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Fabrication and characterization of high lattice matched InAs/InAsSb superlattice infrared photodetector

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ABSTRACT

We have fabricated the new composition structure high-lattice-matched mid-wave infrared Ga-free InAs/InAs$_{0.73}$Sb$_{0.27}$ type-II superlattice (T2SL) pin photodetectors on GaSb substrates. Current-voltage and photocurrent measurements of samples were characterized with different sized mesa structures at 77 K. The resulting of mid-infrared photovoltaic detectors measured at 77 K exhibit a measured dark current density of 6.13×10^{-4} A/cm^2 under a bias of −300 mV, a maximum differential-resistance-area-product of 448 Ω·cm^2 at −47 mV bias, a 50% cutoff wavelength of 5.1 μm, and a peak responsivity of 0.883 A/W over a mesa size of 50 μm × 50 μm. Peak quantum efficiency of 34.6% at 2.78 μm over a mesa size of 50 μm × 50 μm, 23.3% at 2.78 μm over a mesa size of 200 μm × 200 μm, and 14.1% at 2.8 μm over a mesa size of 300 μm × 300 μm are achieved under zero bias at 77 K, respectively.

1. Introduction

Due to higher cost limitations of the HgCdTe materials, antimonide based type-II superlattices (T2SL) have been proposed as an alternative [1,2] to HgCdTe with potentially lower manufacturing cost on large substrates [3] and better device performance with low dark current density due to suppressed Auger recombination rate and tunneling current [4–6]. These advantages of T2SLs enable them to operate at higher temperatures, which is highly desirable for photodetector applications [7,8].

The InAs/GaSb SL material system has demonstrated a long Auger lifetime, which makes it a promising candidate for improving on current HgCdTe (MCT) devices [9,10]. Although the feasibility of T2SLs for IR photodetectors has been widely studied for decades, the T2SL materials properties and device performance still have not reached the level predicted by theory [5]. One of the limiting factors of the most widely studied InAs/(In)GaSb T2SLs is the short minority carrier lifetime due to a comparatively high level of Generation-Recombination (G-R) dark current, which determines the dark current, detectivity, and ultimately the maximum operating temperature. This G-R current arises from a low Shockley-Read-Hall (SRH) carrier lifetime [11–13], which is currently attributed to native defects in the GaSb layer [14]. Recently, the study of another type of T2SL, namely the "Ga-free" InAs/InAsSb T2SLs grown on GaSb substrates developed to avoid the low lifetimes associated with the GaSb layer, has been revisited and revealed very encouraging results [15–21].

Applications in the spectral range of 3–5 μm are found in various domains such as pollutant detection, infrared thermal imaging, lidars, or optical countermeasures. The important applications associated with gas detection and infrared imaging in this spectral range have stimulated considerable interest in the development of mid-infrared photodetectors. Antimonide based materials, such as InAs/InAsSb superlattice have a strong potential for the development of mid-infrared devices such as lasers or detectors operating between 2 and 5 μm.

Only recently, InAs/InAsSb SLs have been grown by molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD) and explored in detail [22–26]. These SLs show excellent structural properties and strong optical responses. As a promising alternative, Ga-free InAs/InAsSb T2SLs can cover a similar infrared bandgap range [27,28], and an InAs/InAsSb T2SL demonstrate a carrier lifetime of more than 412 ns at 77 K [14], which is an order of magnitude greater than that of the conventional LWIR InAs/Ga(In)Sb T2SLs [29–31] and only less than an order of magnitude shorter than that (~1.5 μs) of LWIR HgCdTe materials [29].

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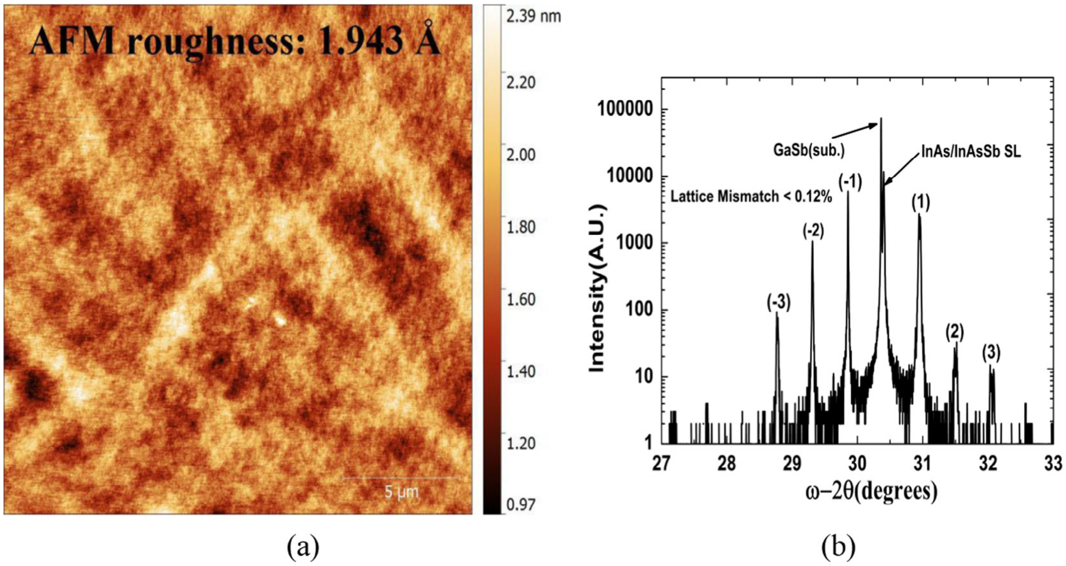

Fig. 1. (a) AFM image (20 µm × 20 µm) and (b) XRD rocking curves of the InAs/InAsSb superlattices grown on a GaSb (001) substrate.

In this letter, we first investigate the properties of a device with new composition structure using high resolution X-ray diffraction (HRXRD) and atomic force microscopy (AFM). We also study the electrical and optical properties of InAs/InAsSb T2SL devices. The sample is subsequently processed into mesa isolated single element diodes using a standard processing technique. The measured dark current uses Agilent B1500 network analyzer and Lakes Shore cryogenic probe system. The spectral response is measured using a Fourier transform infrared spectrometer with a KBr beam splitter and SR-570 low-noise current preamplifier.

2. MBE growth and characteristics

In this study strain-balanced T2SL samples can be designed by varying the InAs and InAsSb layer thickness ratio and the Sb mole fraction in InAsSb layers to cover the bandgap energies corresponding to 3–5 µm and 8–12 µm wavelengths [32]. A 19.2 ML InAs/9.6 ML InAsSb T2SL device structure is designed, grown and fabricated to give 5.5 µm cut-off wavelength, covering the MWIR atmospheric transmission window completely.

The epitaxial growth of these photodetector samples is carried out using a Veeco Gen II molecular beam epitaxy system equipped with valved cracker sources for group V (Sb_2 and As_2) fluxes and Ga/In SUMO® cells, on n-type epiready GaSb (001) substrates. MBE control software is used to simultaneously control the shutter operation, temperature ramps, and As and Sb cracking-cell valve positions. The growth temperature is kept at 520 °C. The III–V ratios and shutter sequences have been optimized in order to get good material quality and smooth surface morphology.

Fig. 1 shows the AFM image of the sample's surface (a) and the X-ray diffraction rocking curve (b). As shown in the Fig. 1, the high-quality $InAs/InAs_{0.73}Sb_{0.27}$ SL materials matched to GaSb have been achieved. By carefully adjusting the flux stability, growth temperature and shutter movements, we have grown $InAs/InAs_{0.73}Sb_{0.27}$ SLs with very smooth surfaces, an RMS roughness of 1.943 Å over an area of 20 µm × 20 µm (shown in Fig. 1(a)), meaning a good crystallinity. And the mismatch between the zeroth-order peak of $InAs/InAs_{0.73}Sb_{0.27}$ SL and the GaSb substrate peak is approximately 100 arcsec, while the FWHM of the zeroth-order peak is below 130 arcsec. The symmetric and narrow widths of the superlattice fundamental X-ray diffraction peak as shown in Fig. 1(b) indicate that very close lattice matching is achieved for the grown devices.

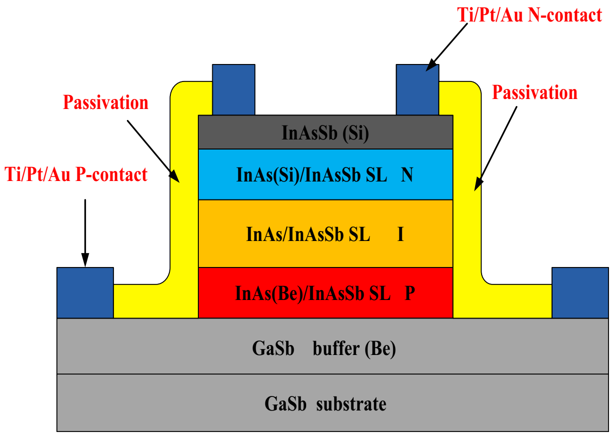

Fig. 2. Epilayer structure diagram of the designed InAs/InAsSb T2SL photodetector after processing.

The schematic sample layer structure is shown in Fig. 2, which consists of a 37 nm n-type top InAsSb contact, a 0.877 µm heavily doped n-type (1–2 × 10^{18} cm^{-3}) InAs (Si) /InAsSb (100 periods) superlattice layer for the n-type contact, a 4.4 µm nominally undoped InAs/InAsSb (500 periods) superlattice absorption layer, a p-type (1–2 × 10^{18} cm^{-3}) 0.877 µm thick InAs (Be) /InAsSb(100 periods) superlattice contact layer, and a bottom p-contact GaSb buffer grown on GaSb substrate. All layers are lattice matched to the GaSb substrate.

Photodetectors are fabricated using an ICP dry etch and a standard photolithographic process. Ti/Pt/Au metallization is evaporated on top of the mesas and on the p-contact layer in a liftoff process to form ohmic contacts. The devices fabricated into single-pixel mesa structures with varying aperture sizes are completed without any anti-reflecting coating and surface passivation. Device processing starts with photolithography to define the mesas, which have open optical apertures. The etching is stopped at the top of the p-type bottom contact, resulting in an etch depth of 5.4 µm. There is a certain deviation between theoretical values (6.2 µm) and experimental values (5.4 µm), due to the fact that the growth rate will change during the device structure growth process.