

Mid-wave infrared InAs/GaSb type-II superlattice photodetector with n-B-p design grown on GaAs substrate

Zhuo Deng *, Daqian Guo *, Jian Huang, Huiyun Liu, Jiang Wu, and Baile Chen

Abstract—In this work, we report the direct growth and characterization of a mid-wave infrared InAs/GaSb type-II superlattice n-B-p photodetector on GaAs substrate. The design consists of an n-doped contact, a wide bandgap unipolar barrier and a p-doped absorber, which uses photogenerated electron as minority carriers to enjoy the longer electron diffusion length as compared to hole diffusion length. At 77 K, the device exhibits a dark current density of 2.9×10^{-5} A/cm² under -0.1 V, and a zero-bias differential-resistance-area product (R_0A) in excess of 8×10^3 $\Omega \cdot \text{cm}^2$. Arrhenius analysis of dark current demonstrates that the dominant mechanism is diffusion at temperature higher than 130 K. 50% cutoff wavelength of the detector is found at 6.4 μm at 77 K under zero bias, with a peak responsivity of 0.56 A/W. The corresponding specific detectivity is 7.6×10^{11} cm $\cdot\text{Hz}^{1/2}/\text{W}$. Key device parameters which limit the further optimization of performance are discussed.

Index Terms—GaAs substrate, InAs/GaSb type-II superlattice, Mid-wave infrared, Photodetector

I. INTRODUCTION

In the past two decades, mid-wave infrared (MWIR) photodetectors based on InAs/GaSb type-II superlattice (T2SL) has been the subject of extensive investigation as a competitive alternative to other detector technologies, such as HgCdTe (MCT), quantum wells and quantum dots, in both civil and military application sectors [1-3]. Flexibility of tailoring the detection wavelength by changing the thickness and composition of constituent layers [4], longer Auger recombination lifetime [5] and larger electron effective mass [6] have been reported in the InAs/GaSb T2SL system. These advantages have enabled the fabrication of high-performance

focal plane arrays (FPAs) based on T2SL to accommodate the application needs covering from the mid-wave to long-wave infrared region [3, 7]. Nevertheless, the significant progress of InAs/GaSb T2SL technology is mainly limited by two constraints. First, multiple dark current mechanisms including diffusion, generation-recombination (G-R) associated with the Shockley-Read-Hall (SRH) processes, tunneling and surface leakage would degrade the device performance in conventional p-i-n architecture. To address these problems, various heterostructures such as n-B-n [6], n-B-p [8], and complementary p-B-i-B-n [9] designs which utilize the engineering freedom of band structure of T2SL have been demonstrated in order to alleviate different dark current component. The second factor, which limits the realization of large format T2SL based FPAs, is the lack of low cost and large area substrates. Traditionally the T2SL detectors with superior performance are only grown on lattice-matched GaSb substrate, which suffers from large absorption coefficient for infrared radiation beyond 5 μm and shortage of supply with diameter larger than 4 inches in semiconductor industry [10]. As an alternative to grow T2SL detectors, GaAs substrate offers several advantages over the native GaSb substrate in terms of infrared transparency, size and cost [11]. However, formation of defects is inevitable while growing the GaSb layers on a highly mismatched ($\Delta a/a \sim 7.8\%$) GaAs substrate. One approach is to use interfacial misfit (IMF) array to completely relieve the strain energy at the GaSb/GaAs interface [12]. In the IMF growth mode, both 90° and 60° misfit dislocations (MDs) could present at the GaSb/GaAs interface. The 90° MDs are pure edge type dislocations which propagate laterally along the [110] and [1-10] directions; the 60° MDs can generate vertical propagated threading dislocations (TDs) along the (111) planes into the device region, which could contribute to high level of dark current [13, 14]. By using the IMF growth mode, T2SL detectors demonstrated on the highly lattice mismatched substrates have shown promising results comparing with the counterparts grown on the native substrates [10, 13].

In this work, we report a MWIR InAs/GaSb T2SL photodetector with a unipolar barrier heterostructure, namely the n-B-p architecture on GaAs substrate. The device design consists of an n-type contact, an n-type wide bandgap barrier and a p-type absorber. Similar to the n-B-n design, in n-B-p structure most of the depletion electric field drops across the wide bandgap barrier layer which is designed to reduce the G-R component of dark current. On the other hand, unlike the n-B-n design, in n-B-p variant the n-barrier/p-absorber junction offers a built-in potential, which enables zero-bias operation of the

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device. In addition, in n-B-n design the photocurrent is based on minority holes, while in n-B-p structure the p-doped absorber enables the higher mobility electrons to be the minority photocarriers, which is capable to attain higher quantum efficiency. The device demonstrated in this study shows a 50% cutoff wavelength of 6.4 μm at 77 K under zero bias. The corresponding quantum efficiency (QE) at near-cutoff is between 10 to 15%, and a peak specific detectivity of $7.6 \times 10^{11} \text{ cm} \cdot \text{Hz}^{1/2} / \text{W}$ is obtained. These device parameters are significantly improved compared with the T2SL detector with conventional p-i-n design grown on GaAs substrate, but further optimizations are needed to achieve comparable performance of the devices on native GaSb substrate.

II. EXPERIMENTAL DETAILS

Schematic diagram of the InAs/GaSb T2SL n-B-p device structure is shown in Fig. 1 (a). The device layers were directly grown on a GaAs (001) substrate using a solid-source molecular beam epitaxy system. The growth was started with a 200 nm thick GaAs layer at 590 $^{\circ}\text{C}$ to smooth the GaAs surface. After closing the arsenic valve, the growth was interrupted for 5s before opening the antimony valve. The growth of GaSb buffer was taken place at 480 $^{\circ}\text{C}$ with a growth rate of 0.7 monolayer (ML) per second. The n-B-p structure consists of a 500 nm thick p⁺-doped bottom contact layer formed by 10 ML InAs:Be ($1.98 \times 10^{18} \text{ cm}^{-3}$)/10 ML GaSb:Be ($1.1 \times 10^{18} \text{ cm}^{-3}$) SLs, followed by a 2000 nm thick p-doped 10 ML InAs:Be ($1 \times 10^{17} \text{ cm}^{-3}$)/10 ML GaSb:Be ($4.9 \times 10^{16} \text{ cm}^{-3}$) SLs absorber layer. Then a 250 nm thick n-doped barrier layer made of 6 ML AlSb/12 ML InAs:Si ($1 \times 10^{16} \text{ cm}^{-3}$) SLs was grown, followed by a 200 nm thick n⁺-doped 5 ML InAs:Si ($1 \times 10^{18} \text{ cm}^{-3}$)/5 ML GaSb SLs top contact layer. Finally the structure was terminated by a 50 nm thick n⁺-doped InAs:Si ($1 \times 10^{18} \text{ cm}^{-3}$) cap layer to assure a good ohmic contact property. Fig. 1 (b) depicts the calculated energy band alignment of the T2SL n-B-p structure under zero bias. The wide bandgap barrier layer provides a large valence band offset and minimal conduction band offset. It is clear that most of the electric field drops across the n-barrier/p-absorber junction while the absorber region remains flat, which helps to alleviate G-R dark current in the device. As mentioned previously, the p-type doping of the absorber layer is intended to utilize the higher mobility electrons as minority photogenerated carriers to improve the collection efficiency and thus quantum efficiency of device. It should be further noted that as a general design guideline, the optimal doping level for T2SL absorber is on the order of 10^{16} cm^{-3} , considering the simultaneous impact of doping concentration on diffusion dark current and minority carrier lifetime [15]. For the n-B-p T2SL structure studied in this work, the p-absorber was intentionally doped to a level of $\sim 5\text{-}10 \times 10^{16}$, aiming to reduce the diffusion current. However, one needs to take the Auger recombination effect into consideration when designing the absorber layer. For instance, Taghipour et al. have investigated the transport properties of minority carriers in a similar MWIR n-B-p T2SL detector grown on GaSb, in which an Auger-limited minority carrier lifetime of ~ 20 ns and a corresponding diffusion length of $< 5 \mu\text{m}$ were reported for temperature higher than 150 K [16]. These results indicate that Auger recombination could be an important limiting factor to

carrier transport when barrier-based T2SL detectors are operating at high temperature regime.

After the material growth, the wafer was processed into a set of mesa-isolated test devices with variable circular diameters using standard UV photo-lithographic processing technique. Mesa structures were defined by wet chemical etching with the solution $\text{C}_6\text{H}_8\text{O}_7:\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ (1:1:4:16) and mesa surfaces were passivated by SU-8. Finally, metal contacts of Ti/Pt/Au (50 nm/50nm/300 nm) were formed at the top and bottom contacts by using e-beam evaporation and lift-off techniques. No anti-reflection coating was used in the device.

In order to probe the crystalline quality of the T2SL device structure, high-resolution X-ray diffraction (HRXRD) was performed on the as-grown device wafers using an X-ray diffractometer in double-crystal configuration. The sample was then cleaved and a test device with 130 μm circular diameter was wire bonded. For electrical characterization, the device was loaded into a variable-temperature probe station and the dark current-bias voltage characteristics were analyzed by a semiconductor parameter analyzer. Afterwards the device was loaded into a variable-temperature cryostat for optical measurements. The relative photoresponse of the device was measured with a Fourier Transform Infrared Spectrometer in normal-incidence, top-illuminated configuration. In order to calibrate the spectral response and obtain the absolute responsivity of the device, a standard blackbody source operating at 700 $^{\circ}\text{C}$ with chopper frequency of 130 Hz was used to illuminate the sample at different temperature. A low-noise current preamplifier was employed to apply external bias to the device and to record and amplify the output photocurrent simultaneously. The signal was then recorded by a lock-in amplifier with reference frequency fed by the optical chopper.

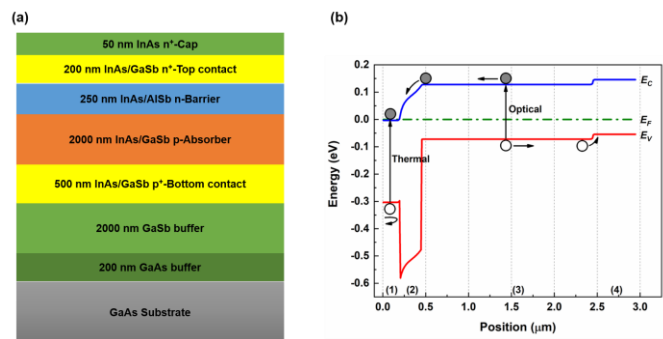


Fig. 1. (a) Schematic layout of the device structure; (b) Calculated energy band diagram of the T2SL device structure under zero bias. The layer sequence from left to right is: (1) n⁺-Top contact, (2) n-Barrier, (3) p-Absorber and (4) p⁺-Bottom contact. E_c , E_v and E_f represent conduction and valence band edge, and Fermi level respectively. Electrons are represented by grey circles while holes are drawn in hollow circles. The transitions associated with the photocurrent and dark current are labelled as “Optical” and “Thermal”, respectively.

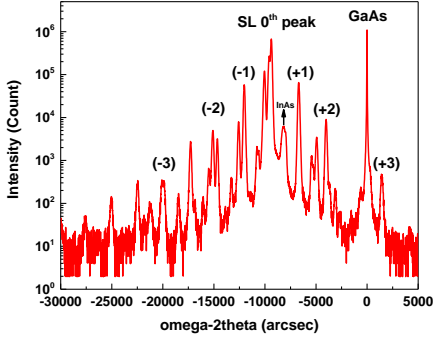


Fig. 2. HRXRD omega-2theta rocking curves measured from the T2SL as-grown device wafer.

III. RESULTS AND DISCUSSIONS

Fig. 2 shows the HRXRD omega-2theta rocking curves measured from the T2SL as-grown device wafer. Up to third-order satellite peaks for both the contacts and absorber superlattices are well defined in the sample. The sharp peak between the SL(0) and SL(+1) peaks is from the InAs cap layer. The Full-Width-at-Half-Maximum (FWHM) of the SL(0) and SL(+1) peaks are estimated to be ~ 140 and ~ 150 arcsec respectively. The FWHM of GaSb (004) peak is ~ 135 arcsec, which is comparable to the FWHM value mentioned in Ref. [12]. The dislocations density ρ_d is estimated to be $\sim 5 \times 10^7 \text{ cm}^{-2}$, based on the equation $\rho_d = (\text{FWHM}/2b)^2$, where the Burgers vector b is 0.431 nm [17].

Dark current density-bias voltage characteristics measured from the T2SL device at different temperatures are presented in Fig. 3 (a). The test device has a circular diameter of $130 \mu\text{m}$. It is noted that the dark current curves measured at 77 K and 100 K show small photovoltaic shifts to the positive bias, which are due to the imperfections in the cold shield of the probe station used in the measurements. At 77 K, the device exhibits a dark current density of $2.9 \times 10^{-5} \text{ A/cm}^2$ under -0.1 V , and it increases to 5.8 A/cm^2 at room temperature. From the temperature dependent dark current curves, the differential-resistance-area product (RA) as a function of bias at different temperatures can be evaluated, as plotted in Fig. 3 (b). The peak RA at 77 K is found at $\sim 1.8 \times 10^4 \Omega \cdot \text{cm}^2$ under -0.1 V bias, and the RA under zero bias (R_0A) is $\sim 8 \times 10^3 \Omega \cdot \text{cm}^2$. Fig. 4 shows the temperature dependent Arrhenius plot of the dark current density under applied bias of -0.1 V . Linear fit at low temperature regime (77-130 K) yields an activation energy (E_a) of $\sim 61.6 \text{ meV}$, and at high temperature range (130-300 K) E_a increases to $\sim 159.9 \text{ meV}$. Since the bandgap energy (E_g) of the T2SL device varies from $\sim 184 \text{ meV}$ (77 K) to $\sim 159 \text{ meV}$ (190 K) as estimated from the absorption edge of the photoreponse spectra (see Fig. 5), at low temperature range $E_a = E_g/3$, indicating that the device dark current is dominated by the G-R mechanism; at high temperature range $E_a = E_g$, suggesting that the device dark current is mainly contributed by diffusion.

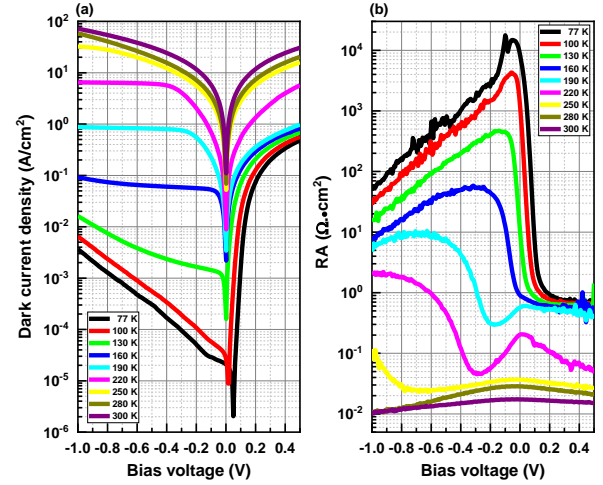


Fig. 3 (a) Temperature-dependent dark current density-voltage characteristics of the T2SL device with a circular diameter of $130 \mu\text{m}$; (b) Differential-resistance-area product (RA) as a function of bias voltage of the T2SL device at different temperatures.

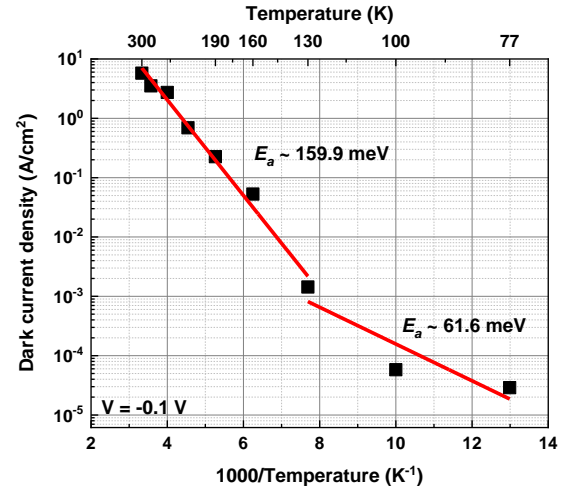


Fig. 4. Arrhenius plot of the dark current density under -0.1 V bias. Solid lines represent the linear fit at different temperature regimes.

The photoreponse spectra of the T2SL device measured at different temperatures are shown in Fig. 5. At 77 K and under zero bias, the 50% cutoff wavelength ($\lambda_{50\% \text{ cutoff}}$) is found at $\sim 6.4 \mu\text{m}$, with a peak responsivity of 0.56 A/W . It shifts to $\sim 7.3 \mu\text{m}$ at 190 K, and the peak responsivity drops to 0.35 A/W . When temperature rises from 77 to 130 K, the photoreponse slightly increases, which can partly be due to improved electron thermionic emission efficiency over the unexpected electron barrier induced in the conduction band, and partly be due to the increase of absorption coefficient with the red-shift of material bandgap, i.e., $\alpha(\lambda) \sim [E(\lambda) - E_g(T)]^{1/2}$. However further increase of temperature from 130 K onwards leads to a rapid drop in responsivity. It is believed this is due to the enhanced recombination rate of carriers at high temperature, thus the diffusion length is reduced and more and more carriers annihilate before they could reach the electrodes and contribute to the photocurrent[18]. Fig. 6 (a) depicts the quantum efficiency (QE) of the T2SL device at different temperatures.

The oscillatory features observed before 4 μm for all spectra, which exist originally in the photoresponse spectra, are due to the multiple reflections between the superlattice/air and the GaSb/GaAs buffer interfaces as a consequence of different refractive indexes of the materials [19]. From 77 to 130 K the QE values at 4 μm under zero bias stay around 15% until the temperature rises above 130 K, as illustrated in Fig. 6 (b). A small bias of -0.05 V is sufficient to recover the QE and fully extract the photogenerated carriers. Fig. 6 (c) shows the QE at 77 K at 4 μm under different applied bias. It is clear that QE saturates at a bias beyond -0.5 V. This bias dependence of QE suggests that not all carriers are extracted at lower bias, which might be attributed to the presence of small unexpected conduction band offset. The QE value of our T2SL device is four times lower than that of the MWIR InAs/GaSb T2SL detector with similar n-B-p design on GaSb substrate [20], which could be due to the thinner (2 μm versus 4 μm) absorber and lower carrier lifetime in our GaAs based device. Additional works are required to increase the QE of our device by optimizing the crystal quality of absorber.

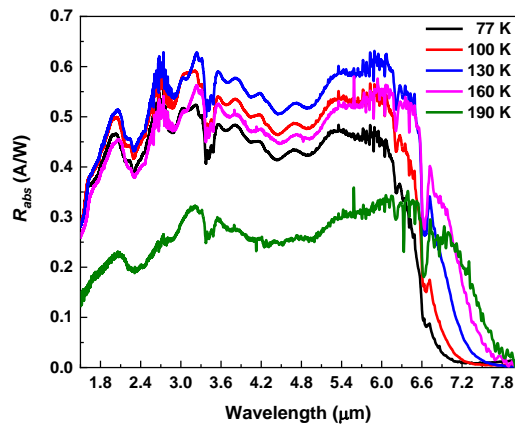


Fig. 5. Absolute responsivity (R_{abs}) of the T2SL device as a function of wavelength under zero bias.

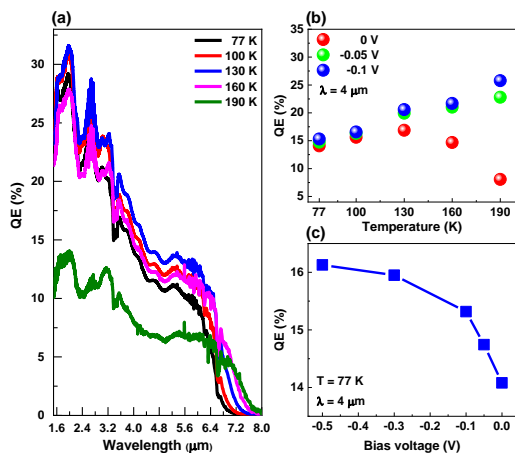


Fig. 6. Quantum efficiency (QE) of the T2SL device (a) at different temperatures under zero bias; (b) QE at 4 μm at different temperatures under three different bias voltages; (c) QE at 77 K at 4 μm as a function of bias.

Finally, the Johnson noise-limited specific detectivity D^* of the T2SL device is calculated by [18, 21, 22]:

$$D^* = R_p A^{\frac{1}{2}} \left(\frac{4k_B T}{R_0} \right)^{-1/2} \quad (2)$$

where R_p is the peak responsivity, A is the device mesa area, k_B is Boltzmann's constant, T is the temperature of the device, R_0 is the differential resistance under zero bias, and q is the electron charge. Specific detectivity curves calculated at different temperatures are shown in Fig. 7. At 77 K, a peak D^* of $7.6 \times 10^{11} \text{ cm} \cdot \text{Hz}^{1/2} / \text{W}$ is achieved under zero bias. This value is six times higher than the MWIR T2SL n-B-n counterpart [10], and an order of magnitude higher than that in the traditional p-i-n device grown on GaAs [23] (see TABLE 1), thanks to the much lower dark current density (~three order of magnitude) contributed by the barrier design. It is worth to note here, despite the additional SRH component, the dark current density in our device is about twenty times lower than the dark current density of the n-B-n on GaAs in Ref [10]. This can be attributed to lower defect density and the application of surface passivation layer. However, our device shows about an order of magnitude higher in dark current as compared with the similar n-B-p on native GaSb substrate. Thus, in order to achieve higher operating temperature and performance comparable with state-of-the-art MWIR T2SL device on native substrate, additional engineering of the present structure should be focused on optimization of defect density in the active layers to further reduce the device dark current, e.g., by growing more and/or thicker layers of dislocation buffer.

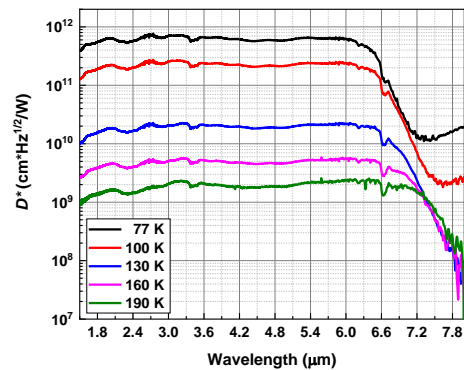


Fig. 7. Specific detectivity (D^*) of the T2SL device at different temperatures.

TABLE 1. Comparison of 50% cutoff wavelength ($\lambda_{50\% \text{ cutoff}}$), dark current density (J_d) and peak detectivity (D^*) of T2SL-based detectors grown on different substrates with various designs. Unless specified otherwise, all data shown are at 77 K and under zero bias.

Device parameters	n-B-p on GaAs	n-B-p on GaSb [20]	n-B-n on GaAs [10]	p-i-n on GaAs [23]
$\lambda_{50\% \text{ cutoff}}$ (μm)	6.4	5 (0.2 V)	4.3 (0.5 V)	4.3
J_d (0.1 V, A/cm ²)	2.9×10^{-5}	4.5×10^{-6}	6×10^{-4}	1×10^{-2}
Peak D^* (Jones)	7.6×10^{11}	N/A	1.2×10^{11}	2.3×10^{10}

IV. CONCLUSION

In conclusion, we have demonstrated an InAs/GaSb type-II superlattice n-B-p photodetector grown on GaAs substrate which operates in the MWIR range ($\lambda_{50\% \text{ cutoff}}=6.4 \mu\text{m}$). Temperature dependent dark current analysis shows the dominance of diffusion at temperature higher than 130 K. At 77 K, a low dark current density of $2.9 \times 10^{-5} \text{ A/cm}^2$ under -0.1 V is achieved, corresponding to a R_0A value in excess of $8 \times 10^3 \Omega\text{-cm}^2$. QE between 10 to 15% is observed at near cutoff wavelength at 77 K under zero bias, and the peak specific detectivity is $7.6 \times 10^{11} \text{ cm-Hz}^{1/2}/\text{W}$. Future works should be focused on the enhancement of QE and reduction of dark current, such as the fine-tuning of absorber thickness and the dislocation buffer layer, in order to compete with the state-of-the-art devices while enjoying the cost benefit of non-native substrates at the same time.

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