Development of III-V Barrier Diode Radiation-Hard Infrared Detectors for Space Applications

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ABSTRACT

Opto-electronic devices destined for space must be suitably radiation-hard, meaning that they must be resilient to the effects of high energy radiation in space. For high performance IR (infrared) space-based applications, the current material of choice is MCT (Mercury Cadmium Telluride). MCT is difficult and therefore expensive to fabricate and the constituent materials are becoming increasingly restricted by regulation. The new generation of barrier diode detectors based on III-V materials offer a promising alternative to MCT, providing comparable performance whilst offering devices that are compatible with volume manufacturing processes.

As part of a DASA Space-to-Innovate Phase 1 funded project we have developed a novel radiation hard unipolar barrier-based ABaT™ III-V MWIR diode detector. The detector is being subjected to gamma and proton radiation testing to demonstrate its suitability for space environments. To compare the radiation performance of this diode, a number of other typical III-V detector diode structures have been fabricated and tested. In this paper we present the results of the project so far and future plans to develop this into detector arrays.

Keywords: Infrared, III-V, MWIR, Unipolar Barrier Diode, Radiation Hard

1. INTRODUCTION

Opto-electronic devices destined for space must be suitably radiation-hard, meaning that they must be resilient to the effects of high energy radiation in space. There can be scope to modify the operating conditions of detectors to account for degradation in performance due irradiation, however this subsequently impacts either the spacecraft design to incorporate this functionality or spacecraft operation and the available observation time. Further if radiation tolerance is particularly poor this will reduce mission lifetime.

For high performance IR (infrared) space-based applications, the current material of choice is MCT (Mercury Cadmium Telluride). MCT is difficult and therefore expensive to fabricate and the constituent materials are becoming increasingly restricted by regulation. The new generation of barrier diode detectors based on III-V materials offer a promising alternative to MCT, providing comparable performance whilst offering devices that are compatible with volume manufacturing processes[1]. Additionally these detectors target HOT (Higher Operating Temperature) operation to achieve the ultimate aim of improved SWaP-C (Size, Weight and Power - Cost) performance. Clearly low SWaP-C detectors are a key requirement for Space use to increase freedom in spacecraft design and integration with different sized platforms.

High performance Infrared (IR) detectors are required for a number of space-based applications over a wide range of wavelengths from SWIR to VLWIR. The MWIR (Medium Wave Infrared) regime is well suited to surveillance of the Earth and Space environment; as well as providing supporting information to visible imagery it also offers detection of high temperature events such as forest fires. A significant benefit of imaging in MWIR as opposed to the visible is the ability to image throughout the day and night without sensitivity to lighting conditions[2]. The DarkCarb satellite from SSTL (Surrey Satellite Technologies Ltd) is an MWIR imaging satellite currently using an MCT detector, it presents an excellent example of an opportunity where a III-V based IR detector could be used as an alternative.

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Teledyne e2v have been awarded funding through the dstl Space Programme via the DASA Space-to-Innovate Phase 1 competition, to develop a III-V barrier-diode radiation-hard MWIR detector for space applications. The development is a collaboration between Teledyne e2v, Amethyst Research Ltd and SSTL. Teledyne e2v are responsible for the overall programme delivery and radiation testing. Amethyst Research Ltd are responsible for the design, fabrication and testing of diode structures via Lancaster University. SSTL is providing end-user specifications to help steer the design of the development.

The programme consists of the design, fabrication and characterization of a novel radiation-hard unipolar barrier-based ABaT™ (Amethyst Barrier diode Technology) III-V MWIR diode detector which is then subjected to gamma and proton radiation testing to demonstrate its suitability for space environments. To compare the radiation performance of this design, a number of other typical III-V detector diode structures are fabricated and tested.

2. RADIATION PERFORMANCE OF III-V BASED BARRIER DIODE DETECTORS

Energetic protons and electrons, the effects of which contribute to ionizing and non-ionizing radiation damage, dominate the space environment. These radiation sources arise from trapped particles in belts surrounding the Earth or other planets, emission from solar events and galactic cosmic rays. The radiation received by a spacecraft and ultimately the detector will be dependent on the orbit, solar activity during the mission and shielding within the spacecraft. Typically conditions in Earth orbit lead to non-ionizing dose fluences in the region of $1x10^{10}$ p/cm^2 [5] or ionizing doses of 10's of kRad. In the case of JUICE the mission to Jupiter's icy moon's where the Jovian radiation environment is more severe conditions are still only expected in the region of $1x10^{11}$ p/cm^2 and 100 kRad[6].

A review into the irradiation effects on the performance of III-V based barrier diode infrared detectors over the past decade is given by C. P. Morath et al [3]. Ionization damage is created in detectors as excess electron holes pairs are either created through incident high energy radiation or high energy particles lose energy in interactions within the material. In semiconductor devices the excess carriers can become trapped in dielectric layers or on the surface of mesa structures. This can induce threshold shifts and increase surface currents which lead to increases in dark current, however for barrier based detectors this layer provides natural radiation hardness and negligible change in performance is seen from ionizing radiation over dose ranges of 100s of kRad [3],[4].

Non-ionizing radiation damage is created in detectors where high energy particles collide with atoms in the material structure displacing them from their lattice position and creating vacancies. These vacanices then migrate through the crystal lattice and either recombine or form stable defects [5]. The increased defects density caused by the irradiation induces two degradations in performance; a decrease in QE (Quantum Efficiency) due to increased recombination of photo-generated minority carriers (holes) and increased dark current via increased SRH (Shockley-Read-Hall) generation.

To improve the tolerance to displacement damage a structure has been designed and fabricated which is proposed to reduce the impact of defect densities by increasing the speed of hole transport and therefore reducing the likelihood of recombination.

3. DETECTOR DESIGN AND INITIAL PERFORMANCE

3.1 Detector Design and Manufacture

Five structures have been designed and fabricated as described in Figure 1. All structures are fabricated using an InAsSb, Ga-free material system on GaSb substrates. Three of the structures are manufactured using Amethyst's ABaT™ unipolar barrier design. The structure designated "ABaT" is the baseline design featuring a standard bulk absorber, "ABaT-RH" is the design proposed to have increased radiation tolerance and "ABaT-SLS" replaces the bulk absorber with an InAsSb/InAs SLS (Strained-Layer Superlattice) to achieve sensitivity across the full MWIR band. Two other structures have also been created for comparison; "*nBn*" which features a basic unipolar barrier design and bulk absorber, and "*p-i-n*" a *pn* diode design with bulk absorber. The structures were manufactured as single element detectors (photodiodes) of various sizes within unit cells on 1/4 2 inch wafers. Manufacturing was conducted in the quantum technology facilities at Lancaster University.

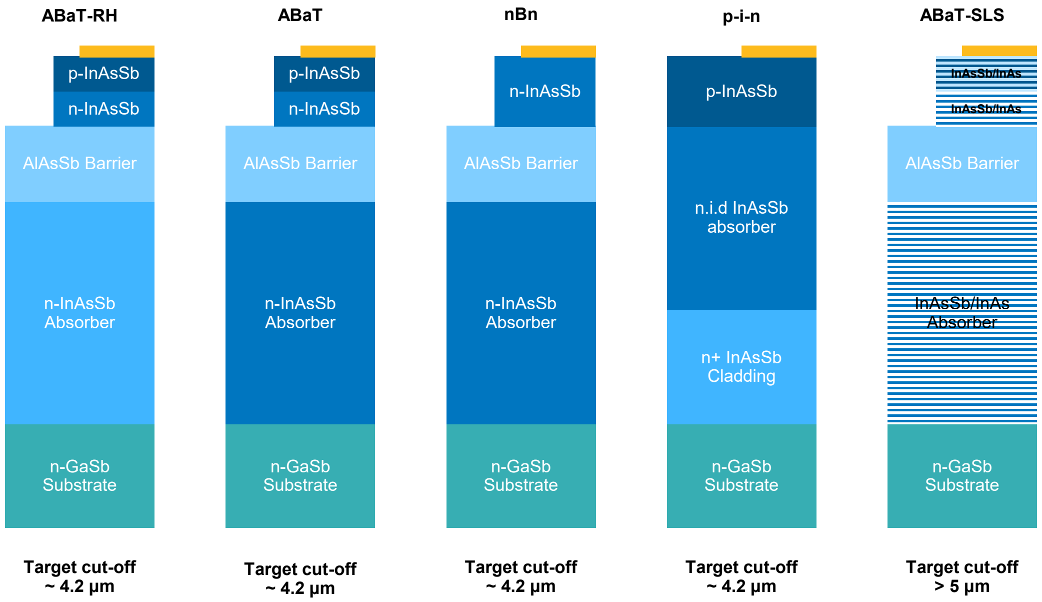

Figure 1. The five different detector structures designed, manufactured and to be tested for radiation tolerance. The name descriptor for each structure is listed at the top and the targeted cut-off wavelength at the bottom of the figure

3.2 Initial Results

Initial characterization results for the ABaT-RH, ABaT, nBn, p-i-n and ABaT-SLS are shown in Figure 2 to Figure 6 respectively, these were acquired using probed IV measurements and wire bonded devices in an Oxford instruments cryostat. The ABaT-RH, ABaT and nBn designs exhibit dark current between 10^{-2} to 10^{-1} A/cm^2 at 250 K and -400 mV bias. The *p-i-n* design exhibits dark current of ~ $5x10^{-1}$ A/cm^2 at 225 K and -100 mV bias, and the ABaT SLS design ~ 10^{-1} A/cm^2 at 250 K and -300 mV bias.

The ABaT-RH design exhibits the highest QE with a maximum at nearly 60% with -400 mV and cut-off wavelength of >4.3 µm at 250 K. The ABaT design exhibits slightly lower QE with maximum at nearly 50% with -400 mV and cut-off wavelength of >4.5 µm at 250 K. The *nBn* design exhibits lower QE again with maximum at nearly 40% with -400 mV and cut-off wavelength of >4.5 µm at 250 K. The *p-i-n* design exhibits QE with maximum at ~15% with -100 mV and cut-off wavelength of >4.4 µm at 250 K. The ABaT-SLS design exhibits QE with maximum at nearly 45% with -300 mV and cut-off wavelength of >5.5 µm at 200 K. Cut-off wavelengths were determined by plotting the square of the response vs 1/Energy and extrapolating to the axis. The slight dip in performance of all structures at 3 µm was due to ice on the cryostat.

We consider that the performance of these structures is comparable to the state of the art reported in the literature[1][6][7][8]. Currently these designs do not feature an AR (Anti-Reflection) coating, however if an AR coating were applied a significant improvement in QE performance is expected.

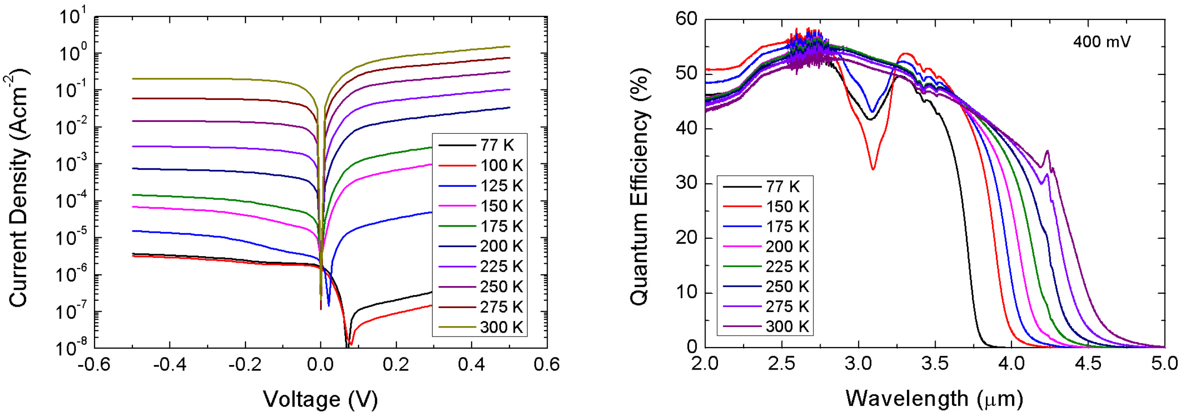

Figure 2. ABaT-RH design, JVT (left) and QE vs temperature measurements at -400mV bias (right) pre-radiation made on wafer

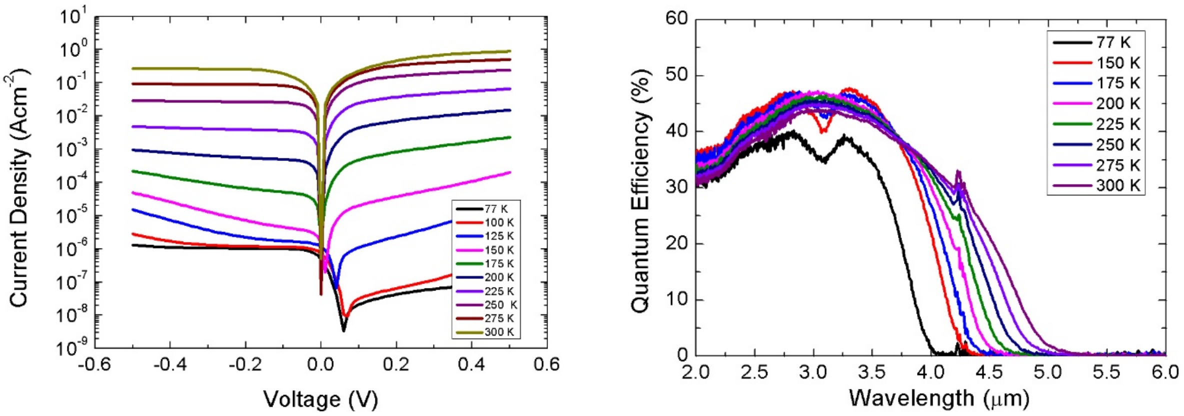

Figure 3. ABaT design, JVT (left) and QE vs temperature measurements at -400mV bias (right) pre-radiation made on wafer

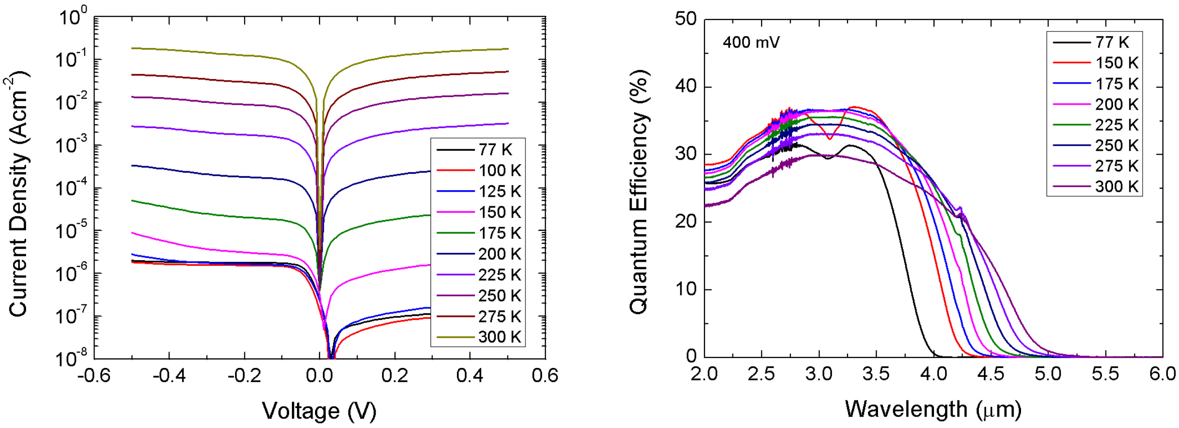

Figure 4. nBn design, JVT (left) and QE vs temperature measurements at -400mV bias (right) pre-radiation made on wafer

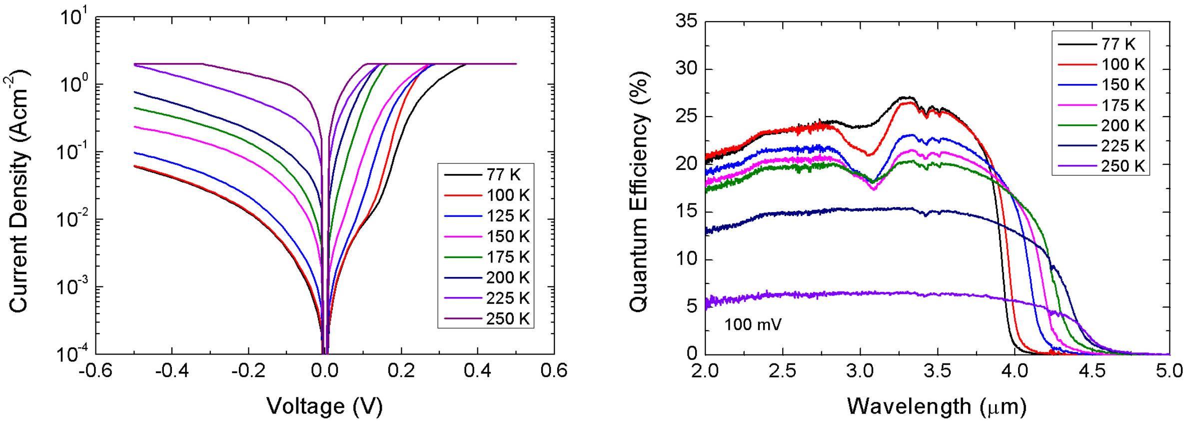

Figure 5. p-i-n design, JVT (left) and QE vs temperature measurements at -100mV bias (right) pre-radiation made on wafer

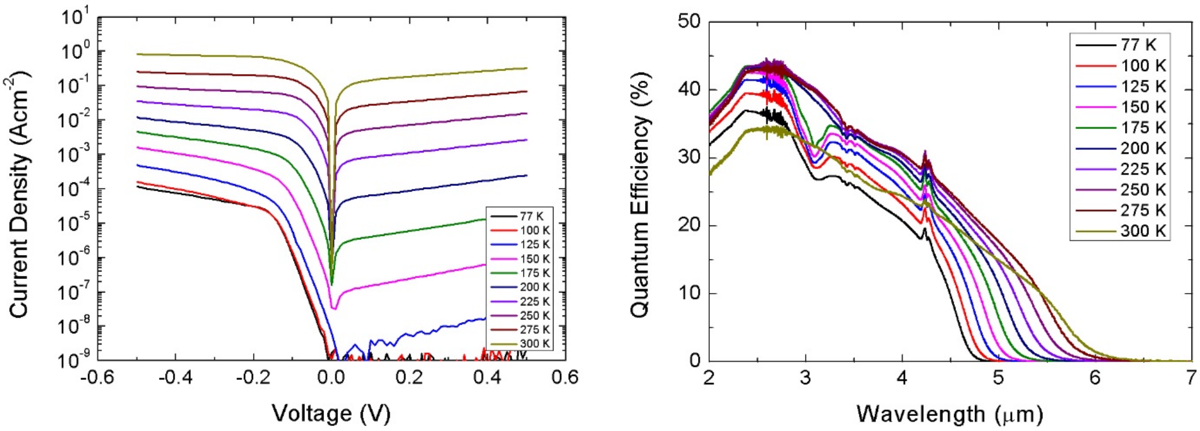

Figure 6. ABaT-SLS design, JVT (left) and QE vs temperature measurements at -300mV bias (right) pre-radiation made on wafer

4. PROGRAMME STATUS AND NEXT STEPS

The programme is progressing well although delay has been incurred due to the Covid-19 lockdown. All structures have been fabricated and initial characterization completed. Some structures have been packaged to allow interface and testing with equipment at Teledyne e2v. Preparations are underway to organize and perform the radiation. Despite the expectation of little performance degradation due to ionizing radiation for completeness both gamma and proton irradiation will be conducted.

Assuming post irradiation the ABaT-RH structure is verified to have improved radiation tolerance, the next step will be to develop this into a large-area detector array. This will involve fabrication of arrays that are then hybridized with a ROIC (Read-Out Integrated Circuit). In addition to verifying the performance of this new radiation-hard MWIR array detector we would like seek to verify performance following typical space qualification activities such as mechanical and environmental testing, and further irradiation testing. Re-evaluating the irradiation performance as a detector array is important to ascertain whether there has been an impact due to growth now as an array and whether there are impacts on aspects such as the uniformity. The performance of the detector array will also not only be impacted by the III-V material sensitivity to irradiation but also the ROICs irradiation performance as a silicon based CMOS (Complimentary Metal Oxide Semiconductor) device.

5. CONCLUSIONS

As part of a DASA Space-to-Innovate Phase 1 competition an MWIR unipolar barrier detector structure with potential for improved radiation tolerance has been designed, fabricated and tested, designated here as ABaT-RH. Other barrier detector designs and diode designs have been fabricated to compare performance and tolerance to irradiation. All structures have been fabricated using an InAsSb (Ga-free) material system. Pre-irradiation characterisation results for the structures; JVT and QE vs temperature and bias voltage show comparable performance with results quoted in the literature. The designs will now be subjected to irradiation to verify their performance and confirm if the radiation-hard structure has improved tolerance.

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