HgCdTe material. These approaches also demonstrate dark current reduction due to reduced material volume. Finite-difference time-domain (FDTD) simulation of these device structures indicates resonance between pillars and that the sloped sidewall acts as a photon trap. The photon trap acts by total internal reflection, effectively serving as a waveguide to direct incident energy away from the removed regions and into the remaining absorber material. The pillars and holes are fabricated in HgCdTe layers that are grown on Si by MBE and CdZnTe by LPE. An example of electromagnetic simulation is shown in Figure 5 below.

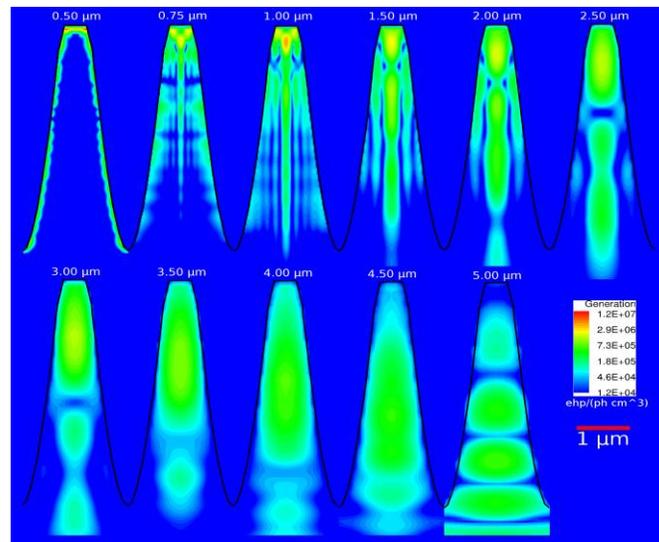


Figure 5. Electromagnetic simulation of photon trap pillared structures in HgCdTe material.

## 4. LAMBDA-SCALE FOCAL PLANE ARRAYS

The lambda scale detector program is developing FPAs with pixel dimensions approaching wavelength scale (Nyquist limit) for developing very high density FPAs. In this program, unit cells are being reduced to  $5\ \mu\text{m} \times 5\ \mu\text{m}$  for LWIR and MWIR. The program is also addressing pixel scaling in SWIR FPAs. The biggest motivation for small unit cell design FPAs is to enable smaller form-factor cameras. The capability to scale pixel size also offers a better design space for a well sampled system. Scaling pixels is a challenge and the program's main intent is to solve the associated challenges, thus providing opportunity for new design space for the infrared system. The new design space can potentially offer smaller optics and smaller size, weight and power for new applications not available today.

In this program three different device designs are being pursued. The program has achieved significant improvements in various challenges associated with small pitch high density FPAs. Paramount among these challenges is crosstalk, integration capacitor and indium bump bonding to the readout integrated circuit (ROIC) chip. There are many other challenges such as ROIC unit cell design and good signal to noise ratio.

One of the team in the program is using their High Density Vertically-Integrated Photodiode (HDVIP®) process, where passivated p-type HgCdTe is bonded to the ROIC prior to diode formation. Vias are etched using an inductively-coupled plasma reactor. Via sidewall metallization connects the HgCdTe to the ROIC landing pad. The HgCdTe surrounding the via is converted to n-type during the via etch, forming a p-n junction photodiode. The process goal for the  $5\ \mu\text{m}$  pixel pitch is to have a via diameter of  $1.2\ \mu\text{m}$ - $1.6\ \mu\text{m}$ , which consumes only 5-8 % of the optical pixel area. In order to fabricate these small vias, I-line (365 nm) lithography that is capable of printing  $0.6\ \mu\text{m}$  vias and  $0.4\ \mu\text{m}$  lines is employed.

To achieve the 30 mK sensitivity goal of AWARE-Lambda Scale LWIR FPAs requires the ability to handle large amounts of integrated charge in a very small pixel. For a  $5\ \mu\text{m}$  planar unit cell, the charge capacity in standard ROIC technology is less than 1 million electrons, whereas 8 to 12 million electrons are required for good sensitivity – a reason why small pitch IR detectors are not available today. As an enabler for this small pitch LWIR detector, the challenge of charge storage in small pixels is being addressed by fabricating MEMS capacitors suited to a 3D ROIC design. The MEMS capacitor array can be fabricated in a separate 8" wafer. This technology yielded 20 million electrons in a 5 micron unit cell. This breakthrough opens the door for small pitch FPAs to operate with very high sensitivity. Achieving very small pixels will enable large format FPAs with small optics and cold shield, better resolution and yielding a huge reduction in system size and weight.

The overall AWARE lambda-scale architecture uses a 3D vertically integrated design as depicted in Figure 6(a). In one approach, three layers (detector array, ROIC and MEMS capacitor array) are being developed separately, followed by integrating individual cells via indium bumps and through silicon vias (TSV). Figure 6(b) shows a Transmission Electron Micrograph (TEM) picture of a portion of the MEMS capacitor array.

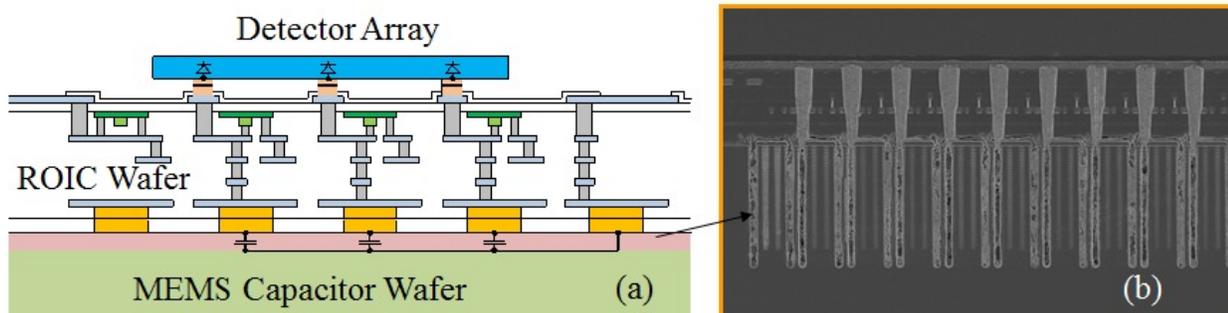


Figure 6. Schematic illustration of the 3D integrated AWARE Lambda-Scale LWIR FPA design (a); Transmission Electron Micrograph of the MEMS capacitor array cross section (b).

Using the HDVIP technology a fully functional 1280X720, 5  $\mu\text{m}$  unit cell LWIR FPA has been produced. The characterization shows excellent results with 99.8% response operability within 50% of the median. Detailed characterization results will be published in a separate paper. A TEM picture of this FPA is shown in Figure 7 with inset illustrating the pixel geometry. Both FPA technologies, Figures 6 and 7, are being developed using HgCdTe molecular beam epitaxy (MBE) and liquid phase epitaxy (LPE), respectively. A third approach using metal organic vapor phase epitaxy (MOVPE) on GaAs substrates is also being employed, but details are not presented in this paper.

Within the AWARE program smaller pitch SWIR and MWIR technologies are also being developed. For the SWIR applications, InGaAs on InP substrates as well as Si/Ge on Si and HgCdTe on Si is being pursued. The MWIR small pitch activity with 4.2  $\mu\text{m}$  and 5.2  $\mu\text{m}$  cutoffs is developing 5  $\mu\text{m}$  and 6  $\mu\text{m}$  pitch FPAs. Small pitch MWIR development utilizes barrier detector design using III-V alloys and HgCdTe material to evaluate performance and potential for different applications. Details of these projects will be published at a later date.

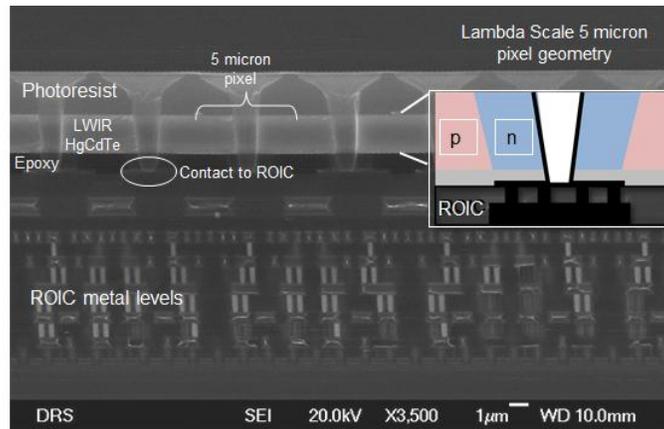


Figure 7. Transmission Electron Micrograph of a 1280X720 LWIR, 5  $\mu\text{m}$  pitch 3D integrated using HDVIP technology. The inset depicts the HDVIP pixel geometry developed by DRS Technologies.

The challenge of indium bumps for small pitch detectors are being addressed using two approaches. One is the so called “Loop-Hole” process and the other is the “Pin and Socket” process. Conventional indium bump technology is not adequate for the hybridization of large arrays of 5  $\mu\text{m}$  pitch detectors. Indium tends to slip and/or extrude laterally a few microns during cold welding (near room temperature). For larger pixels this tolerance may be acceptable, but would result in very poor yields for 5  $\mu\text{m}$  pixels. The approaches for In-bump process is shown in Figures 8(a & b).

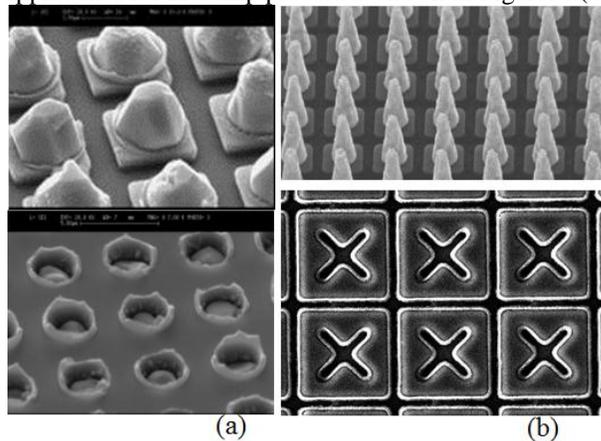


Figure 8. Transmission Electron Micrographs of “Loop-Hole: (a) and “Pin & Socket” (b) for 5  $\mu\text{m}$  size detector arrays.

## 5. MULTIBAND FOCAL PLANE ARRAYS

The main objective of the program is to develop a single sensor that will allow day/night imaging with inherent image alignment in multiple bands (Visible, NIR, SWIR and LWIR), while providing the capability to see laser lights, designators, and range finders. This integrated multi-band focal plane array will enable use of a single aperture, which will reduce system volume and weight. Furthermore, the integrated detector approach will eliminate the need for image registration via electronic alignment, thereby reducing computational requirements and the associated power requirement and mechanical alignment methods that increase imager system complexity. The key technical challenges include: transmission of VNS radiation through the LWIR sensor, a single chip, dual function (VNS and LWIR) ROIC, high performance VNS and LWIR detectors, VNS sensor process and materials compatible with LWIR micro-bolometer fabrication processes, and broadband compact optics.

The approach is to develop the integrated, dual-band uncooled focal plane array by stacking a Vanadium Oxide (VOx) bolometer (LWIR) on top of an InGaAs detector (Visible-SWIR). A notional layout of the integrated dual band detector is shown in Figure 9. The demonstration thus far shows the feasibility of an integrated InGaAs and micro bolometer device processing methodology with the first 640x512 InGaAs/Bolometer integrated FPA. The LWIR bolometers are fabricated on top of InGaAs detectors to form an umbrella-like structure [4] that greatly improves sensitivity. The demonstration establishes for the first time a single interface for LWIR, SWIR and NIR with 80% transmission through the LWIR layer. This technology will offer the opportunity for a single multi-band rifle scope with see-spot, designation, higher resolution SWIR and thermal capabilities. Based on the successful achievement of the Phase I goals and the current progress on Phase II, it is clear that most of the technological challenges deemed to be the show stoppers, are now resolved and proof of concept demonstrated.

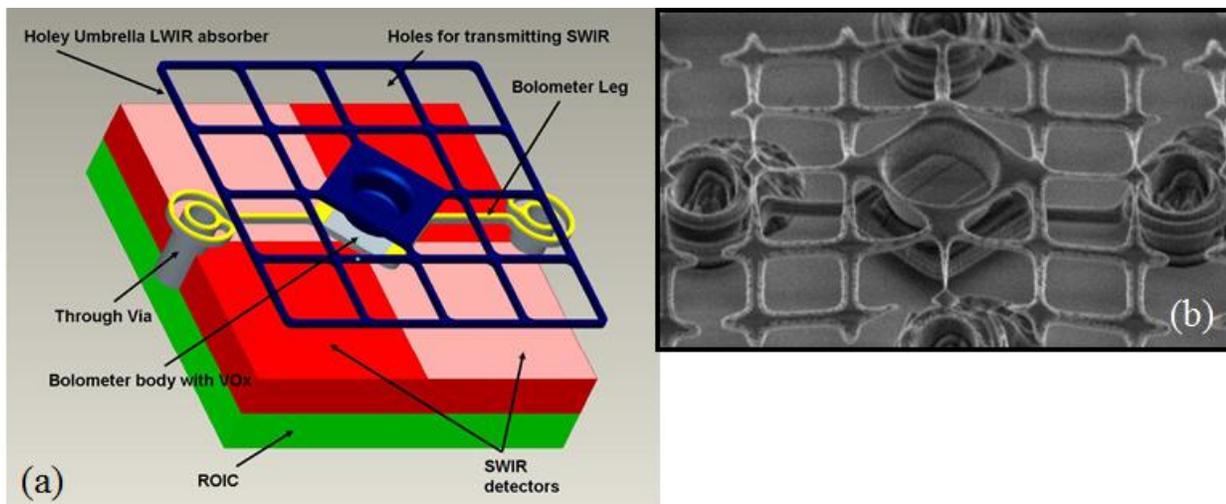


Figure 9. Schematic illustration of the vertically integrated bolometer and InGaAs detectors with a common ROIC (a). Transmission Electron Micrograph of the “DRS Holey Umbrella” microbolometer design (b).

## 6. SUMMARY

The results presented on the DARPA-MTO AWARE program indicate that the proposed imaging concepts are being validated by the design and experimentation of the performers. Preliminary results indicate for the first time that broadband, wavelength scale and multiband infrared performance can be achieved and with performances beyond SOA. The research teams have solved the broadband absorption challenge by using novel pyramidal and pillared II-VI and III-V semiconductor microstructures. They have demonstrated 10X lower dark current and uniform QE than SOA. This achievement paves the way to replace four cameras with one. It also allows for using in hyper spectral or multispectral mode for better target discrimination compared to a single narrow band camera. The AWARE program has demonstrated a

single interface for LWIR, SWIR and NIR with 80% transmission. Previously, this was not possible with a single interface. This technology will offer the opportunity for a single multi-band rifle scope with see-spot, designation, higher resolution SWIR and thermal capabilities. The program has also solved the challenge of charge storage in small pixels by fabricating MEMS capacitors suited to a 3D ROIC design. The performers have achieved 20 million electrons in a 5 micron pixel. This charge capacity will allow the FPA to operate with very high sensitivity and will avoid the need for frame averaging or shared pixel architecture in the ROIC. Achieving very small pixels will enable large format FPAs with small optics and cold shield, several times better spectral resolution and yielding a huge reduction in SWaP.

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