Invited Paper

Recent Success on SLS FPAs and MDA's new Direction for Development

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Over the past few years, the Missile Defense Agency Advanced Technology Directorate (MDA/DV) has funded the development of a new III-V infrared (IR) sensor focal plane material: type II strained layer superlattice (SLS). Infrared sensors are crucial to missile defense capabilities for target acquisition, tracking, discrimination, and aim point selection; they serve other military sensing applications as well. Most current infrared military systems use mercury-cadmium-telluride (HgCdTe), a II-VI semiconductor material, for long-wavelength (LW) (8-12 um) focal plane array (FPA) applications. It is difficult to achieve large-format FPAs in HgCdTe at long wavelengths (LW) due to their low yield. The situation is aggravated by the limitation of the small cadmium-zinc-telluride (CdZnTe) substrates. SLS is the only known IR material that has a theoretical prediction of higher performance than HgCdTe. Over the past three years, SLS technology has progressed significantly, demonstrating experimentally its potential as a strong candidate for future high-performance IR sensor materials. In this paper, we will discuss the most recent progress made in SLS. We will also discuss MDA's new direction for this technology development. The plan is to use a horizontal integration approach instead of adhering to the existing vertical integration model. This new horizontal approach is to increase the number of industrial participants working in SLS and leverage existing III-V semiconductor foundries. Hopefully it will reduce the cost of SLS IR technology development, shared foundry maintenance, and future SLS production.

1. Introduction

IR sensors are critical in ballistic missile defense and many other military applications. IR FPAs at LWIR with very high sensitivity, large formats, and multicolor capabilities are much needed. The desired operating temperatures are maximized to reduce the cooling system weight, size, power consumption, and cost. The choices of IR materials that can fulfill the above requirements are limited. HgCdTe's small substrate size limits the FPA size. Also, the HgCdTe FPA yield for LWIR and multicolor capability is very low, even for small formats, making it expensive. The quantum well infrared photodetector (QWIP) is affordable and has a very large format for multicolor capability, but the quantum efficiency and the optical gain product are low, limiting its application to high photon flux situations. InSb and InGaAs are mature and have large formats, but they have limited cutoff wavelengths and no multicolor capability. Si:As is mature, but has to be operated at 10K. New IR materials are needed to fulfill future military system needs.

In this paper, we discuss a new type of IR FPA material which is not in any U.S. military system yet. In Germany, two-color MW/MW SLS FPAs are in limited initial production for military aircrafts. This new material is antimonide (Sb)-based Type II Strained Layer Superlattice (SLS).

2. Advantages of Type II Strained Layer Superlattice

SLS is the only known IR material that has a theoretically predicted higher performance than HgCdTe. The distinct advantages of SLS, as compared with HgCdTe, are that it is a III-V material that provides potential for low-cost material and substrates, high operability, uniformity and yield at LWIR and VWLIR, and higher operating temperatures. As a III-V semiconductor, SLS material has much stronger chemical bonds, which give the material higher stability. The large substrate offers potential for very large formats. Potential high yield and the ability to leverage commercial foundries for growth offer FPA affordability. The rapid maturation of this material has demonstrated low cost for its development.

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SLS is an Sb-based III-V material system with very thin layers of indium arsenide (InAs) and gallium antimonide (GaSb) (or indium gallium antimonide [InGaSb]) alternating to form superlattice structures. The major advantage of the SLS material system is that it is a mechanically robust III-V material like the QWIP; it offers all the advantages of the III-V material, and has a direct bandgap like HgCdTe resulting in high quantum efficiency. As described in Fig 1, the type I superlattice has two materials forming a quantum well where the conduction band and valence band are well separated. The QWIP is one example of a type I superlattice material with a wide barrier, commonly referred to as quantum wells. The disadvantage of this structure is that the natural band gaps of the two materials are too wide for IR absorption. Intersubbands are used for the IR absorption, but the absorption is not in the normal incidence direction. Gratings have to be used to direct the incident light to the planar direction, causing the small quantum efficiency in QWIP FPAs.

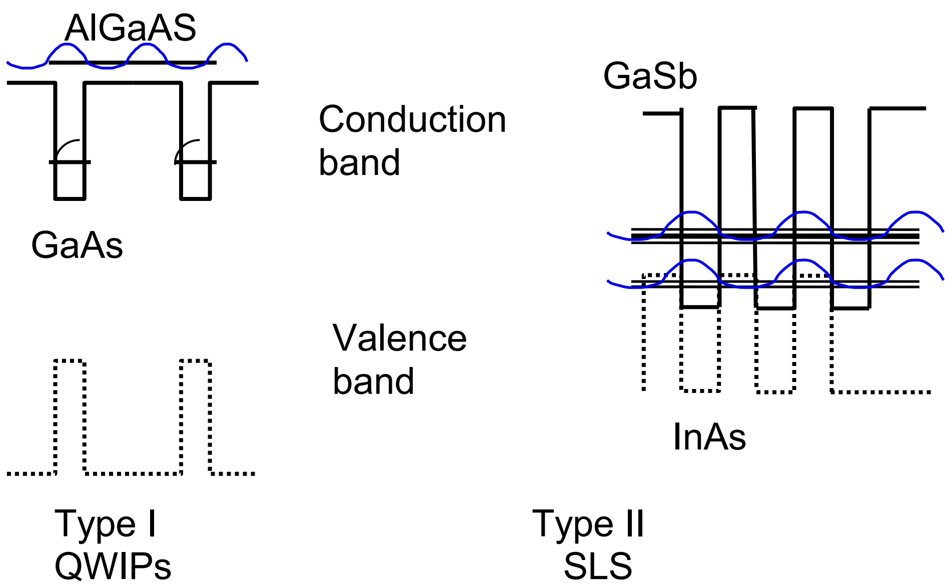

Figure 1. Type I Superlattice and type II Superlattice

The two materials forming type II superlattice have a staggered conduction band (solid line in Fig. 1) and a valence band (dotted line in Fig. 1). In the InAs/GaSb case, the valence band of the GaSb is higher than the conduction band of the InAs. Due to the coupling of the energy states, the superlattice forms an energy bandgap in the IR region between the valence band and the conduction band of the two materials. Normal incidence is allowed just as it is in a natural narrow bandgap material, such as HgCdTe and InSb; therefore, high quantum efficiency can be obtained in SLS.

SLS takes advantage of bandgap engineering and can tailor the IR detection wavelengths from 3 to 25 µm. Currently HgCdTe has a low yield in highly uniform LWIR and VLWIR FPAs, partially due to the cutoff wavelength uniformity control, as well as other manufacturing factors.

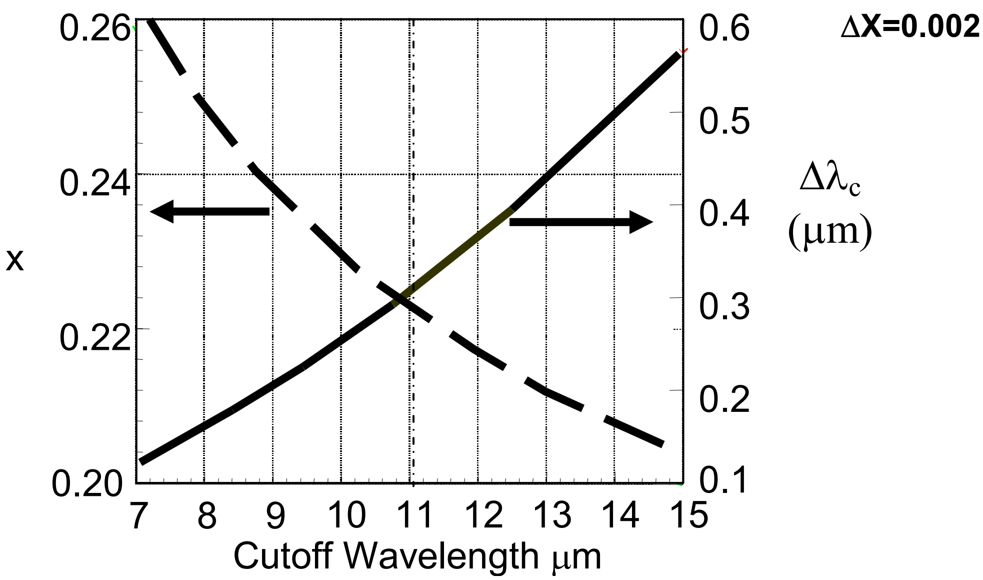

Fig. 2. The cutoff wavelength variation (right Y-axis) of $Hg_{1-x}Cd_xTe$ as a function of cutoff wavelengths (x-axis) with a fixed composition fluctuation of ΔX=0.002 during the growth.

As shown in Fig. 2, the cutoff wavelengths of $Hg_{1-x}Cd_xTe$ can be tuned by changing the composition of the Hg and Cd contents. If we fix the composition variation during the growth at ΔX=0.002, the cutoff wavelengths only vary 0.12 μm if the FPA is designed at 7 μm cutoff, but will vary 0.56 μm if the FPA is designed at 15 μm cutoff. The longer the cutoff wavelengths, the more non-uniformity the HgCdTe wafers will have. This cutoff wavelength non-uniformity at the FPA level can be spectrally corrected by using a cold filter, but the dark current variation caused by the variation of cutoff wavelengths will still exist.

One advantage of using SLS for LW and VLWIR FPAs is the ability to fix one component of the material and vary the other to tune the wavelength. As shown in Fig 3 from reference 1, by fixing the GaSb layer thickness at 40 angstroms and varying the thickness of the InAs from 40 angstroms to 66 angstroms, the cutoff wavelength of SLS can be tuned from 5 μm to 25 μm . There is no material composition change needed.

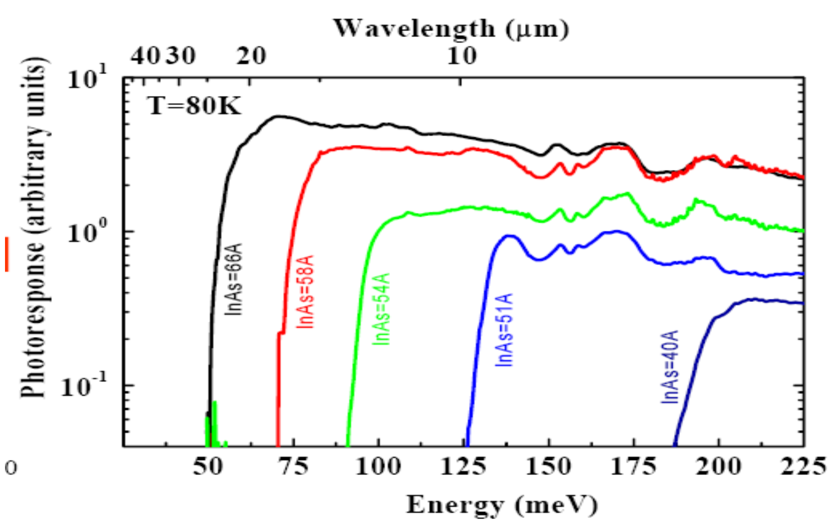

Fig 3.Experimental data of SLS cutoff wavelengths change with the InAs thickness while GaSb is fixed at 40 angstroms (Ref 1.)

Another advantage is SLS's high effective mass, which prevents high tunneling dark current. Compared with HgCdTe, which has an effective mass of about $0.012m_o$ at 12 μm, SLS' effective mass is about 0.03 m_o at the same cutoff wavelength. Here m_o is electron mass. HgCdTe's effective mass decreases with increased cutoff wavelengths, which is another issue with HgCdTe at VLWIR. SLS's effective mass does not change with the cutoff wavelengths, explaining why SLS will work better at LWIR and VWLIR than HgCdTe. Because SLS's design is flexible using bandgap engineering for cutoff wavelengths, there are many design possibilities. The valence energy bands can be designed to separate the heavy holes from the light holes, thereby reducing the Auger 7 recombination (Fig 4, Ref 2). The results are that SLS can achieve BLIP at a low background at higher operating temperatures than HgCdTe. At the same cutoff wavelengths, it is theoretically predicted that SLS will perform as well as HgCdTe at about 30 K higher operating temperatures at LWIR, and 10 K higher at MWIR.

Using bandgap engineering and MBE growth, SLS device structures can be easily designed for multicolor FPAs. The expectation is for this material to have a higher yield for large format multicolor FPAs.

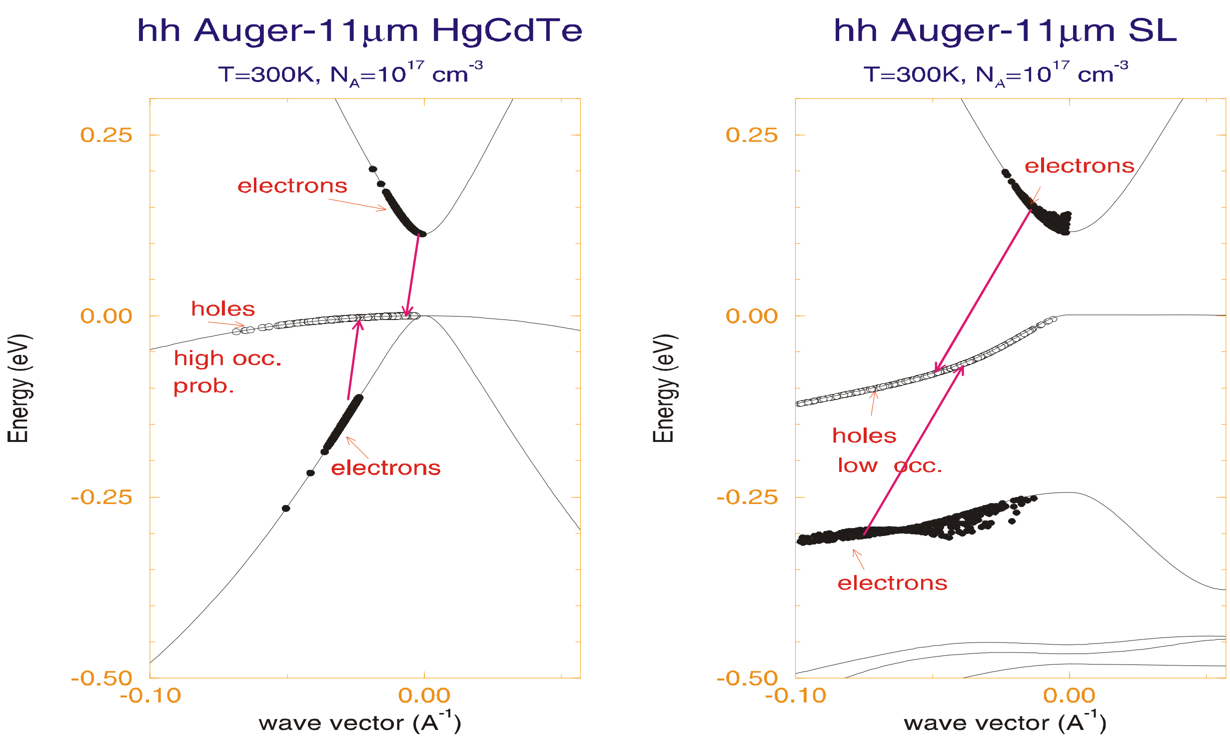

Fig 4. Theoretical calculation of the band structures of HgCdTe and SLS. The SLS has a large separation of the light hole from the heavy hole, giving a large suppression of the Auger dark current (Ref. 2)

3. Recent Progress Made in SLS

The low production cost of the SLS FPA is still basically a prediction since SLS FPAs are not being produced at this time in the United States. The MW/MW two-color SLS FPAs are in production in Germany for European military aircraft, but there are no statistics on the production cost yet. However, the low cost of the SLS technology development has been supported by the significant progress made in the past few years. MDA has funded several industries, Federal laboratories, universities and small businesses to develop LWIR SLS technology and, through this development many challenges were presented. We have identified several potential showstoppers during the past years, such as passivation at LWIR, low quantum efficiency, and low RoA product. With collaborative efforts, we resolved these issues one at a time and have achieved significant progress.

SLS LWIR passivation was a major challenge since the surface leakage current significantly reduces FPA performance. Solutions using various methods have been developed during the past few years, such as polyimide for test devices and silicon oxide (SiO_2) for FPAs. Higher bandgap passivation materials using MBE re-growth methodology have also been explored. Current 320x256 SLS FPAs are passivated with good performance; further improvement of passivation is still needed.

Theoretically predicted quantum efficiencies for SLS should be as high as those for HgCdTe, since SLS is a direct bandgap transition material, but the actual value achieved at the beginning of the SLS program in 2005 was roughly 10 to 25%. The major challenge was to grow thick SLS structures without degrading the material quality. High-quality SLS materials thick enough to achieve acceptable quantum efficiencies is crucial to the success of the technology. Various approaches have been explored to maintain the strain balance while growing thick material. Strict interface control was the key to maintain the strain balance. Significant progress has been made on the quality of the material during the past few years. The wafer surface roughness achieved was 1 to 2 angstroms. The high crystal quality demonstrated by high-resolution x-ray diffraction full-width-at–half-maximum was about 25 arc-sec for SLS structures with a thickness of more than 6 μm. With this material thickness, an absorption quantum efficiency (QE) higher than 75% in FPAs was demonstrated in 2008 (Ref 3). Fig 5 gives examples of the fast improvement in QE at Northwestern University (NWU) and Jet Proportion Laboratory (JPL).

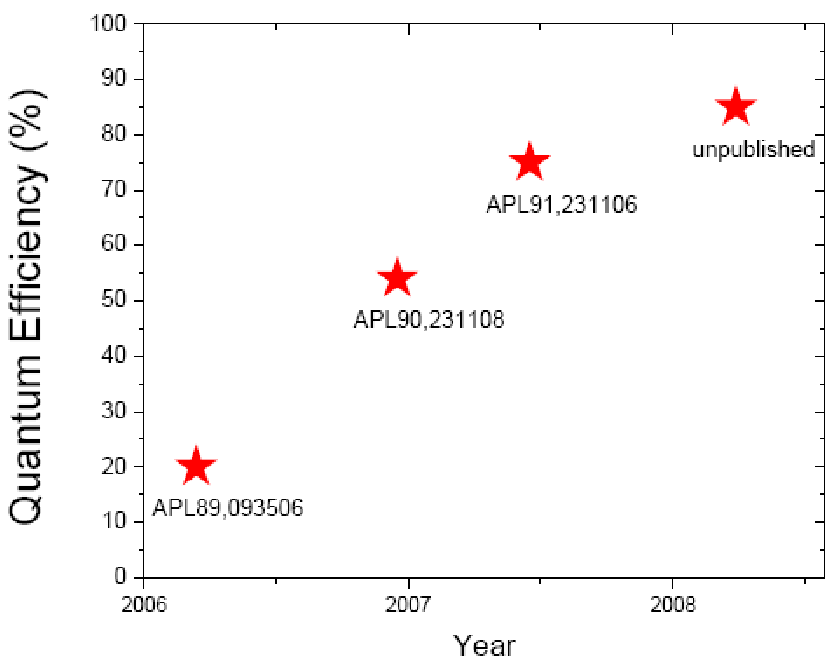

Fig 5 a. NWU quantum efficiency improvements from 2006 (20%) to 2008 (75%) for double-pass FPAs

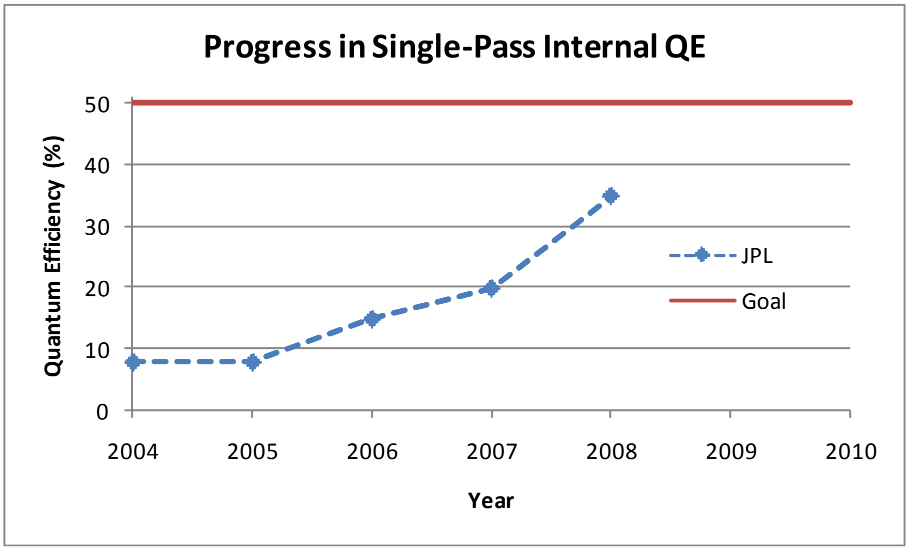

Fig 5 b. JPL quantum efficiency improvements from 2005 (<10%) to 2008 (35%), single diode data with single pass

After achieving high quantum efficiency, the next obstacle was the high dark current, which gives a low RoA product. A low RoA product gives the FPA a high dark current noise, and also makes it difficult to have an impedance match to most of the existing readout integrated circuitry (ROIC). From theoretical calculations, SLS should have a lower dark current than that of HgCdTe due to SLS's larger effective mass and lower Auger recombination. Surface passivation has reduced the surface leakage dark current, but the current passivation approach still has room to improve. The dominant SLS noise comes from generation-recombination (g-r) noise and tunneling associated with intentional higher doping (Ref. 4). Various SLS device structures were explored to reduce the dark current. The device structures have improved from simple homo-junction to hetero-junction and then double hetero-junction structures. When the device changed from a homo-junction to a hetero-junction structure, the dark current improved through 320x256 FPA demonstration by one order of magnitude to be ~ 1.3 nA at 80K for a 9 µm cutoff wavelength and 30 µm pitch (Ref. 5). At the single device level, the double hetero-junction structure was demonstrated to have RoA product up to 700 Ohm/cm^2 (Ref. 6) for a 10 µm cutoff and greater than 5,000 Ohm/cm^2 for a 9.3 µm cutoff at 77K (Ref. 7). Fig. 6 exemplifies how quickly the RoA has improved in the past few years, based on research conducted by NWU and JPL.

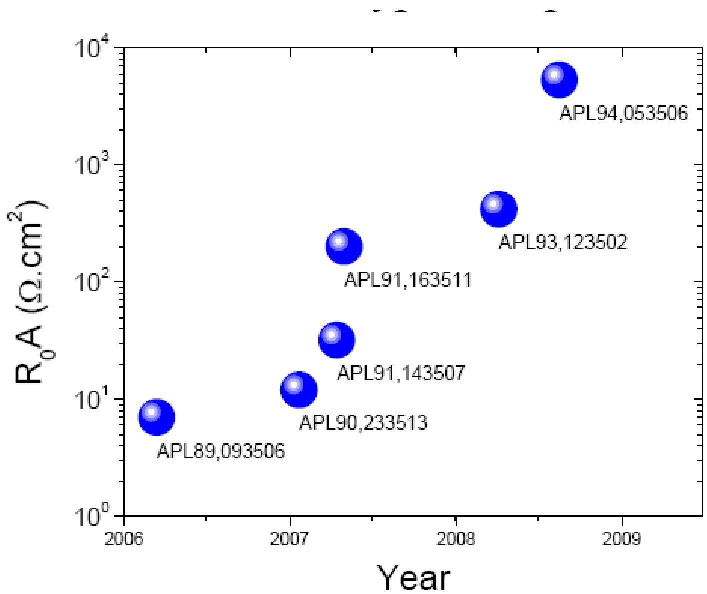

Fig 6 a. RoA improvement at Northwestern University from 2006 (<10 Ωcm^2) to 2008 (>5000 Ωcm^2) for 10 µm cutoff diodes

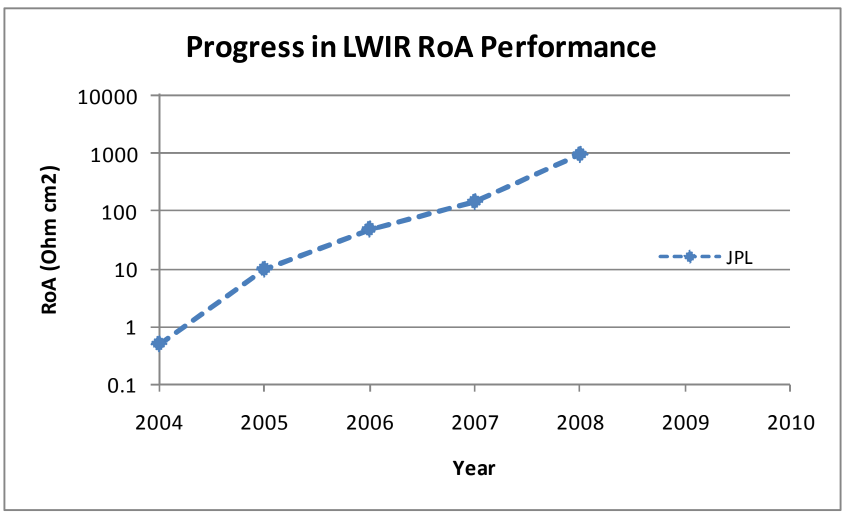

Fig 6 b. RoA improvement at JPL from 2004 (<1 Ωcm^2) to 2008 (~1000 Ωcm^2) for 9.5 um cutoff diodes

The best SLS LWIR FPA results from NWU at 320x256 demonstrated a low NEDT of 23 mK with a response operability of 98%. The FPA data is still not as good as the single device data, and additional improvements are needed to further advance the technology.

4. Comparing SLS FPAs with State-of-the-Art Infrared Technology

Over the past few years, SLS has proved to be relatively inexpensive as compared to HgCdTe to develop and shows promise of likewise being relatively inexpensive to produce. How does SLS FPA performance compare with the current state-of-the-art technology? HgCdTe is regarded as the standard and is typically used as a comparison. Due to the ITAR

control on HgCdTe FPA data, it is very difficult to publicly use HgCdTe FPA data for comparison. Reference 8 has developed a simple empirical relationship that describes the dark current behavior with temperature and wavelengths for the better Teledyne HgCdTe diodes and arrays. It is called Rule 07.

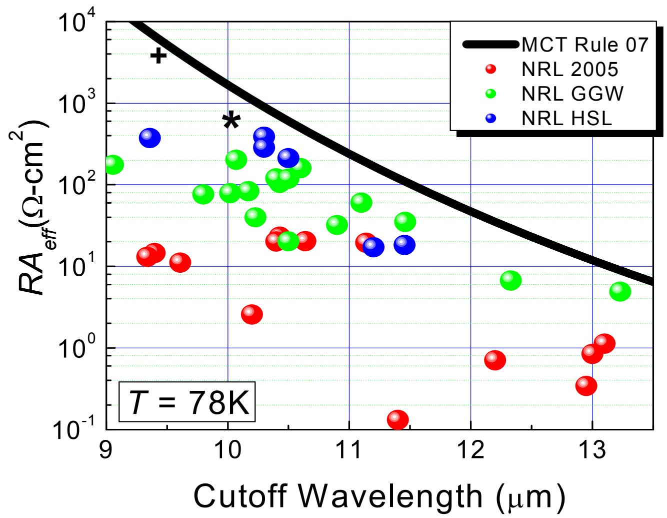

Fig 7. Comparison of SLS with HgCdTe using Rule 07 with Naval Research Lab data

From Fig 7 (Ref 9) we can see that the Naval Research Laboratory (NRL) SLS FPA performance data are improving from red dots to blue dots while improving the detector structures and are approaching the MCT Rule 07 trend line at 78K. The data from Reference 7 (+) and from Reference 6 (*) are single photodiode configuration data, which are very promising with double hetero-junction devices.

In developing Rule 07, twenty six different MBE wafers at Teledyne are used. All are double layer planar hetero-junction structure devices and diffusion limited. Data includes SWIR from 295K to 160K, MWIR from 295K to 82K, and LWIR for 8.6μm at 78K to 15.6μm with large diodes at 100K. No temperature data lower than 78K was used in the empirical fitting. From Figure 8, one can observe that the data fit very well at 100K; almost all experimental data are on the trend line. The data does not fit as well at 77K and even worse at 65K. Rule 07 is an excellent tool for a quick comparison of RoA product with HgCdTe. However, caution should be taken when expanding it to other FPA parameters, such as D*, lower operating temperatures, and very large format FPAs. One should also consider cost and availability of the FPA when comparing the materials.

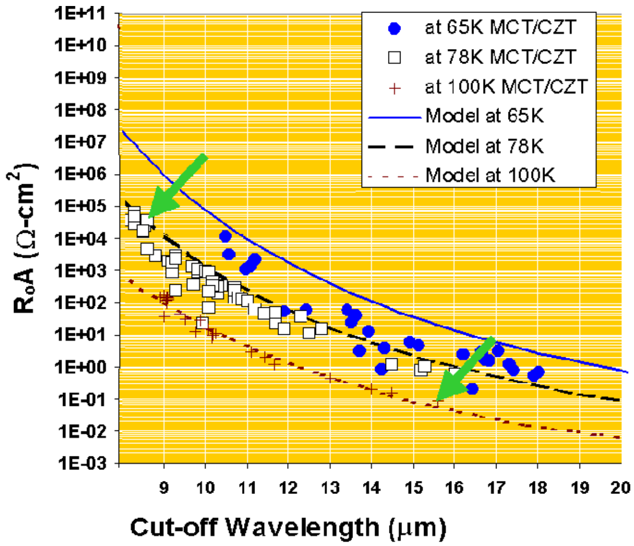

Fig 8. From reference 8, Rule 07 trend line for MCT at 100K, 78K and 65K.

5. What is next?

The rapid progress made in SLS over the past few years showed a great promise of this material as a future IR solution. It is a very exciting period for this technology development. Much research is still needed to improve the material growth, device and FPA processing, substrate preparation, and device passivation. Two-color and very large format FPAs are still under development. Current GaSb substrates for SLS are relatively small and the p-type substrate absorbs IR radiation. Substrate polishing is critical in growing high-quality material. Eventually, growth of SLS on GaAs or Si is strongly desired for large-format and low-cost production.

The minority carrier lifetime of current SLS material is still a mystery. Empirical fitting data on current FPAs and devices gave a minority carrier lifetime from 35 nanoseconds (ns) to 200 ns, with similar absorption layers but different device structures. There is no clear understanding why the minority carrier lifetime varies within the device structure. So far, there is no experimental evidence to indicate that SLS minority carrier lifetime is a showstopper for SLS FPA performance. It may become an issue when SLS achieves diffusion limited performance. Further improvement of SLS will need a better understanding of the minority carrier lifetime and how to increase it. Both theoretical analysis and experimental measurements of the minority carrier lifetime are needed and are underway to understand the value of the lifetime and how it affects the device performance.

For multicolor devices, the material will need to be very thick and the etching depth will need to be deep. Dry etching is essential to achieve the needed depth and keep a high fill factor at the FPA level. We have some excellent results on the dry etching development and are developing two-color FPAs in the 320x256 format (Ref.10). Various single-color and multicolor device structures are also under study to achieve better FPA performance. Buried junction devices, nBn, pBp, pBn device structures as well as various heterojunction devices are under exploration (Ref 11 and 12).

6. MDA's new direction in SLS development

The best SLS FPA performances achieved so far are from universities, research laboratories and some businesses working with research laboratories. In addition to further technology development, researchers will need to demonstrate the SLS FPA manufacturability with high yield. In order to do so, the SLS technology has to be well developed in U.S. industries. Because very high-performance and very large-format (1Kx1K and beyond) LWIR and two-color FPAs do not currently exist with the state-of-the-art technology, there is an urgency to demonstrate and produce these arrays for systems where very large-format and high-performance LWIR FPAs are needed. Examples are airborne wide-area infrared search and track sensors (IRSTs), space-based acquisition and searching systems, and persistent surveillance systems.

MDA just started the FastFPA Program in 2009 to establish industry capabilities to demonstrate the SLS FPA fabrication process. This program plans to fund three tasks: SLS material growth, ROIC development, and FPA processing and fabrication. The FastFPA Program promotes a horizontal integration of IR FPAs instead of the current IR FPA fabrication approach, which is vertically integrated inside one company. For the SLS material growth, we leverage the III-V commercial epilayer growth foundries, which currently also grow materials for commercial products, such as cell phone chips. The expensive MBE machines are already purchased and maintained, significantly reducing the cost of the SLS material growth. In this way, the FPA fabrication houses have an option not to maintain the growth facility in-house, or to have a back up when needed. The FPA fabrication houses are encouraged to focus on the FPA processing, passivation, hybridization and substrate removal. The goal of the program is to develop the SLS technology in industry so that the SLS FPAs can be repeatedly reproduced and manufactured for military systems. Commercial ROICs with both polarities that are suitable for single- and two-color FPAs will be developed.

6. Summary

Type II SLS technology has progressed significantly over the past few years with funding from the MDA/DV Passive EO/IR Program. Small format (320x256) LWIR FPAs with performances approaching state-of-the-art HgCdTe FPAs have been demonstrated. SLS shows great potential to be the future alternative IR material to HgCdTe; however, it requires many performance improvements before it can approach its own theoretical limit and fully compete with HgCdTe.. High-quality material growth, advanced device structure design, FPA processing, passivation and minority carrier lifetime are examples of areas that need further study. In parallel, MDA is pushing forward to address the SLS technology development in U.S. industry. Ultimately our goal is to ramp up the U.S. infrared industrial base both in terms of technical capability and production. In doing so, the United States will eventually have readily available domestic suppliers in place and producing SLS FPAs whenever the Nation’s military systems need this important capability.

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