Type II Strained Layer Superlattice: A Potential Infrared Sensor Material for Space

L. Zheng[a], M. Z. Tidrow[b1], A. Novello[b], H. Weichel[c], S. Vohra[d]
[a]Institute for Defense Analyses
[b]Missile Defense Agency, 7100 Defense Pentagon, Washington, DC 20301
[c]Computer Sciences Corporation
[d]SPARTA Corporation

ABSTRACT

The Missile Defense Agency's Advanced Technology Office is developing advanced passive electro-optical and infrared sensors for future space-based seekers by exploring new infrared detector materials. A Type II strained layer superlattice, one of the materials under development, has shown great potential for space applications. Theoretical results indicate that strained layer superlattice has the promise to be superior to current infrared sensor materials, such as HgCdTe, quantum well infrared photodetectors, and Si:As. Strained layer superlattice-based infrared detector materials combine the advantages of HgCdTe and quantum well infrared photodetectors. The bandgap of strained layer superlattice can be tuned for strong broadband absorption throughout the short-, mid-, long-, and very long wavelength infrared bands. The electronic band structure can be engineered to suppress Auger recombination noise and reduce the tunneling current. The device structures can be easily stacked for multicolor focal plane arrays. The III–V semiconductor fabrication offers the potential of producing low-defect-density, large-format focal plane arrays with high uniformity and high operability. A current program goal is to extend wavelengths to longer than 14 µm for space applications. This paper discusses the advantages of strained layer superlattice materials and describes efforts to improve the material quality, device design, and device processing.

Keywords: Type II strained layer superlattice, infrared material, infrared detector, focal plane array, large format, alternative substrate, multicolor, Missile Defense Agency, ballistic missile defense system

1. INTRODUCTION

Space-based infrared technology is important to long-range ballistic missile defense for incoming missile acquisition, tracking, and discrimination. Ballistic missile defense against various targets requires tactical and strategic sensors and sensor platforms. The Missile Defense Agency Advanced Technology Office has an established Passive Electro-optical/Infrared Sensor Technology Program. The objectives of this program are to develop advanced infrared sensor technologies for future ballistic missile defense system capabilities and to bridge the gap between technology development and ballistic missile defense system needs. Depending on the application, space-based sensors can be at different orbital altitudes and may operate at different wavelengths. The selected wavelengths are based on the observational characteristics of the targets. Fig. 1 shows several space-based infrared sensor systems located at different orbital altitudes with various infrared sensors, each designed to observe a different target set. The Space Tracking and Surveillance System, a major acquisition program under the Missile Defense Agency, is a constellation of satellites in low-Earth orbits. It detects and tracks cold targets at a far distance. It requires sensors with large field of view for wide area coverage.

[1] E-mail Meimei.tidrow@mda.mil; Phone (703) 882-6188.

Quantum Sensing and Nanophotonic Devices V, edited by Rengarajan Sudharsanan, Christopher Jelen,
Proc. of SPIE Vol. 6900, 69000F, (2008) · 0277-786X/08/$18 · doi: 10.1117/12.768420

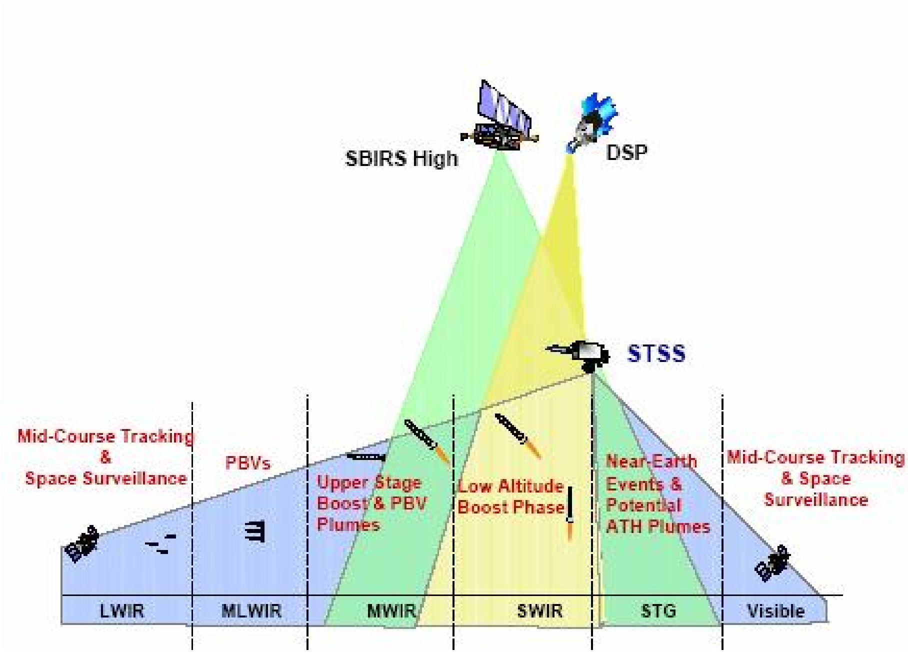

Fig. 1. Space-based infrared systems in various Earth orbits, with various infrared sensors each designed to observe a different set of targets.

Infrared materials and sensors are available at medium wave infrared using InSb and HgCdTe. HgCdTe also works well for long wave infrared applications and at high background. Using infrared materials and sensors for space is difficult in long wave and very long wave infrared regions with a low background. The ideal candidate for very long wave infrared is arsenic-doped silicon (Si:As). However, Si:As infrared focal plane arrays have to be operated at around 10 K, which requires a high-efficiency, low-weight, low-power-consumption, and long-life 10 K cryocooler. Currently, the II–VI compound semiconductor HgCdTe/ZnCdTe is used in most long-wave infrared sensors. Its development history may be traced back to 1959, when Lawson et al. reported that at 0 K, the bandgap energy of $Hg_{1-x}Cd_xTe$ varied from –0.3 meV to 1.605 meV, depending on the value of x.[1] The negative sign indicates that the bottom of the conduction band is lower than the top of the valence band. Since then, various empirical expressions have been developed relating the bandgap energy to the temperature and the cadmium fraction x, and it has become the most widely used infrared detector material.[2] There are several advantages of using this material in an infrared detector. The material has an intrinsic energy gap with a high absorption coefficient at infrared spectral bands. The wavelength response can be tailored by changing the cadmium molar fraction value of x. By some accounts, the material is one of the most studied semiconductors. Many of the difficulties in developing HgCdTe infrared detectors and focal plane arrays encountered in the early days, such as finding a lattice-matched substrate, growing low-defect crystals, forming p-n junctions, processing, and passivation, have been overcome by the collective efforts of the infrared detector community.

While continuous improvement is still being made on HgCdTe detectors, it is also recognized that for certain applications the material may have severe limitations.[3] Because of the difficulties associated with producing homogeneous material, detectors arrays are limited to small format at long wave infrared and very long wave infrared. Compositional non-uniformities cause different detectors to have different cutoff wavelengths, resulting in non-uniform detector response between individual detector elements. This also leads to decreased wafer yield at the high performance specifications required for space applications. Excessive dark currents due to the band-to-band tunneling of carriers, trap-assisted tunneling and its variation from cool-down to cool-down, and defect-mediated generation-recombination degrade device performance and operability in the very long wave infrared region. HgCdTe photodiodes are also sensitive to 1/f noise, which is linearly dependent on surface-leakage current. The thermal expansion coefficient difference between CdZnTe substrate and readout circuit may put additional stress on focal plane arrays in the very long wave infrared region, where the operating temperature is at about 40 K. The Missile Defense Agency has been funding HgCdTe focal plane array development at wavelengths longer than 12 μm. The molecular beam epitaxy material-growth technique allows tight control of many parameters, and significant progress has been made. However, due to the nature of the HgCdTe and its substrate material, it is challenging to push large-format HgCdTe focal plane arrays to operate in the very long wave infrared domain. The investment in this area starts to show diminishing returns when developing HgCdTe FPA on CdZnTe substrate for very long wave infrared at a low background. Therefore, besides Si:As and HgCdTe, The Missile Defense Agency is exploring several other advanced alternative infrared materials that have the potential for VWLIR sensors in space at low background.

2. ADVANCED ALTERNATIVE INFRARED MATERIALS FOR SPACE

The Missile Defense Agency Passive Electro-optical/Infrared Program focuses on developing advanced infrared materials and focal plane arrays for ballistic missile defense sensor systems. These sensor systems are used for space surveillance, target tracking, discrimination, and engagement during boost, ascent, midcourse, and terminal phases. Ideal electro-optical/infrared sensors are characterized by wide-area coverage during surveillance, long detection ranges, a capability to discriminate targets from clutter having very large temperature ranges and spectral characteristics, fast update rates, and precision in tracking and engagement. To address these diverse needs, the program is developing several infrared focal plane arrays and supporting technologies based on different infrared detector materials. Several criteria are used in the technology selection process. The materials and detector arrays have to be easy to produce, potentially low cost, and enable the manufacture of very large format focal plane arrays. Ideally, one single material family can cover the entire infrared spectrum, thus simplifying system configuration and reducing production costs. The material should also be sensitive for very long wave infrared detection, and the detector array can be made to perform simultaneous multiband detection with pixel-level co-registration. The ideal material should also enable the sensor system to operate at an elevated temperature, thus reducing system size and weight associated with using a cooler and increasing system reliability and lifetime.

Three infrared detector materials have been explored recently: HgCdTe infrared detectors on silicon substrates (HgCdTe/Si), high quantum efficiency quantum well infrared photodetectors, and Type II strained layer superlattice infrared detectors.

The key advantage of HgCdTe/Si technology is its potential to produce high-quality, very large size focal plane arrays at low cost. The maximum size of the lattice-matched substrate material, CdZnTe, is 7 cm × 7 cm. The cost of this material is about 25 times that of silicon. Growing and processing detector arrays on high-quality, large-area silicon substrates makes it possible to take advantage of standard silicon processing equipment and to improve yield. For space applications such as surveillance, detection, and tracking, large focal plane arrays are necessary to obtain a large field of view.

Another advantage of this technology is that there is no thermal mismatch problem between the silicon substrate and the read-out integrated circuit made of silicon. The major challenge for this technology is the 19% lattice mismatch, which causes increased threading dislocation density in HgCdTe layer and CdTe buffer layers. At long wave infrared and very long wave infrared, higher dislocation density is linked to shorter minority carrier lifetime and carrier diffusion length, higher dark current noise, and the long tail in dark current operability histogram.[4] Innovative approaches to overcome this challenge have been proposed and tested, but dislocation density is still at least one order of magnitude larger than that in HgCdTe detectors grown on CdZnTe. Further reduction in dark current noise and improvement in quantum efficiency operability and uniformity are necessary.

The advantage of quantum well infrared photodetectors results from their construction: They are made of III–V semiconductor material GaAs/AlGaAs grown on large-size, high-quality substrate GaAs. This material is widely used in commercial optoelectronics and has a wide industry base. Focal plane arrays based on these materials are easy to fabricate and have high uniformity and operability due to low material defect rates. There is also intrinsic radiation hardness built into quantum well infrared photodetectors. Although multicolor focal plane arrays can also be fabricated with clever device design,[5] the performance of a quantum well infrared photodetector is fundamentally limited by its low quantum efficiency and relatively high thermal dark current due to its photoconductive mode of operation. Dielectric relaxation at low background is another disadvantage. Although the quantum well infrared photodetector is an excellent candidate for certain applications, it is not an ideal detector for low-background space applications.

Type II strained layer superlattice material has the advantages of both HgCdTe and quantum well infrared photodetector materials. Theoretical calculations and modeling predict that strained layer superlattice detectors can have higher detectiviy than HgCdTe detectors. We believe that strained layer superlattice has the most potential for operation in the very long wave infrared region and is the best candidate for future infrared space-based sensors. The remainder of this paper details the theoretical advantages, current program efforts, recent achievements, and future challenges of strained layer superlattice.

3. ADVANTAGES OF TYPE II SUPERLATTICE INFRARED MATERIAL

The Type II superlattice was proposed as an alternative infrared material to overcome some of the problems associated with HgCdTe. In 1977, Sai-Halasz, Tsu, and Esaki published a theoretical work on the unusual band structure of a Type II superlattice made of InAs and GaSb semiconductor materials.[6] In 1987, Smith and Mailhiot proposed the idea of introducing strain to Type II superlattice by adding Indium to GaSb, predicting that such material should have favorable optical properties for infrared detection.[7] Much progress has been made through improved theoretical understanding and experimental demonstration, as reflected in many published original papers and review articles.[8]

Band structure engineering is the essential idea used when designing and fabricating superlattice-based infrared detector materials. For many years, high-quality detectors could only be made with natural semiconductor materials or alloys, such as HgCdTe, in which a fixed energy band structure is characteristic of the material and its composition. In artificial crystal structure superlattices, the energy band structure can be changed by altering the layer parameters, such as layer thickness and composition. In a Type I superlattice, the alternating layers are composed of semiconductors in which the bandgaps are approximately aligned (i.e., the valence band of one does not overlap the conduction band of the other), and the conduction bands are of Γ_6 symmetry and the valence bands are of Γ_8. An example is the GaAs/AlGaAs quantum well infrared photodetector system. A Type II superlattice is similar to Type I, except for overlapping conduction and valence bands in adjacent layers. An example is InAs/GaSb. In a Type III superlattice the alternating layers are of different conduction and valence band symmetry. An example of a Type III superlattice is HgTe/CdTe.[9] All three types of superlattices have been proposed for use as infrared materials. When considered as infrared detectors, Type II and Type III superlattices are essentially minority-carrier-dominated intrinsic semiconductor materials. Current emphasis is on Type II materials because of their theoretical promise, easier III–V material growth and processing, and limited funding available at the moment.

The bandgap of lattice-matched InAs/GaSb superlattice can be tuned by adjusting the thickness of individual semiconductor layers. Because of the Type II band alignment, the InAs/GaSb superlattice can have a bandgap smaller than that of either InAs or GaSb. For a fixed GaSb layer thickness, the bandgap of this binary/binary superlattice decreases when the InAs layer thickness increases. For example, calculations by Corbin et al.[10] show that if GaSb layer thickness is fixed at 10 monolayers, the bandgap of the superlattice is about 250 meV at an InAs width of 8 monolayers and decreases to about 100 meV at an InAs width of 16 monolayers. However, the Type II band alignment also means that electrons tend to be localized within the InAs layer, whereas holes tend to be localized within GaSb layers. When the layer thickness decreases, the electron-hole wave function overlap increases and optical absorption increases. Conversely, when layer thickness increases to larger than 5 nm, the wave function overlap decreases and optical absorption becomes too small for infrared detector application. For long-wave infrared detection purposes, the simultaneous requirements of small bandgaps and large optical absorption coefficients impose restrictions in detector design space.

By alloying GaSb and InAs to form InAs/$Ga_{1-x}In_xSb$ binary/ternary Type II superlattice, the design space is expanded to allow simultaneous tuning of the bandgap and the optical absorption coefficient using two independent variables—indium composition x and layer thickness. The introduction of indium leads to an increased lattice constant in the GaInSb layer. This causes lattice mismatch and strain between alternating layers. As a consequence, the valence band splits into heavy hole and light hole bands, effectively decreasing the bandgap. Meanwhile, the absorption coefficient can still be tuned by adjusting layer thickness. With bandgap engineering, broadband coverage throughout the 3–30 μm regime is possible. For space applications, this is especially attractive since it allows the very long wave infrared (>14 μm) coverage that is desired by the Missile Defense Agency's Space Tracking and Surveillance Systems and Multiple Kill Vehicles but which cannot be easily achieved with current technology. Other missile defense elements such as Terminal High Altitude Area Defense, Standard Missile 3, and Airborne Laser may also benefit from superlattice infrared detectors as seekers and surveillance sensors in their systems.

Note that strain can also be introduced to the binary/binary system by using unequal layer widths although the degree of freedom in design space is limited. In practice, binary/binary is easier to grow, with less sensitivity to the growth temperature and the III/V flux ratio. The absence of an alloy layer means minimal interlayer strain compared with InAs/GaInSb, so strain-induced defects are less likely. However, it could be argued that the weaker strain does not allow full exploitation of all the advantages of the Type II superlattice, such as Auger suppression, discussed next. In fact, it may be advantageous to make other variations of superlattice composition, such as quarternary component and structures with more than two layers per unit cell, as has been proposed and developed by some researchers.[11]

Band structure engineering is an effective means to suppress band-to-band Auger recombination noise for the application of long wave infrared and very long wave infrared. Auger recombination in direct-gap semiconductors involves the interaction of three carriers. The Auger-1 mechanism in n-type material involves the recombination of a minority carrier hole and an electron, with the resulting energy and momentum conserved by a second hot electron in the conduction band. In p-type material the primary Auger mechanism involves the recombination of a minority carrier electron and a heavy hole, with excess energy and momentum conserved by the production of a hot light hole. This mechanism is referred to as Auger-7. It is predicted by theory and demonstrated by laboratory experiment that the Auger recombination rate is roughly two orders of magnitude smaller in InAs/GaInSb superlattice than in HgCdTe at long wave infrared.[12] In p-type superlattice, Auger rates are suppressed due to lattice-mismatch-induced strain that splits the highest two valence bands. The highest light hole band lies significantly below the heavy hole band and thus limits available phase space for Auger transitions. In n-type superlattice, Auger rates are suppressed by increasing the InGaSb layer widths, thereby flattening the lowest conduction band and thus limiting available phase space for Auger transition. However, this is far less effective than the band structure adjustments possible in the valence bands.

Another advantage of strained-layer superlattice is its ability to simultaneously achieve a small bandgap and a large effective electron mass, which is absent in bulk material such as HgCdTe. The electron effective mass can be calculated from the energy dispersion relationship. Strain-induced band splitting causes large energy dispersion along the growth axis, thus a large effective mass can be achieved. In bulk semiconductors, the effective mass is proportional to bandgap, which means that at longer wavelengths the effective mass becomes smaller. At 12 µm, the effective electron mass of HgCdTe is about 0.01 m_0 at 12 µm wavelength, while the effective mass of InAs/InGaSb is about 0.03 m_0. At 20 µm, the effective electron mass of InAs/InGaSb is about the same, but that of HgCdTe decreases to 0.007 m_0..[13] Here m_0 is electron mass. This is significant because band-to-band tunneling current depends exponentially on the effective mass as described in the following equation

$$J_T = C_1 (m^*/E_g)^{1/2} e^{-C_2 m^{*1/2} E_g^{3/2}} \, . \quad (1)$$

In the equation, J_T is the tunneling current, C_1 and C_2 are constants, E_g is the bandgap, and m^* is the electron effective mass. In HgCdTe, small effective electron mass causes large interband tunneling dark current at long and very long infrared wavelengths. This has been a problem that affects the performance of HgCdTe detectors. Type II superlattice has an edge here over HgCdTe.

Type II superlattices are usually made from alternating layers of two different III–V semiconductor materials, most commonly InAs/GaSb and InAs/InGaSb. Epitaxial growth of III–V materials produces a higher degree of uniformity, which is important for making detector arrays. III–V materials are also widely used in the telecommunications industry, which has invested heavily in material growth, device modeling and design, and device processing and packaging. Type II strained layer superlattice detector development can benefit from many of the mature technologies as well as the commercial industrial base. In addition, there is the greater availability of well-behaved substitutional impurity dopants. For molecular beam epitaxy growth, silicon and beryllium are well-behaved dopants. Silicon is a well-behaved p-type dopant for GaSb, and it is an n-type dopant for InAs. Beryllium is known to be an acceptor for all of the conventional III–V compounds.[14]

4. CURRENT PROGRAM EFFORT AND RECENT EXPERIMENTAL RESULTS

There are several parallel efforts under the Passive Electro-optical/Infrared Program to develop strained layer superlattice infrared focal plane arrays. Participants include Naval Research Laboratory, Jet Propulsion Laboratory, Teledyne Scientific Imaging, Raytheon Vision Systems, and MP Technologies. The ultimate goal is to develop large-format, multiple-color, high-performance infrared focal plane arrays and passive sensor systems at long and very long wavelengths. The Passive Electro-optical/Infrared Program also co-manages several strained layer superlattice-related research programs funded under several small business and university research programs, such as the Small Business Innovation Research (SBIR) Program, Small Business Technology Transfer (STTR) Program, the Missile Defense Science, Technology, and Research (MSTAR) Program, and the Historically Black Colleges and Universities and Minority Institutions (HBCU/MI) Program. Current participants include QmagiQ, Nova, SVT, Epitaxial Technologies, the University of New Mexico, and Northwestern University. The emphasis is to develop innovative ideas and technologies in the area of material and device modeling, high-quality material growth, device processing, and FPA signal processing.

In the past few years the emphasis was on demonstrating high-quantum-efficiency, low dark current, single-color, long-wavelength infrared focal plane arrays. Tremendous progresses have been made. Figure 1 shows an image obtained with a superlattice long wave infrared FPA. The detector array has a format of 256 × 256, pixel pitch of 30 µm, and cutoff wavelength of 10.5 µm.[15] Dark is warm. The array is back-side illuminated with no filter, with an integration time of 900 µs. The FPA temperature is 78 K. A more recent image is shown in Figure 2. It was taken with a different superlattice FPA with the following parameters: detector array size 320 × 256, pixel pitch 30 µm, cutoff wavelength 10 µm, operating temperature 81 K, integration time 0.11 ms, average detectivity about 10^{11} Jones, and operability 96%.[16] The following summarizes the key underpinning technological advances responsible for these images:

1. *Innovative superlattice detector design, one of the key contributors*—The research team modeled and experimented with various diode structures, including high-quantum-efficiency and low-dark-current p-i-n design, double-heterostructure superlattice M-structure, high quantum efficiency W-structure, and dark-current-suppressing graded-gap W-structure.[17] In a W-structure design, a quarternary AlGaInSb barrier layer is inserted at the two sides of InAs electron wells located on either side of InGaSb hole well. The barriers confine the electron wave functions, increasing the electron-hole overlap while nearly localizing the wave functions, thus increasing absorption near the band edge. Meanwhile, the barrier height is optimized to improve collection efficiency by increasing minority carrier mobility. In M-structure design, a thin AlSb layer is inserted in the GaSb layer to form a barrier in the conduction band and a double quantum well for holes in the valence band. This adds wavelength tunability that is independent from the lattice matching constraint.

2. *Continuous improvement in superlattice materials*—Growth precision is down to half an atomic layer in superlattice layer thickness and layer variation in the active and cap regions. Strain at each superlattice layer is more balanced so that a thicker absorption region can be grown without causing defects, thus increasing quantum efficiency. For example, MPT has achieved a quantum efficiency of larger than 50% at 9 µm and 78 K, with $R_0A = 12\ \Omega\text{-cm}^2$.

3. *Step-by-step device processing optimization with precision operational parameter control*—Precise and repeatable temperature setting is one example. Another example is dry-etching process development. Etch-rate, etch rate uniformity, and mask design will affect fill factors and passivation quality of mesas. Other processing improvements include GaSb surface preparation, metallization with good ohmic contact, and smooth morphology.

4. *Systematic search for the perfect passivant among candidates such as SiO_2, polyimide, lattice-matched epitaxial re-growth*—Surface leakage pathways in III–V superlattice material system can arise from the termination of the periodic semiconductor crystal that results in the pinning of the Fermi energy level at the band edges. The degree of the induced band bending varies as a function of the surface potential. As a consequence, an accumulation of carriers can occur near the diode surface of low-bandgap photodiodes, leading to strong tunneling currents. One effective passivation is low-temperature, ion-beam sputtered SiO_2 passivation. Passivation with polyimide hass also proved very effective.[18] Another approach is shallow-etch mesa isolation with bandgap-graded junction.[19] In this approach, the mesa etch terminates at just past the junction and exposes only a very thin (300 nm), wider bandgap region of the diode. Subsequent passivation is therefore in wider gap material. It reduces electrical junction area, increases optical fill factor to 100%, and eliminates deep trenches within detector array. These innovative passivation approaches have led dark current to be reduced by half to as much as 1/10 its original value.

5. *Substrate thinning to reduce the n-type GaSb substrate thickness, thus reducing photon absorption in the substrate*—A process has been developed to completely removal the GaSb substrate, thus further increasing quantum efficiency.

6. *Progress in FPA hybridization and testing*—By changing diode polarity to p-on-n, which matches commercial readout integrated circuit chip (such as Indigo ISC9705 320 × 256), better injection efficiency is achieved.

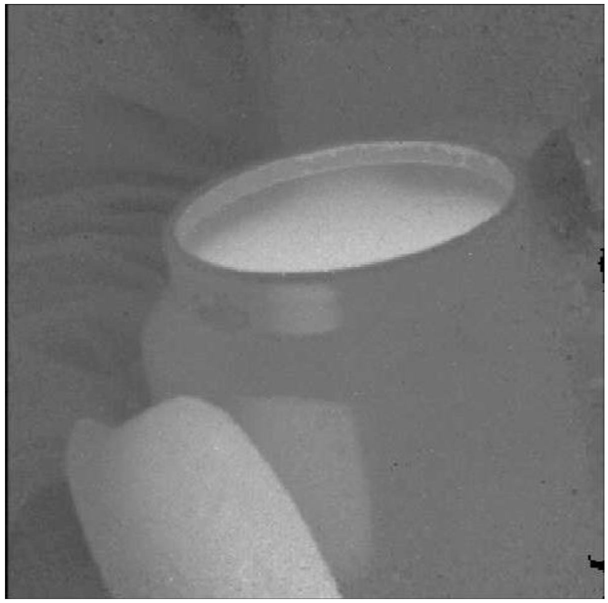

Figure 1 This image is obtained with a strained layer superlattice long wave infrared FPA fabricated at Raytheon Vision Systems. The detector array has a format of 256 × 256, pixel pitch of 30 µm, and cutoff wavelength of 10.5 µm.[20] Dark is warm. The array is back-side illuminated with no filter, with an integration time of 900 µs. The FPA temperature is 78 K.

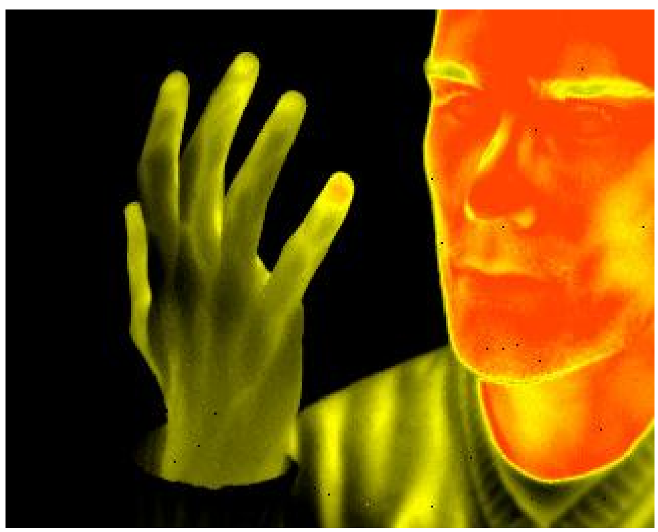

Figure 2. An image taken with a superlattice FPA at MP Technologies with the following parameters: detector array size 320 × 256, pixel pitch 30 µm, cutoff wavelength 11 µm, operating temperature 81 K, integration time 0.11 ms, average detectivity about 10^{11} Jones, and operability 96%.

5. CHALLENGES AND FUTURE DIRECTIONS

Further improvements in superlattice material growth, device design and modeling, and device processing are necessary to push the performance of superlattice-based infrared focal plane arrays to its predicted theoretical limit. More innovation is required to overcome many challenges. One challenge is to further decrease dark current noise. Dark current noise measured by R_0A should be reduced by two orders of magnitude. This means further reduction in material defects and better understanding of interface between superlattice layers. It also means further reduction in surface leakage current. It is highly desirable to decrease the background unintentional doping because Auger lifetimes are strongly dependent on carrier densities. Additional device structure optimization may be necessary to grow a thicker absorption region without increasing dark current noise. Innovation is needed to minimize detector cross talk while maintaining high quantum efficiency. This is especially important for small pixel pitches. Some innovation is probably required to perfect dry-etching techniques or other processing techniques to achieve higher fill factor than currently achieved, which is around 70% for 30 μm pixel pitch. More theoretical work could also help. This includes further exploitation and understanding of device structure, interfaces between layers, and doping compensations.

For very large format focal plane arrays, the community needs to overcome challenges associated with lattice mismatch and thermal expansion mismatch that manifest themselves when focal plane array size increases. Improvement in uniformity, yield, and operability are the ultimate metrics for performance measurement. All superlattice focal plane arrays developed under this program so far have been grown on lattice-matched GaSb substrate. The size of GaSb substrate is currently limited to 2 inches in diameter. A new endeavor is to develop technologies that allow superlattice growth on GaAs or silicon substrates. Large 6-inch GaAs substrates and 12-inch silicon substrates are already used in semiconductor foundries. This technology will lead to new capabilities of fabricating very large format focal plane arrays at low cost and high yield.[21] MPT is currently leading this effort. A related effort is to develop two-color LW/LW focal plane array, first on GaSb substrate, and eventually on GaAs or silicon substrates.

One area that needs to be addressed is long wave infrared and very long wave infrared focal plane array radiation hardness. Detectors developed under current technologies need to be fully characterized under a missile-defense-relevant radiation environment.

Once this is achieved, we will push further to achieve higher operating temperatures (HOT). Theory predicts HOT for strained layer superlattice materials due to suppression of Auger recombination. A related topic is to improve cooling efficiency. This is important for large focal plane arrays. The current cryogenic cooler is about 10–12% of the Carnot limit. Technologies should be developed to improve it to 30% of the Carnot limit.

6. SUMMARY

In summary, Type II superlattice is a promising infrared detector material and a serious contender for infrared sensing for space applications. Its key advantages include wavelength tunability over the entire infrared spectrum. It has favorable optical properties and allows photovoltaic operation. It is a III–V semiconductor material with a higher degree of uniformity and a well-understood device fabrication process. It has potentially smaller leakage currents due to the suppression of tunneling in the long wave infrared and very long wave infrared regions. Through band structure engineering, it can achieve lower Auger recombination rates and potentially high operating temperature or detectivity. In the past few years, significant progress has been made in developing single-color superlattice detectors and focal plane arrays at long wavelengths. Further improvement in material growth, device structure, and focal plane array processing is needed to realize the theoretical promise of the material. Future program effort focuses on making very large format single-color and multicolor focal plane arrays with alternative substrates and extending the waveband to very long wavelengths.

REFERENCES

1 W. D. Lawson, S. Nielsen, E. H. Putley and A. S. Young, "Preparation and properties of HgTe and mixed crystals of HgTe-CdTe," *J. Phys. Chem. Solids,* Pergamon Press, Vol. 9 (1959): 325–329.

2 P. Norton, "HgCdTe infrared detectors," *Opto-Electronics Review* 10(3), 159–174, 2002.

3 S. Krishnamurthy, M.A. Berding, H. Robinson, and A. Sher, "Tunneling in long-wavelength infrared HgCdTe photodiodes," *Journal of Electronic Materials,* Vol. 35, No. 6 (2006): 1399; Angelo Scotty Gilmore, James Bangs, and Amanda Gerrish, "VLWIR HgCdTe detector current-voltage analysis," *Journal of Electronic Materials,* Vol. 35, No. 6 (2006): 1403; Stephen P. Tobin, "Thermal cycling-induced changes in excess dark current in very long-wavelength HgCdTe photodiodes at low temperature," *Journal of Electronic Materials,* Vol. 35, No. 6 (2006): 1411.

4 M. Carmody, J.G. Pasko, D. Edwall, R. Bailey, J. Arias, M. Groenert, L.A. Almeida, J.H. Dinan, Y. Chen, G. Brill, and N.K. Dhar, "LWIR HgCdTe on Si detector performance and analysis," *Journal of Electronic Materials,* Vol. 35, No. 6 (2006): 1417; Richard Bornfreund, Joe Rosbeck, Yen Thai, Edward Smith, Daniel Lofgreen, Mauro Vilela, Aimee Buell, Michael Newton, Kenneth Kosai, Scott Johnson, Terry Delyon, John Jensen, and Meimei Tidrow, "High-performance LWIR MBE-grown HgCdTe/Si focal plane arrays," *Journal of Electronic Materials,* vol. 36, no. 8 (2007): 1085.

[5] Kwong-Kit Choi, Carlos Monroy, Venkataraman Swaminathan, Theodor Tamir, Ming Leung; John Devitt, David Forrai, Darrel Endres, "Optimization of corrugated-QWIPs for large format, high quantum efficiency, and multicolor FPAs," *Proc. of SPIE,* Vol. 6206 (2006): 62060B.

[6] Sai-Halasz, G. A., R. Tsu, and L. Esaki, "A new semiconductor superlattice," *Appl. Phys. Lett.* 30 (1977): 651–653.

[7] D. L. Smith and C. Mailhiot, "Proposal for strained Type II superlattice infrared detectors," *J. Appl. Phys.* 62 (1987): 2545.

[8] Gail J. Brown, "Type II InAs/GaInSb Superlattices for infrared detection: An overview," *Proc. of SPIE* Vol. 5783 (2005): 65–77; G.C. Osbourn, "Strained-layer superlattices: A brief review," *IEEE J. Quantum Electronics,* Vol. QE-22 (1986): 1677; C. Mailhiot, "Far-infrared materials based on InAs/GaInSb Type II, strained-layer superlattices," in *Semiconductor Quantum Wells and Superlattices for Long-Wavelength Infrared Detectors,* ed. M. Manasreh, 1993; E. L. Dereniak and G.D. Boreman, *Infrared Detectors and Systems,* John Wiley & Sons, Inc., 1996; M. Kinch, *Fundamentals of Infrared Detector Materials,* forthcoming; Jagmohan Bajaj, Gerry Sullivan, Don Lee, Ed Aifer, Manijeh Razeghi, "Comparison of Type II Superlattice and HgCdTe infrared detector technologies," *Proc. of SPIE* Vol. 6542 (2007): 65420B; A. Rogalski, "Competitive technologies for third generation infrared photon detectors," *Proc. of SPIE* Vol. 6206 (2006): 62060S-1.

[9] C. H. Grein, P. Boieriua, M. E. Flatté, "Single- and two-color HgTe/CdTe-superlattice based infrared detectors," *Proc. of SPIE* Vol. 6127 (2006): 61270W-1.

[10] E. Corbin, M. Shaw, M. Kitchin, J. Hagon and M. Jaros, "Systematic study of Type II Ga1−xInxSb/InAs superlattices for infra-red detection in the 10–12 µm wavelength range," *Semicond. Sci. Technol.* Vol. 16 (2001): 263–272.

[11] B-M. Nguyen, M. Razeghi, V. Nathan, Gail J. Brown, "Type II 'M' structure photodiodes: An alternative material design for mid-wave to long wavelength infrared regimes," *Quantum Sensing and Nanophotonic Devices IV,* ed. Manijeh Razeghi, Gail J. Brown, *Proc. of SPIE Vol.* 6479 (2007): 64790S; E. H. Aifer, J. G. Tischler, J. H. Warner, I. Vurgaftman, W. W. Bewley, J. R. Meyer, J. C. Kim, and L. J. Whitman, C. L. Canedy and E. M. Jackson, "W-structured Type II superlattice long-wave infrared photodiodes with high quantum efficiency," *Applied Physics Letters* 89 (2006): 053519; Mingrong Shen, Wenwu Cao, "Electronic band-structure engineering of GaAs/AlxGa1_xAs quantum well superlattices with substructures," *Materials and Engineering* B103 (2003): 122–127.

[12] E. R. Youngdale, J. R. Meyer, C. A. Hoffman, F. J. Bartoli, C. H. Grein, P. M. Young, H. Ehrenreich, R. H. Miles and D. H. Chow, "Auger lifetime enhancement in InAs-Ga1-xlnxSb superlattices," *Appl. Phys. Lett.* 64 (23), p. 3160, 6 June 1994; C. H. Grein, P. M. Young, M. E. Flatte, and H. Ehrenreich, "Long wavelength InAs/InGaSb infrared detectors: Optimization of carrier lifetimes," *J. Appl. Phys.* 78(12), p. 7143, 15 December 1995; C.H. Grein, "Modeling of recombination in HgCdTe and superlattices," Advanced Infrared Technology and Applications International Workshop, Leon, Mexico, 8–12 October 2007.

[13] E. Aifer, E. Jackson, B. Bennett, I. Vurgaftman, J. Meyer, and G. Jernigan, "Suppression of bulk defects in antimonide superlattice infrared photodiodes," *Mat. Research Soc. Symp. Proc.,* Vol. 722 (2002): K10.1.1–12.

[14] D.H. Chow, R.H. Miles, J.N. Schulman, D.A.Collins, and T.C. McGill, "Type II superlattice for infrared detectors and devices," *Semicond. Science Technology,* Vol. 6 (1991): C47.

[15] David R. Rhiger, Robert E. Kvaas, Sean F. Harris, Richard E. Bornfreund, Yen N. Thai, Cory J. Hillb, Jian V. Lib, Sarath D. Gunapala, and Jason M. Mumolo, "Progress with Type II superlattice IR detector arrays," *Proc. of SPIE* Vol. 6542 (2007): 654202.

[16] Binh-Minh Nguyen, Darin Hoffman, Yajun Wei, Pierre-Yves Delaunay, Andrew Hood, and Manijeh Razeghi, "Very high quantum efficiency in Type II InAs/GaSb superlattice photodiode with cutoff of 12 µm," *Applied Physics Letters* 90 (2007): 231108; Andrew Hood, Pierre-Yves Delaunay, Darin Hoffman, Binh-Minh Nguyen, Yajun Wei, and Manijeh Razeghi, Vaidya Nathan, "Near bulk-limited R0A of long-wavelength infrared Type II InAs/GaSb superlattice photodiodes with polyimide surface passivation," *Applied Physics Letters* 90 (2007): 233513; M. Razeghi, private communications, July 2007.

[17] B. Nguyen, M. Razeghi, V. Nathan, G. Brown, "Type II 'M' structure photodiodes: An alternative material design for mid-wave to long wavelength infrared regimes," *Quantum Sensing and Nanophotonic Devices IV,* ed. Manijeh Razeghi, Gail J. Brown, *Proc. of SPIE* Vol. 6479 (2007): 64790S; E. H. Aifer,a_ J. G. Tischler, J. H. Warner, I. Vurgaftman, W. W. Bewley, J. R. Meyer, J. C. Kim, L. J. Whitman, C. L. Canedy, and E. M. Jackson, "W-structured Type II superlattice long-wave infrared photodiodes with high quantum efficiency," *Applied Physics Letters* 89 (2006): 053519.

[18] Andrew Hood, Pierre-Yves Delaunay, Darin Hoffman, Binh-Minh Nguyen, Yajun Wei, and Manijeh Razeghi, Vaidya Nathan, "Near bulk-limited R0A of long-wavelength infrared Type II InAs/GaSb superlattice photodiodes with polyimide surface passivation," *Applied Physics Letters,* Vol 90, p. 233513, 2007.

[19] E. H. Aifer, J. H. Warner, R. R. Stine, I. Vurgaftman, C. L. Canedy, E. M. Jackson, J. G. Tischler, J. R. Meyer, D. Y. Petrovykh, and L. J. Whitman, "Passivation of W-structured Type II superlattice long-wave infrared photodiodes," *Proc. of SPIE* Vol. 6542, 654203, 2007.

[20] David R. Rhiger, Robert E. Kvaas, Sean F. Harris, Richard E. Bornfreund, Yen N. Thai, Cory J. Hillb, Jian V. Lib, Sarath D. Gunapala, and Jason M. Mumolo, "Progress with Type II superlattice IR detector arrays," *Proc. of SPIE* Vol. 6542, p. 654202, 2007.

[21] W. E. Hoke, C. S. Whelan, P.F. Marsh, P.J Lemonias, P.S. Lyman, S. M. Lardizabal, R.E. Leoni, T.E. Kazior, A. Torabi, J.-H. Jang, D.C. Dumka, I. Adesida, K.L. Chang, K.C. Hsieh, "Progress in GaAs-based metamorphic technology," 2001 GaAsMANTECH Conference, www.gaasmantech.org; M. Chertouk, D. W. Tu, P. Meng, C. G. Yuan, W. D. Chang, C. Y. Kuo, C. C. Chang, A. Chang, H. H. Chen, C. H. Chen, P. C. Chao, "Manufacturable 0.15 μm PHEMT Process for High Volume and Low Cost on 6″ GaAs Substrates : The first 0.15 μm PHEMT 6″GaAs foundry fab," 2002 GaAsMANTECH Conference, www.gaasmantech.org; Dan Nystedt, "Semiconductor industry looks ahead to 18-inch wafers," *InfoWorld,* April 24, 2007, http://www.infoworld.com/article/07/04/24/HN18inchwafers_1.html.