Infrared photodiodes based on Type-II strained layer superlattices

Sankha dip Das, Yu Ling Goh, Chee Hing Tan, John David,
Department of Electronic & Electrical Engineering, University of Sheffield

Sir Frederick Mappin Building, Mappin Street, Sheffield, S1 3JD

Abstract

We report on the growth and characterisation of Type-II InAs/GaSb strained layer superlattice photodiodes for mid-wave infrared detection on GaAs substrates. Comparisons with similar structures grown on GaSb substrates show very similar structural, optical and electrical characteristics. Responsivity measurements on these devices reveal good external quantum efficiency value of 32% at 77K.

Introduction

High-performance infrared detection technology is very important for both civilian and military applications. HgCdTe is primarily used for these applications as it is a mature technology and can provide devices with excellent detectivity values. However, HgCdTe still suffers from significant challenges in growth, fabrication and high dark currents at elevated temperatures. To obtain a high quantum efficiency, the thickness of the absorption region has to be very thick and achieving high crystal quality and high wafer uniformity in very thick HgCdTe is challenging, particularly for large area LWIR focal plane arrays (FPAs). Moreover, HgCdTe as well as alternate technologies such as quantum well infrared detectors (QWIPs) or quantum dot infrared detectors (QDIPs) based on III-V materials require significant cooling to reduce the dark currents. Other problems with QWIPs & QDIPs are the need for gratings to detect normal incidence light in the former and the poor quantum efficiency due to the small absorbing volume in the latter. The InAs/GaSb Type II strained layer superlattice (SLS) is a promising III-V material system for IR devices due to the ability to engineer its bandgap between 3-30 μm, while avoiding many of the problems in current technologies. These structures provide high responsivity with relatively thinner structures compared to HgCdTe and established III-V technologies gives highly uniform defect free structures, which is suitable for large area focal plane arrays [1,2].

These Type II strained layer superlattice structures comprise alternating layers of thin InAs and GaSb and the overall system is latticed matched to a GaSb substrate. The band alignment of this material system is such that the conduction band minimum of InAs overlaps the valence band maximum of the GaSb and the band gap occurs between electron states localised in InAs layers and the hole states localised in GaSb layers. The intensity of the band edge optical transition is determined by exponential decaying envelope wave function tails. The overlap of the wave function tails is a function of layer thickness and decrease in thickness causes increase in the overlap. The bandgap is engineered by changing the period of the superlattice, a decrease in the period results in a smaller cutoff wavelength, or by introducing indium in the GaSb as $Ga_xIn_{1-x}Sb$. This gives the option of designing binary-binary or binary–ternary superlattices to achieve the same effective bandgap with different quantum efficiency while keeping the thickness of the absorption region the same.

However, an issue with this material system is that it relies on growth on GaSb substrates. These substrates are significantly more expensive than the silicon, used for HgCdTe detectors, suffer from poor quality and are only available commercially in relatively small diameters. Recent publications suggest that good quality bulk GaSb can be grown on GaAs substrates using interfacial misfit array in place of a thick buffer layer. Due to the relative spacings between atoms in a GaSb lattice and GaAs, dislocations can be constrained to the hetero-interface and no threading dislocations occur. This has been demonstrated on lasers [3].

In this paper we investigate the feasibility of growing Type II strained layer superlattice p^+-i(SLS)-n^+ photodiodes on GaAs substrates.

Growth and processing

A simple bulk epitaxial layer of GaSb was grown on a $n+$ GaAs substrate with a 100 nm GaAs buffer. This showed an AFM r.m.s roughness of 1.5 nm as shown in Fig 1. Fig.2. shows the X-ray diffraction rocking curve from this sample, with a reasonable narrow GaSb peak of 218.1 arc.sec and the much narrower GaAs substrate peak. The GaSb appears almost fully relaxed to the GaAs substrate and its large FWHM is a consequence of lattice bending due to this relaxation process. These results indicate good quality bulk GaSb can be grown on GaAs substrate.

Two MWIR p^+-i(SLS)-n^+ structures were grown, one on a Te doped n-type GaSb substrate and another on a 3 inch GaAs substrate as illustrated in Fig.3. (a) & (b). The diode structure in both devices was identical, comprising of 8x8 monolayers (ML) of InAs/GaSb superlattice for p^+, undoped absorption region and n^+ regions. Having the same effective band-gap for all these regions reduces the possibility that photogenerated carriers will get trapped at band-gap discontinuities and reduce the quantum efficiency. Both structures were capped with a thin p-type GaSb contacting layer and showed smooth defect free surfaces after the growth.

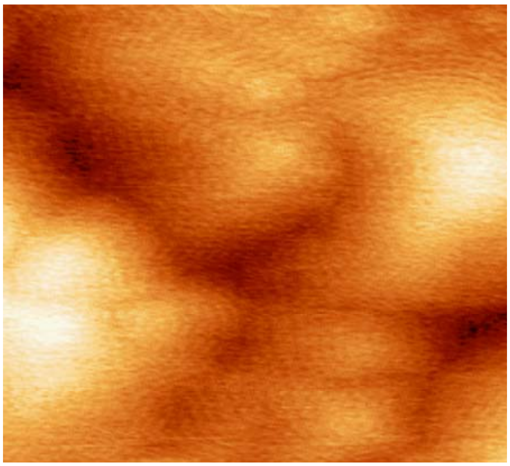


Fig.1. *1μm^2 AFM image of a 2μm bulk GaSb/ GaAs epilayer.*

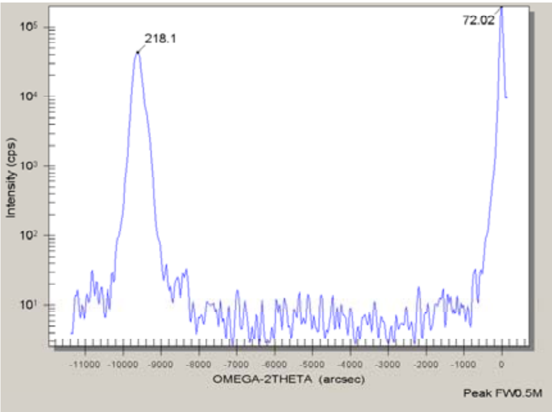
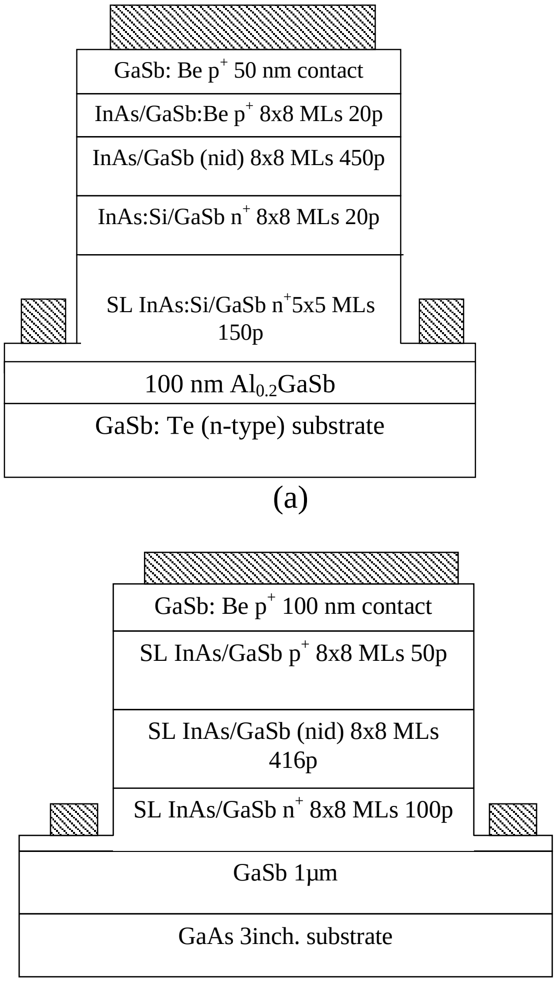


Fig.2. *X-ray diffraction rocking curve for bulk GaSb/ GaAs epilayer.*

The X-ray diffraction rocking curves (XRDs) of the MWIR p^+-i(SLS)-n^+ grown on GaSb and GaAs substrates (Fig. 4(a) & (b)) showed intense narrow peaks indicating good quality of the as-grown structures. Fig. 4.(a) shows a full width half maximum (FWMH) of 25.2 arc sec. for the 8x8 monolayer (ML) superlattice and a substrate peak at ~30.4°corresponding to the GaSb substrate. The satellite peaks correspond to the superlattice structure. Fig. 4 (b) is broadly similar but the peaks are broadened, suggesting that the growth on the GaAs substrate results in some non-uniformity or roughness in the layers.

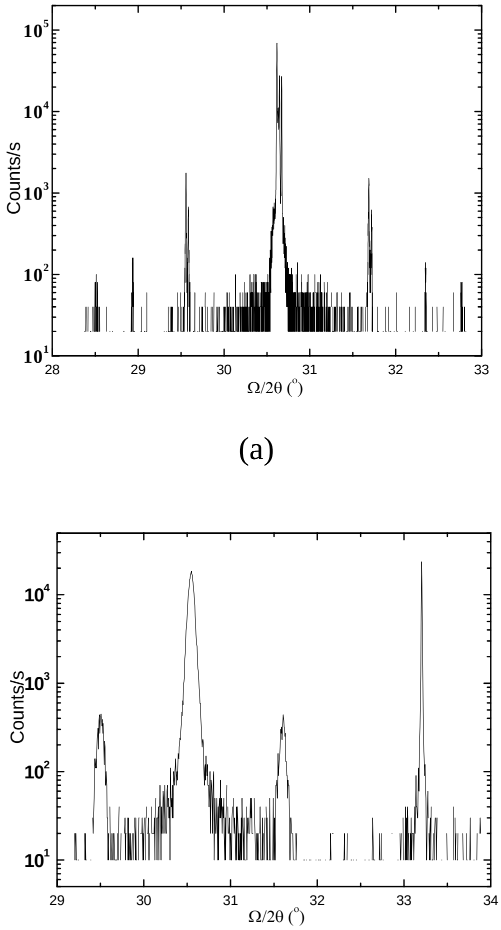


(a)

(b)

Fig.3. p$^+$-i(SLS)-n$^+$ *structures grown on (a) GaSb substrate (b) GaAs substrate*

In addition to a peak corresponding to the effective GaSb Bragg angle at ~30.4°, there is also a peak from the GaAs substrate ~ 33.2°. The broadening of the main peak as well as the satellite peaks on the GaAs substrate indicates that there is still room for improvement in the growth, however it indicates an almost identical 8x8 ML SL structure can be grown on the GaAs substrate.



(a)

(b)

Fig.*4. X-ray rocking curves for* p$^+$-i(SLS)-n$^+$ *structures grown on (a) GaSb substrate (b) GaAs substrate*

Mesa structures with diameters ranging from 50µm to 400µm, shown in Fig.5, were fabricated from these p$^+$-i(SLS)-n$^+$ structures using a combination of dry reactive ion etching (RIE) and wet etching. RIE dry etch utilizes Cl_2 and Ar plasma at a low pressure of 3 mT. The etch rate was found to be approximately 0.2 µm/min and gives reasonably vertical sidewalls. Immediately after the dry etch, the devices were dipped in diluted H_2O_2 and H_3PO_4 for a few seconds to provide a finishing etch which removes any surface damage caused by the RIE. The larger devices had top optical windows enabling photocurrent measurements to be undertaken.

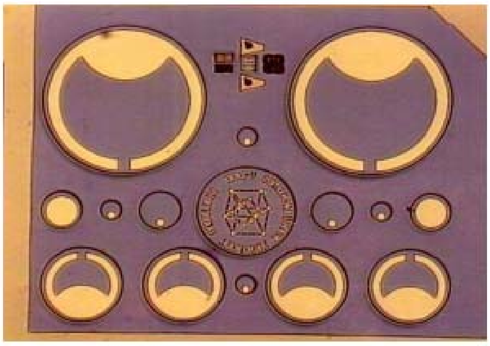


Fig.5. *Plan view of mesa diodes showing diameter varying from 400 μm - 50μm*

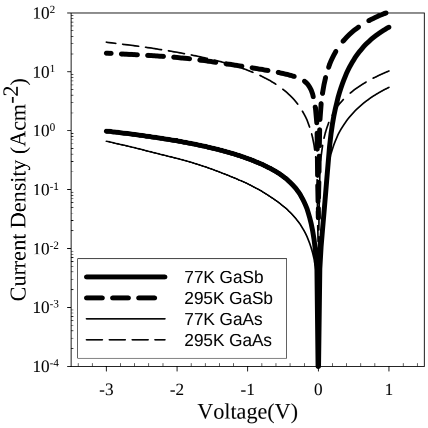
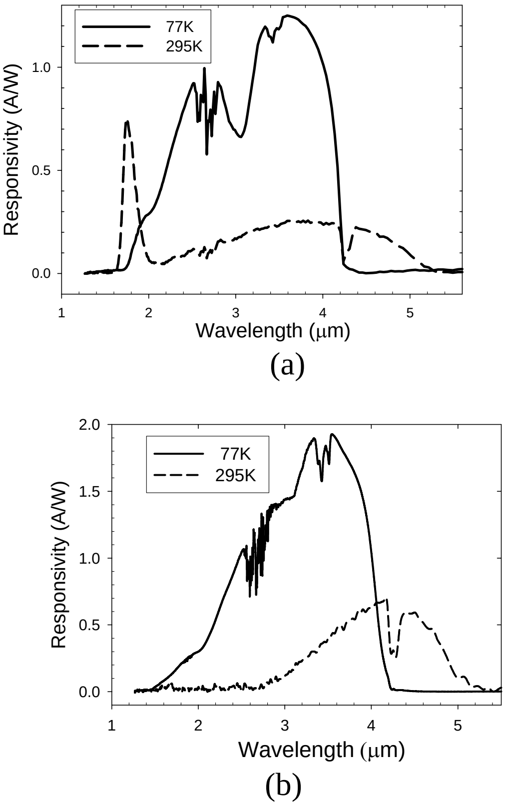


Fig.6. *Temperature dependent dark current density of unpassivated MWIR* p^{+}-i(SLS)-n^{+} *devices*

Experimental Results

On-wafer temperature dependent dark current measurements were performed using liquid nitrogen cooled ST-500 Janis probe station and a Keithley 236 source measurement unit. Results from the unpassivated devices showed relatively high dark currents of ~10^{-1} A/cm^{2} and ~ 10^{-2} A/cm^{2} at 77K for devices on GaSb and GaAs substrate respectively as shown in Fig.6.

In both sets of devices, the dark currents decreased by 2 orders of magnitude as the temperature decreased from room temperature to 77K. Published results [4] on similar MWIR structures show significantly lower dark currents are achievable.

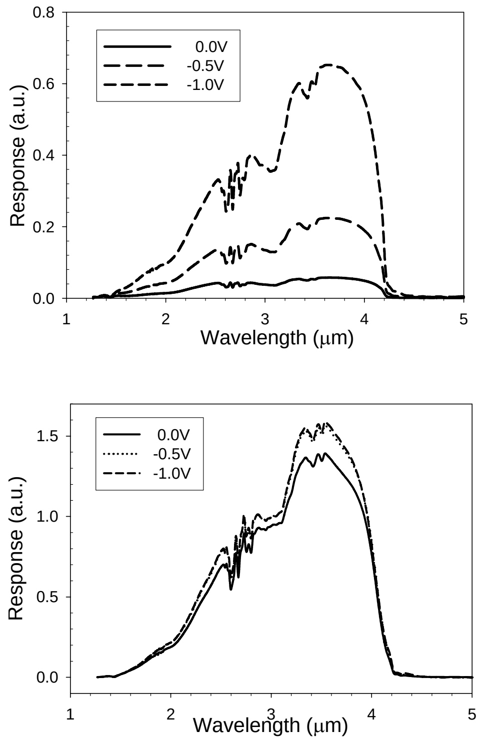


(a)

(b)

Fig.7. *Temperature dependent* responsivity *of large area* p^{+}-i(SLS)-n^{+} *devices grown on (a) GaSb substrate (b) GaAs substrate.*

Spectral measurements were performed using a Varian 7000e FTS system with standard ceramic IR source and KBr beam splitter (with extended range of 7500 cm-1 to 400 cm-1). Results in Fig 7 (a) & (b) showed good absorption in the expected 3-5 μm region. Both the designs showed 5% cutoff wavelength, with respect to peak, of 5 μm at room temperature. Expected shift to lower wavelengths at lower temperature due to change in the bandgap of superlattice constituents with decrease in temperature was also observed. Fig.8 (a) and (b) show the effect of an increasing reverse bias on the photoresponse at 77K. For the structure on the GaSb substrate, there is a significant increase in the peak response with increasing bias, however for the structure on GaAs, there is virtually no change with bias.



(a)

(b)

Fig.8. Bias dependent spectra at 77K of large area p$^+$-i(SLS)-n$^+$ *devices grown on (a) GaSb substrate (b) GaAs substrate*

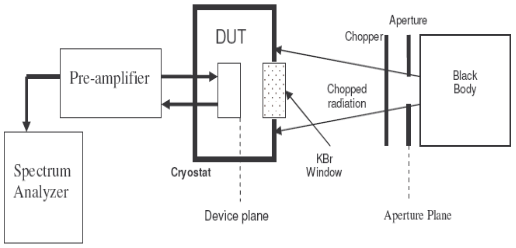
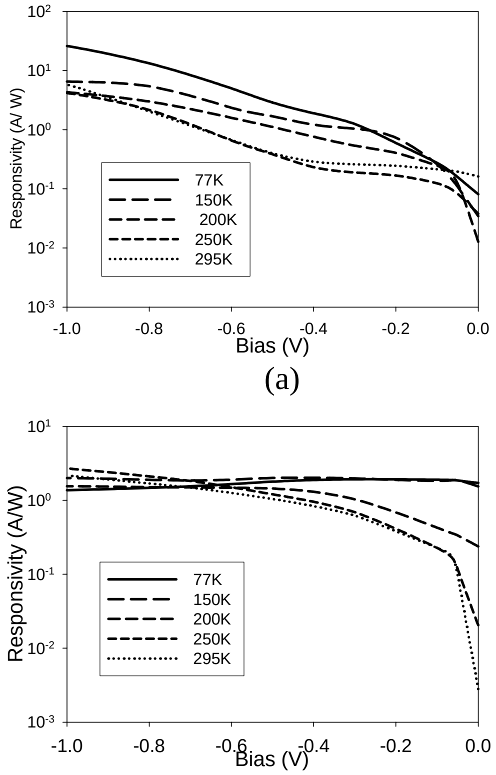


Fig.9. *Schematic diagram of blackbody photocurrent measurement setup*

Blackbody photocurrent measurements were done, for determination of responsivity, as illustrated in the fig 9. An IR- 564/301 blackbody was used at a temperature of 1257 K and a mechanical chopper was used to chop the radiation at 830 Hz. The photocurrent produced was amplified using the SR570 low noise preamplifier and measured using a SR760 single channel Fast Fourier Transform spectrum analyzer while the device was biased using the SR570's biasing facility. Photocurrent thus obtained was converted to peak current responsivity, using the definition

$$R_{peak} = \frac{I_{signal}}{A\int_a^b R'(\lambda)Q(\lambda)d\lambda},$$

where I_{signal} is the measured blackbody photocurrent, A is area of device, $R'(\lambda)$ is spectra of the device normalised to peak and $Q(\lambda)$ is IR power incident on the device at λ, calculated from Plank's Law for spectral excitance. Fig 7 (a) & (b) show responsivity of 1A/W, measured at 77K (-0.3V, 4 μm), resulting in 32% external and 49 % internal quantum efficiencies. An increase in the magnitude of the responsivity also occurs as the temperature decreases. Fig. 10 (a) and (b), shows the temperature and bias dependent responsivity of these devices. At 0V for the structure on GaSb substrate the responsivity initially drops significantly as the temperature decreases, before increasing to almost its 300K value at 77K. Although the responsivity does not appear to change significantly with reverse bias at 300K, at low temperatures a significant increase is observed. The behaviour is different for the structure grown on the GaAs substrate, where a very low responsivity is observed at 300K and at 0V. This value increases dramatically as the temperature decreases; however unlike the structure grown on GaSb, the responsivity here is not significantly dependent on the reverse bias voltage. At 77K and low reverse bias both devices appear to have very similar responsivity.



(a)

(b)

Fig.10. *Temperature and bias dependent responsivity of large area* p^+-i(SLS)-n^+ *devices grown on (a) GaSb substrate (b) GaAs substrate*

Conclusions

We have demonstrated that reasonably good quality bulk epitaxial layers of GaSb can be grown on GaAs substrates, and showed that p_+-i(SLS)-n_+ with a 8x8 ML of GaSb/InAs works well with both GaSb and cheaper GaAs substrates. Although a reasonably high responsivity is obtained, further work on optimising the dark current will be required in the future. We are currently continuing to extend this work into strained layer superlattices capable of detection in the long wavelength infrared (LWIR) region on GaAs substrates.

References

[1] A. Rogalski, Infra. Phys. & Tech. 50(2007) 240-252.

[2] P. Tribolet al., J. Elec. Mat., vol. 30., No.6, 2001

[3] J. Tatebayashi et al., App. Phys. Lett., 91, (2007), 141102.

[4] J. B. Rodriguez et al., Proc. of SPIE, vol. 6542 (2007) 654208-1

Acknowledgements

The work reported in this paper was funded by the Electro-Magnetic Remote Sensing (EMRS) Defence Technology Centre, established by the UK Ministry of Defence and run by a consortium of SELEX Galileo, Thales UK, Roke Manor Research and Filtronic.

We are also grateful to Prof. Sanjay Krishna and colleagues at the University of New Mexico for the growth of superlattice structures.