

Development of LWIR photodiodes based on InAs/ GaSb Type II strained layer superlattices

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Abstract

We report on the development of long-wave infrared (LWIR) Type-II InAs/GaSb strained layer superlattice photodiodes on GaSb substrates with p-on-n configuration. The design of the superlattice involves 13 monolayers (MLs) of InAs and 7 MLs of GaSb with InSb forced interface to balance the strain due to lattice mismatch between InAs and GaSb. Cutoff wavelength $\sim 8.8 \mu\text{m}$ was repeatedly obtained for several growths. Current voltage measurements reveal dark current densities $\sim 5.45 \times 10^{-5} \text{ A/cm}^2$ (77K) at -0.2V is achievable. Maximum D^ were estimated to be $1.3 \times 10^8 \text{ cmHz}^{1/2}/\text{W}$ (77K) at -0.3V for structure with 250 periods of superlattice.*

Introduction

Infrared detectors based on InAs/ GaSb superlattice has been around for past two decades since they were first proposed by Smith and Malhoit [1]. This 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 such as HgCdTe, quantum well (QWIP) or quantum dot (QDIP) based infrared detectors. These structures provide high responsivity with relatively thinner structures compared to HgCdTe and established III-V technologies gives highly uniform, which is suitable for large area focal plane arrays. In comparison to HgCdTe the current state of the art for infrared detectors, InAs/GaSb has shown a great deal of promise in both the long wavelength infrared (LWIR) and very long wavelength infrared (VWIR) regions because it is easier to vary layer thickness to tune the bandgap in the superlattices rather than to control the precise molar composition to tune the bandgap of HgCdTe. Moreover, InAs/GaSb has the ability to operate at high temperatures. Apart from HgCdTe alternate technologies

such as QWIP or QDIP also require significant cooling to reduce the dark currents [2,3].

Designing of these structures involves theoretical prediction of superlattice bandgap at operating temperature[4]. This is done by identifying the superlattice period for a particular bandgap from the theoretically calculated bandgap vs. superlattice period plot at the operating temperature. A decrease in the period results in a larger (smaller) bandgap (cutoff wavelength). This step is followed by determination of thickness of barrier and well layers. The guiding principle behind this choice is that the electron barrier should be thin enough for sufficient overlap of electronic wave-functions which in turn should give high values of optical transition matrix. So, the thinner GaSb layer better is the quantum efficiency.

Designing is followed by growth of strain balanced superlattice structures. As in InAs/GaSb superlattice different types of interface bonds could be formed due to noncommon anion and noncommon cation, the interface could either have an InSb-like character or a GaAs-like character [5]. Since the lattice constant of InSb (GaAs) is

much larger (smaller) than that of the GaSb substrate, a few monolayers of these materials leads to a large compressive (tensile) strain, which could alter the structural, optical and electrical properties of the superlattice. Moreover, the effect of the strain between the constituent layers enhances the broken band alignment and this causes shift in the superlattice bandgap as compared to theoretical prediction [6]. Hence growth of strained balanced structure becomes important and theoretical calculations must include effects of strain to accurately predict the bandgap.

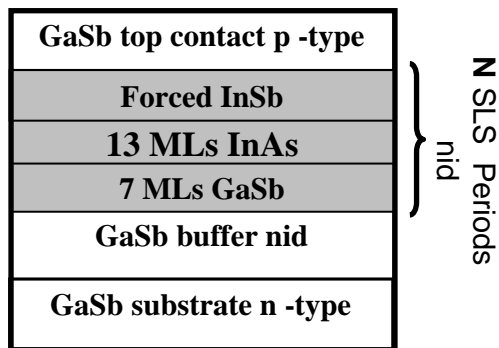


Fig.1. Schematic of the superlattice photodiode structures.

In this paper we report the development of LWIR Type II InAs/ GaSb superlattice photodiodes with p-on-n polarity on GaSb substrate.

Design, growth and fabrication of Type II InAs/GaSb strain balanced superlattices

For this work, the superlattice design of 13 MLs of InAs and 7 MLs of GaSb with InSb forced interface was chosen to give cutoff wavelength in the LWIR 7.7 – 9.6 μm region. The structure of the devices consists of undoped GaSb buffer layer on n-type GaSb substrate, followed by undoped superlattice absorption region. This was topped by a thin p+ type GaSb: Be ($\sim 2 \times 10^{18} \text{ cm}^{-3}$) top contact layer. Schematic of structure is shown in the Fig.1.

These structures were grown using solid source molecular beam epitaxy (MBE) on Te doped n-type epi-ready GaSb (001) single side polished substrates. All the growths were performed on cleaved 2 inch quarter wafer. The MBE reactor used was a VG-V80 equipped with Sb cracker source and As valved cracker source. The substrates were initially outgassed in vacuum, and the surface oxide was then removed at 530°C under Sb flux. Indium and gallium growth rates were determined by monitoring intensity oscillations in the reflected high-energy electron diffraction (RHEED) patterns and set to 0.4 ML/s for Ga and 0.33 ML/s for In. Group-V fluxes were adjusted using a conventional ion gauge to satisfy group V/III BEP flux ratio equal to 10 for InAs and 6 for GaSb respectively. GaSb growth temperature and V/III BEP ratio were optimized on separated samples to minimise the surface roughness until atomic flatness was achieved. The growth temperature of superlattice was estimated using the 1x3 to 2x5 surface reconstruction transition observed on the static GaSb surface under Sb_2 flux (0.8ML/s) and was equal to 400 °C.

For the purpose of strain balancing the choice of shutter sequence becomes very important since it determines which type of interface (“GaAs-like” or “InSb-like”, or both) will be formed between compositionally abrupt GaSb and InAs layers. In this work we chose mixed interface technique to strain balance our superlattice, i.e., both GaAs-like and InSb-like interfaces were formed. Fig.2 illustrates the shutter sequence for the LWIR superlattice.

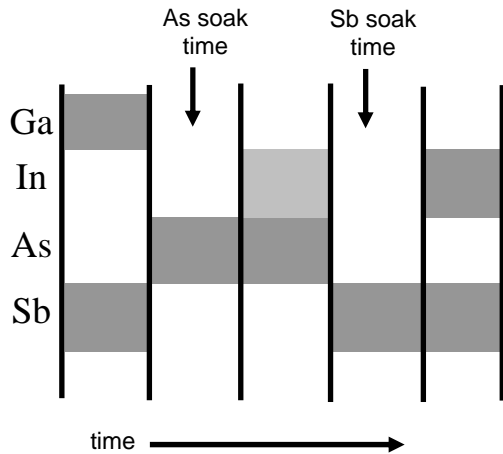


Fig.2. Shutter sequence of MBE machine for the growth of strain balanced superlattice.

The shutter sequence is designed to form a GaAs (InSb) interface on GaSb (InAs). For this purpose the Sb (As) shutter was closed and the As₂ (Sb₂) flux was left open for a limited time. This time is known as the “soak time”. The duration of the As soak time is 3 seconds while that of Sb soak time is of 8 seconds. A further intentional growth of InSb was under taken to balance the tensile strains introduced by the GaAs-like interfaces and InAs layers in superlattice. Since the lattice constant of InSb (GaAs) is much larger (smaller) than that of the GaSb, a few monolayers of these materials leads to an insertion of additional source of strain in a whole structure. An insertion of 0.8 ML InSb into each period was found to well balance the strain in the whole structure. The optimization was carried out over several trials with different thicknesses of InSb layers and determining the lattice mismatch between superlattice zero peak (SL₀) and GaSb substrate peak of the X-ray rocking curves of test structures (undoped 80 periods of 13ML InAs/ 7ML GaSb superlattice on GaSb substrate).

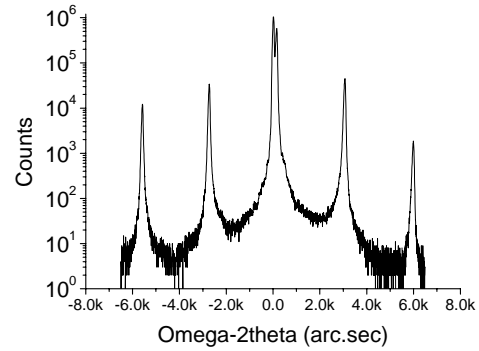


Fig.3. X-ray rocking curve of strain balanced 80 periods of 13 InAs/ 7 GaSb superlattice test structure.

Fig.3. shows the X-ray rocking curve of the strain balanced superlattice test structure. 0.1% lattice mismatch is obtained between superlattice and GaSb substrate; with satellite peak full width half maximum of 30 arcsec which is in the same level as that of the substrate peak. These suggests good quality LWIR superlattice have been achieved.

After growth of the LWIR superlattice p-i-n diodes, mesa structures with diameters ranging from 50µm to 400µm were fabricated using wet etching only. Initial etching was done using phosphoric acid based etchant H₃PO₄:H₂O₂:H₂O (1:2:20) followed by nitric acid based etchant HNO₃:H₂O (1:1). It was observed that HNO₃:H₂O (1:1) produces smaller surface leakage as compared to H₃PO₄:H₂O₂:H₂O (1:2:20) but HNO₃:H₂O (1:1) produces undercuts in mesa structures beyond 1µm of etching. Hence combination of H₃PO₄:H₂O₂:H₂O (1:2:20) and HNO₃:H₂O (1:1) wet etchants were used. However, surface leakage is still dominant at lower biases showing there is still room for improvement.

Results and discussions

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 low dark current density of 5.45×10^{-5} A/cm² (77K) at -0.2V is achievable, as shown in Fig.4. This value is lower than the published results [7].

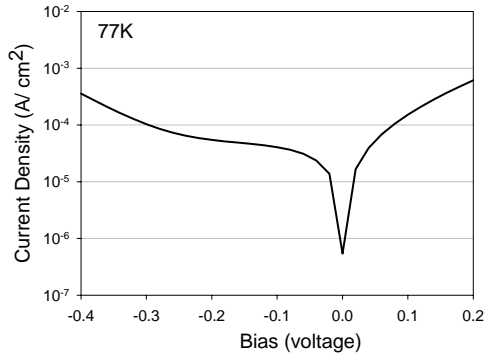


Fig.4. Current- voltage relationship of a p-i-n diode under 2π field of view (FOV) from a 300K scene.

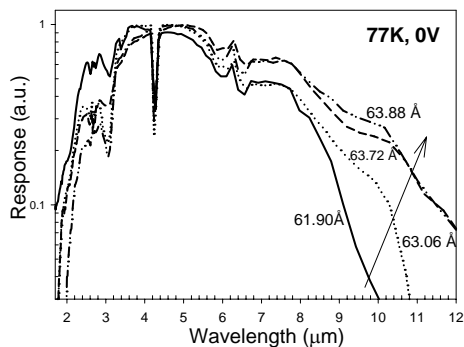


Fig.5. Spectral responses of 4 different layers for 200µm diameter devices.

Spectral measurements were performed using a Varian 7000e FTS system with standard ceramic IR source and KBr beam splitter. Fig.5. shows the spectral response from four different layers for 200 µm devices at 77K and zero bias. These layers differ in number of superlattice periods (N=80, 80, 150, and 250) only. This shows good repeatable LWIR response has been achieved, which can be verified from Table.1. Table.1. tabulates the X-ray rocking curve results of these layers along with its LWIR 50% cutoff defined as the

wavelength corresponding to 50% of the response obtained at 7.7 µm.

Table.1. X-ray rocking curve results and cutoff wavelengths of four different layers.

Layer	FWHM arc. sec.	SLS Period (Å)	LWIR 50% Cutoff
A, N=80	70.1	61.90	8.44 µm
B, N=80	56.2	63.06	8.94 µm
C, N=150	42.7	63.72	8.95 µm
D, N=250	69.0	63.88	8.98 µm

The X-ray rocking curve results in Table.1. showed reasonable FWHM between 42.7 - 70.1 arc. sec., indicating good quality growth of LWIR superlattice. The measured superlattice period from the X-ray rocking curves vary from 61.90 – 63.88 Å, which are very close to the designed value of 62.40 Å. The increase of the superlattice period has caused expected increase in the superlattice cutoff wavelength, as shown in Fig. 5.

Blackbody photocurrent measurements were done, for determination of responsivity. 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 [8]. Responsivity so obtained was converted into D^* values by measuring the noise spectral density using

$$D^* = \frac{R_{peak} \sqrt{A}}{i_n / \sqrt{\Delta f}}$$

Where, $i_n / \sqrt{\Delta f}$ is the measured noise spectral density (white noise includes shot noise and Johnson noise) using SR760 single channel Fast Fourier Transform spectrum analyzer. Table.2. shows the D^* values of all the four layers. The maximum D^* value of 1.3×10^8 $\text{cmHz}^{1/2}/\text{W}$ was obtained for $N=250$ period at 77K and -0.3V , which is lower than the published result of $\sim 10^{12}$ $\text{cm Hz}^{1/2}/\text{W}$ [7, 9]. This low D^* value can be attributed to lower number of superlattice periods (thinner absorption region) and to the problem of extraction of carriers at the interface of GaSb and superlattice due to very large bandgap discontinuity. Current work is on going on designing of proper cladding layers using LWIR or MWIR (mid-wave infrared) superlattice. In this regard progress has been made with successful growth of MWIR superlattice with 8 InAs/ 8 GaSb design and cutoff wavelength of $5.1 \mu\text{m}$ at 77K.

Table.2. Measured D^* of the four layers at 77K and -0.3V

Layer	D^* ($\text{cmHz}^{1/2}/\text{W}$)
A	9.3×10^7
B	6.1×10^7
C	2.4×10^7
D	1.3×10^8

Conclusion

We have demonstrated that good quality LWIR Type II 13 InAs/ 7GaSb superlattice can be repeatedly grown with LWIR 50% cutoff wavelength of $\sim 8.8 \mu\text{m}$ at 77K on GaSb substrate. We have been also successful in demonstrating strain balancing up to $N=250$ periods of superlattice. Lower than published result of dark current density $\sim 5.45 \times 10^{-5}$ A/cm^2 (77K) at -0.2V have been achieved with these p-i-n diodes. However, there is still room for improvement for low D^* value of 1.3×10^8 $\text{cmHz}^{1/2}/\text{W}$ obtained for $N=250$ period at 77K and -0.3V . Further work on cladding layer optimization and thicker superlattice structures are ongoing. As continuation of this work we would attempt to demonstrate the optimised superlattice structure on GaAs substrate.

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