Manufacture of Sb-Based Type II Strained Layer Superlattice Focal Plane Arrays

Meimei Z. Tidrow
US Army CERDEC-NVESD, 10221 Burbeck Rd.; Ft. Belvoir, VA 22060-5806; meimei.tidrow@us.army.mil

Lucy Zheng, Hank Barcikowski, James Wells, Leslie Aitcheson
Missile Defense Agency, 7100 Defense Pentagon, Washington DC 20301

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Abstract

Infrared sensors are very important to military sensing systems for target acquisition, tracking, discrimination and aim point selection. Most current infrared military systems use mercury-cadmium-telluride (HgCdTe), a II-VI semiconductor material, for long-wavelength (LW) (8-12 µm) focal plane arrays (FPAs). HgCdTe has difficulty in achieving large format FPAs at long wavelengths due to its low yield, aggravated by the limitation of the small cadmium-zinc-telluride (CdZnTe) substrates. Antinomide (Sb)-based type II strained layer superlattice (SLS) has the potential to perform better than HgCdTe, and at a lower cost by leveraging the commercial III-V foundries for manufacturing. The Missile Defense Agency Advanced Technology Directorate (MDA/DV) has been developing SLS material for the past few years and has made significant progress. The success in SLS LW has warranted a new SLS program at MDA to address SLS manufacturing issues. This program promotes horizontal integration of IR sensors instead of the current IR FPA fabrication approach, which is vertically integrated within one company. This paper will give the most recent progress made in SLS and describe the new approach of the SLS manufacturing program.

INTRODUCTION

Infrared (IR) sensors are very important to military sensing systems for target acquisition, tracking, discrimination, aim-point selection, as well as night vision and persistent surveillance. IR sensors are either uncooled, which operate at room temperatures but with limited performance, or cooled to a much lower temperature for very high performance. All cooled IR detectors and focal plane arrays (FPA) use semiconductor materials, either II-VI, such as HgCdTe, VI-VI, such as lead (Pb) salt material, or III-V, such as indium-gallium-arsenide (InGaAs), indium antimonide (InSb), quantum well infrared photodetectors (QWIP) and type II strained layer superlattice (SLS). Arsenic-doped silicon (Si:As) is also a traditional IR material which has a wide band absorption from 1 µm all the way to 23 µm; however, Si:As has to be operated at very low temperatures (~10K). Low-temperature operation adds to the cooling requirements and therefore increases system size, weight, cost and power consumption. Si:As also has no cutoff wavelength tenability for multicolor. InGaAs only works in the near IR (~1 µm) and short wavelength IR (SWIR 1-3 µm) spectrum. InSb only works at mid-wavelength IR (MWIR 3-5 µm). Both InGaAs and GaSb are excellent III-V IR materials and have a higher quality and much lower cost than the II-VI IR material. Very large-format InSb FPAs at 2K x 2K are available and 4K x 4K FPAs are under development. The limitations, however, of InGaAs and InSb to the cutoff wavelengths and a lack of multi-color capability limit their applications.

HgCdTe is the most used IR material for long-wavelength IR (LWIR 8-12 µm) and also works at SWIR and MWIR. It offers high performance at a moderate operating temperature (77 K for 10 µm cutoff). The cutoff wavelength can be tuned by varying the composition of the HgCd and CdTe materials. However, due to the intrinsic difficulty of this II-VI material and the small available substrates, HgCdTe has been very expensive to produce in large formats. The HgCdTe FPA is very difficult to fabricate when the cutoff wavelength extends 10 µm and is multicolor.

QWIP uses III-V materials and has excellent uniformity and operability. QWIP is currently the only LWIR FPA solution for very large format and multicolor detectors at an affordable cost. There are commercially available 320x256 and 640x480 LWIR QWIP FPAs. The 1024x1024 two-color MW/LW QWIP array has been demonstrated and 2048x2048 two-color MW/LW QWIP arrays are under development. QWIP performs well at very large formats for wide field-of-view systems and multicolor applications, as long as there is enough photon flux. However, QWIP has a low quantum efficiency ranging from 5 to 40%, the latter being the highest thus far. Its quantum efficiency is low compared to that of HgCdTe, which exceeds 75%. QWIP is a photoconductor; the optical gain is usually around 0.2, which makes the collection efficiency (Quantum efficiency times gain) down to <10%. For most tactical applications, QWIPs can fulfill the mission requirements and have a very low cost. Because QWIP is a photoconductor and has an intersubband transition, the dark current noise is higher than HgCdTe at the same operating temperature and cutoff wavelength. In order to have similar sensitivity as HgCdTe, QWIPs have to operate at a lower temperature which is a disadvantage for certain applications. The low collection efficiency and operating temperatures prevent QWIPs from being an ideal candidate for space-based and low-background applications, even though the very large format and multicolor features are very attractive.

In this paper, we will discuss a new type of IR material which is not, with the exception of Germany where two-color MW/MW FPAs are in production for military aircraft, in any military systems yet This new material is Sb-based type II strained layer Superlattice (SLS).

ADVANTAGES OF SLS

SLS is an Sb-based III-V material system with very thin layers of InAs and GaSb (or GaInAb) alternating to form superlattice structures. The major advantages of the SLS material system are that it is a mechanically robust III-V material like QWIPs which offers all the advantages of the III-V material, and has a direct bandgap like HgCdTe which gives it a high quantum efficiency. It uses bandgap engineering and can tailor the IR detection wavelengths from 3 to 25 µm. Device structures are easily designed for multi-color FPAs using bandgap engineering. Currently, SLS is the only IR material that has a theoretical prediction of higher performance than HgCdTe. It has potential to have a high uniformity due to the high III-V material quality, a low tunneling current due to a high effective mass, a low Auger 7 recombination rate due to the separation of the heavy holes and light holes, and therefore a high operating temperature to achieve BLIP at a low background. 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. SLS will also outperform QWIPs with significantly higher quantum efficiencies. SLS operates in a photovoltaic mode with an optical gain of 1. When operated at similar background and cutoff wavelength, SLS gives a much higher BLIP temperature than QWIPs. Comparing SLS with Si:As, SLS has the potential to operate at 40K for a 23 µm cutoff wavelength, instead of at 10K. SLS also will potentially cost less than HgCdTe because the Sb-based industry can tap into investments in lasers and transistors, leveraging and creating future commercial markets. The SLS FPAs are expected to have high operability and high yield.

RECENT PROGRESS MADE IN SLS

The theoretical prediction of SLS as a high-performance IR material is not news. The news is the recent breakthrough advancement made in this material. Over the past few years, SLS technology has progressed significantly, demonstrating experimentally the potential as a strong candidate for future high-performance IR sensor materials. The high precision of molecular beam epitaxy (MBE) machine made it possible to lay down the semiconductor materials layer by layer at the atomic thickness. MDA has been funding several industries, government laboratories, universities and small businesses to develop SLS technology in the LWIR. There were many challenges during the SLS technology development. During the past years, we have identified several potential show stoppers such as passivation at LWIR, low quantum efficiency, and low RoA product. With collaborative efforts, we solved these show stoppers one at a time and achieved significant progress.

Passivation at MWIR for SLS has been demonstrated by Fraunhofer and AIM in Germany and their two-color MW/MW SLS FPAs are in production for European military aircrafts. SLS LWIR passivation had been a major challenge since the surface leakage current significantly reduces the 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 has also been explored.

Theoretically predicted quantum efficiencies for SLS should be as high as those for HgCdTe, since SLS is a direct bandgap transition material, but the real value achieved at the beginning of the SLS program in year 2004 was roughly 25%. The major challenge was to grow thick SLS structures without degrading the material quality. High-quality SLS material with enough thickness is crucial to the success of the technology. Various approaches have been explored to maintain the strain balance while growing the 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 several years. The wafer surface roughness achieved 1 to2 angstroms. The high crystal quality is demonstrated by high-resolution x-ray diffraction full width at half maximum of around 25 arc-sec for SLS structures with a thickness of more than 6 µm. With this material thickness, an absorption quantum efficiency higher than 75% in FPAs has been demonstration in 2008 (reference 1). This resulted in the world's first LWIR SLS image.

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 calculation, 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, even though the passivation approach still has room to improve. The dominate SLS noise comes from g-r noise and tunneling with intentional higher doping (reference 2). Various SLS device structures are being explored to reduce the dark current. The device structures have been improved from simple homo-junction to hetero-junction and then double hetero-junction structures. When the device structure changed from the homo-junction to a hetero-junction, 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 (reference 3). At the single device level, the double heterojunction structure has demonstrated to have RoA product up to 700 Ohm/cm^2 (reference 4) for 10 µm cutoff and greater than 5,000 Ohm/cm^2 for 9.3 µm cutoff at 77K (reference 5).

FUTURE DIRECTIONS

HgCdTe is the major IR sensor material for military, especially at LWIR. HgCdTe has very large formats at SWIR and MWIR; however, it is hard for HgCdTe to compete with InGaAs and InSb FPAs due to cost. Over the years, the market for HgCdTe has shrunk due to the success of the InGaAs, InSb, QWIPs, and uncooled microbolometers. Because HgCdTe is a II-VI material that has no other commercial leveraging, it becomes more and more difficult to maintain the whole industry base with limited demands on quantity. Over years of development, the investments on HgCdTe have begun to see diminishing results. However, it is important to support HgCdTe and maintain its industrial base since most current LWIR military systems depend on it.

On the other hand, SLS is a III-V material. Even through Sb-based semiconductor material is not as mature at GaAs-based and InP-based material, there is still a good opportunity for SLS to leverage the large III-V opto-electronics industry. We would like to take advantage of the existing III-V industry infrastructure to produce SLS at a low cost. These existing facilities are supported by commercial products, such as cell phone chips and millimeter wave integrated circuits, which will present a less problem for the government to maintain the IR industry base.

The rapid progress made in SLS in 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 substrate gallium antimonide (GaSb) for SLS has relatively small size and the p-type substrate absorbs IR radiation. Substrate polishing is very 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 best performance made so far are from universities, research laboratories and some industries working with research laboratories. In addition to further technology development, it will be very important to demonstrate the SLS FPA manufacturability with high yield. Because very high-performance and very large-format LWIR FPAs do not 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 IRSTs, space-based acquisition and searching systems, and persistent surveillance systems. MDA just started a FastFPA Program in 2009, establishing industry capabilities to demonstrate SLS FPA fabrication process. This program promotes a horizontal integration of IR sensors instead of current IR FPA fabrication approach, which is vertically integrated inside one company. We will leverage the III-V commercial epilayer growth companies to grow the SLS material, so that the fabrication houses have an alternative to maintaining an in-house growth facility, and have a back up when there is a need. The FPA fabrication houses are encouraged to focus on the FPA processing, passivation, hybridization and substrate removal. Commercial ROICs that are suitable for single color with both polarities and two-color FPAs will be developed.

CONCLUSIONS

Type II SLS technology has made significant progress in the past few years funded by MDA/DV’s Passive EO/IR Program. Researchers have demonstrated 320x256 LWIR FPAs with performance approaching the state-of-the-art HgCdTe FPAs. SLS showed a great potential to be the future alternative IR material to HgCdTe; however, it requires many performance improvements before it can be fully compared with HgCdTe and approaches its own theoretical limit. High-quality material growth, advanced device structure design, FPA processing, passivation, and minority carrier lifetime are examples of areas that need further studies. In parallel, MDA is pressing forward to address the SLS industry fabrication issues to prepare the IR industry to catch up with the technology and prepare to produce SLS FPAs for military systems.

REFERENCES

[1] P.Y. Delaunay and M. Razeghi, SPIE Photonic West Proceedings – Quantum Sensing and Nanophotonic Devices V, Vol. 6900, p. 69000M-1-10. (2008)

[2] D. Hoffman, B.M. Nguyen, P.Y. Delaunay, A. Hood, M. Razeghi and J. Pellegrino, APL, Vol. 91, No. 14, p. 143507-1 (2007)

[3] J. Hubbs and P. Y. Delaunay, Presented at the SPIE Photonic West, (2009)

[4] C. J. Hill, Al .Soibel, S. A. Keo, J. M. Mumolo, D. Z. Y. Ting and S. G. Gunapala, presentation at QSIP 2009, Yosemite Park, CA

[5] Edward Kwei-wei Huang, Darin Hoffman, Binh-Minh Nguyen, Pierre-Yves Delaunay and Manijeh Razeghi, APL 94, 1 (2009).

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