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Molecular beam epitaxy growth of antimony-based mid-infrared interband cascade photodetectors

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ABSTRACT

The molecular beam epitaxial growth and optimization of antimony-based interband cascade photodetectors, on both GaSb and GaAs substrates, are presented. Material characterization techniques, including X-ray diffraction, atomic force microscopy, and cross-sectional transmission electron microscopy, are used to evaluate the epitaxial material quality. This work has led to the demonstration of mid-infrared photodetectors operational up to a record-high 450 K, and a dark current density as low as 1.10×10^{-7} A/cm^2 at 150 K. The results also suggest that further improved material quality and device performance can be expected via optimization of growth parameters.

1. Introduction

The InAs/GaSb type-II strained layer superlattice (T2-SL) is widely regarded as a viable alternative to the dominant HgCdTe technology for infrared (IR) detection [1]. Over the past decade, significant progress in both scientific and technological aspects has been made [2]. Despite the relatively short carrier lifetime in InAs/GaSb T2-SLs, researchers managed to take advantage of the great versatility in energy band alignment. The detector performances are steadily approaching the well-investigated HgCdTe and InSb technologies [1,2]. Driven by the increasing demand to shrink the size, weight, and power consumption (SWaP) of IR imaging systems, the development of high operating temperature (HOT) IR detectors and imagers is of great interest. The key issue/challenge for the InAs/GaSb T2-SL HOT applications is the relatively short carrier lifetime, which results in pronounced generation-recombination noise and inferior photo-carrier collection at HOTs, therefore degrading the attainable detector performances. One possible way to promote the photo-carrier extraction in InAs/GaSb T2-SL photodetectors at HOTs is to use a multi-junction/stage design with multiple thin absorbers, such as Interband Cascade (IC) detectors [3–7]. The multi-stage design could also be beneficial for detector noise suppression, by means of incorporating unipolar barriers and designing devices to operate under/near zero-bias conditions [5–7].

This paper describes the development of HOT InAs/GaSb T2-SL photodetectors. By adopting the so-called IC structure [4–9], high performance mid-IR detectors operational well above room temperatures are realized. By uniquely combining several different carrier transport mechanisms, many distinctive and highly desirable features are obtained in IC photodetectors [4–7]. The devices consist of multiple stages that are electrically connected in series. In each stage, there are three different regions: an electron barrier (eB), an InAs/GaSb T2-SL absorber, and an electron relaxation (eR) region.

The basic operation principle of IC detectors is shown in Fig. 1: the incoming photons are absorbed in the moderately thin InAs/GaSb T2-SL region, creating photo-excited electrons. Due to the existence of unipolar barriers to the left of the absorber, photo-generated electrons can only travel towards the right. The electrons will then travel through the eR region via ultra-fast longitudinal optical-phonon assistance inter-subband relaxation, and subsequently tunnel into the valence band of the next stage. By implementing this ultra-fast electron transport channel into the device, a large lifetime contrast (between carrier recombination and transport) is created in the IC detectors, despite the short carrier lifetime in InAs/GaSb T2-SLs. Combined with the implementation of unipolar barriers and its zero-bias operation capabilities, IC detectors are capable of very high temperature operation [6,7].

In order to facilitate such a relatively complicated device concept, a quantum-engineered AlSb/InAs/GaSb-based layered structure is adopted. As shown in Fig. 1, an IC photodetector consists of several alternating chirped superlattice or coupled quantum wells (QWs) regions, whose constituent materials and layer thicknesses vary. The eB region is made of GaSb/AlSb multiple QWs, the absorber consists of InAs/GaSb superlattices, and the eR region is made of a series of InAs/AlSb coupled QWs. The optimum growth conditions for these constituent materials, for example the growth temperature for InAs/InSb and AlSb, are quite different. More

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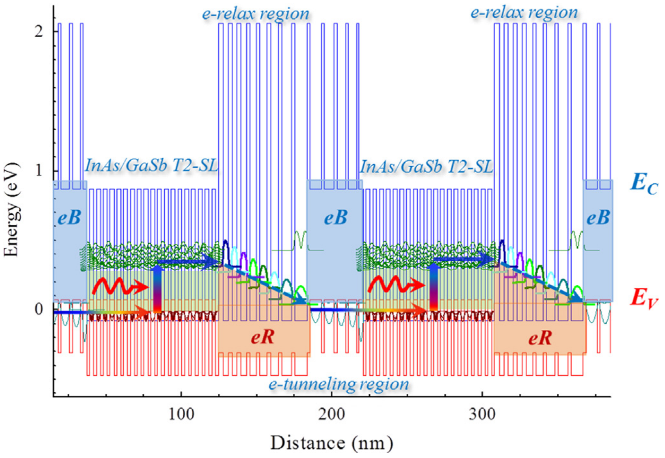

Fig. 1. Band structure diagram in (two-stage) interband cascade photodetectors. Incoming photons are absorbed in the InAs/GaSb T2-SL absorbers, generating electron–hole pairs. Electrons diffuse into the electron relaxation region, and then effectively transport into the valence band of the next stage, through fast LO phonon-assisted inter-subband relaxation and interband tunneling.

importantly, as the operation of IC detectors depends entirely on the proper energy band alignment, enabled by the quantum-confinement effect in the QW structures, these layer thicknesses are critical and therefore need to be precisely controlled. This is particularly true for mid-IR IC devices, where thinner QW layers are used and the band alignment is more sensitive to layer thickness variations. In addition, the strain in each stage and in individual regions has to be balanced in order to ensure better crystal quality. Therefore, the growth of such a complicated IC detector structure is very challenging, particularly for epitaxial systems without redundant sources. This paper elaborates the epitaxial growth and optimization of mid-IR IC photodetectors.

2. Experimental procedure

The materials are grown with a Veeco Gen-10 molecular beam epitaxy (MBE) system, which is equipped with group-III SUMO cells and group-V valved crackers. For the group-III SUMO cells, the tip filament for Gallium and Indium cells are kept at higher temperatures (100–120 °C higher than the base temperatures) to reduce the spitting/oval defects, and a cold-lipped Aluminum SUMO cell is used to avoid source material creeping. For the group-V As and Sb crackers, the cracking zone temperatures are set to 900 °C (a mixture of dimers and monomers). The growth rates of the group-III sources are determined by multiple-point Reflection High-Energy Electron Diffraction (RHEED) oscillations, and are routinely verified by monitoring the beam equivalent pressure (BEP) of each source, as well as from constituent layer thicknesses in superlattice calibration samples. The optimum growth temperatures, growth rates and V/III ratios are determined by the optical (maximum photoluminescence PL intensity) and crystal qualities (as determined from the surface morphology and X-ray diffractions) through a series of superlattice calibration samples prior to the growth of device wafers.

The typical MBE growth sequence for IC detectors grown on (001) GaSb substrates is as follows: the substrate is transferred into the growth chamber for oxide desorption, performed under excess Sb flux at 540–550 °C, as determined by an InGaAs pyrometer. Complete oxide desorption from the GaSb substrate is ensured by a streaky 1 × 3 RHEED reconstruction pattern. The substrate is then cooled down to ~500 °C for a 200–400 nm *p*-GaSb buffer layer growth, to obtain a smooth surface. The GaSb buffer layer, which is doped to 5×10^{18} cm^{-3} with Beryllium, also serves as the bottom contact. The 5-stage IC structure is subsequently grown, with the overall strain balanced in each individual region. In this work, strain balancing is achieved by two approaches – proper device structure design and carefully tuned growth sequence and parameters. The growth is then finalized by a thin (10–15 nm) *n*-InAs top contact layer doped with Tellurium. For the cascade stage growth, the substrate temperature is set at 400–420 °C. During the growth of InAs/GaSb T2-SL absorber region, the growth rate of InAs is 0.9 Å/sec, with an As/In ratio of ~3, and the GaSb growth rate is 0.9 Å/sec, with a Sb/Ga ratio of 4.5. InSb-like interfacial layers are used in the InAs/GaSb T2-SL absorber regions for better crystal and optical quality [10]. Because of the existence of residual As flux during the GaSb layer growth and the higher sticking coefficient of As over Sb, about 9% Arsenic was found to be incorporated into the GaSb thin layers. In fact, As incorporation is found in all Sb-containing layers, which will require further attention in fine tuning the device design and strain balancing.

There has also been considerable interest in the development of high performance IR photodetectors on GaAs substrates, to further reduce cost and enable large-format focal plane arrays (FPAs). The major challenge here is to properly accommodate the 7.8% lattice mismatch between GaAs and GaSb, which could produce excessive amount of threading dislocations, resulting in severely degraded crystal quality and carrier lifetime. Nonetheless, due to the uniquely high lifetime contrast in IC detectors, one would expect IC detectors to be less susceptible to the inferior material quality. In this study, for IC detectors grown on (001) GaAs substrates, an interfacial misfit array (IMF) method [11] is adapted. After the oxide desorption on GaAs substrate, a 300-nm GaAs layer is first deposited to obtain a smooth surface, and then the sample is exposed to excess Sb overpressure while the substrate temperature is brought down to ~500 °C. An 800-nm *p*-GaSb buffer layer (which also serves as the bottom contact) is then grown. The 5-stage mid-IR IC device structure is grown subsequently, with identical growth parameters.

After growth, the crystal quality and surface morphology of the epitaxial structures are characterized by X-ray diffraction (XRD), atomic force microscopy (AFM), and cross-sectional transmission electron microscopy (TEM). The samples are then processed into single-pixel devices, to further characterize electrical and optical performances of the detector. One sample grown on GaSb substrate is processed into a 320 × 256 FPA, and IR images acquired by the mid-IR IC FPA are demonstrated.

3. Results and discussion

The sample surface morphology and crystal quality are evaluated by optical and electron microscopy, AFM, XRD, and room temperature photoluminescence (PL). The XRD rocking curves are recorded in the vicinity of the symmetrical (004) GaSb diffraction spot. The representative XRD pattern of an IC detector sample is shown in Fig. 2, and the inset is an enlarged view of the rocking curve close to the substrate peak. Sharp satellite peaks up to 8th order are observed, indicating high structural quality of the samples. The InAs/GaSb T2-SL absorber overall shows good material quality, as indicated by the strong room temperature PL (not included here) and the sharp satellite peaks in XRD rocking curves (the FWHM of the satellite peaks is around 26 arcseconds, as measured from InAs/GaSb T2-SL calibration samples). The overall strain in the epitaxial structure is within 50 arcseconds for the 5-stage IC detector samples. The extracted period of the cascade stage is around 220 nm, which is in good agreement with the device design (about 0.4% thicker than the design).

The wafers are then processed into single-pixel photodetectors for device performance evaluation. These mid-IR IC detectors are operational up to 450 K under zero-bias, as shown in Fig. 3a. To the best of our knowledge, this is the highest operation temperature reported for IR photodetectors [7,9]. The promising optical performance of IC detectors is attributed to the high lifetime contrast and efficient

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