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Photocapacitance study of GaSb: In, As for defect analysis in InAs/GaSb type-II strained layer superlattices

B. Klein *, C. Hains, Z. Taghipour, E. Plis, S. Krishna

Center for High Technology Materials, 1313 Goddard Street SE, Albuquerque, NM 87106, United States

HIGHLIGHTS

- GaSb doped with In and As and InAs/GaSb type-II superlattice was grown and fabricated into devices.
- Steady-state photocapacitance measurements were used to identify defect levels in these devices.
- A defect level was observed in the GaSb samples, that was not effected by the In or As content.
- A defect level was also seen near midgap for the superlattice sample.

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ABSTRACT

Steady-state photocapacitance measurements were used to characterize GaSb incorporated with In, As, and a control sample. Evidence of a trap level at 0.55 eV was observed for all samples. The change in the capacitance for the sample with indium was about half the change for the other samples, indicating that the addition of indium modified the near-mid-gap trap levels. Another change in capacitance starting at 0.71 eV was attributed to electrons from the valence band filling levels close to the conduction band.

1. Introduction

InAs/GaSb type-II strained-layer superlattices (T2SL) is a promising candidate as an IR detector material. T2SL has a higher level of mechanical robustness than its leading competitor HgCdTe [1], as well as higher compositional uniformity [2]. Furthermore, T2SL has been shown both in theory [3] and practice [4] to suppress Auger recombination, yet in spite of this suppression, Shockley–Read–Hall (SRH) recombination dominates, leading to short (30 ns for long-wave IR, 100 ns for mid-wave IR) minority carrier lifetimes [5–9]. This short lifetime is one of the greatest challenges limiting T2SL. Without an order of magnitude improvement in minority carrier lifetime, T2SL loses its competitive edge against HgCdTe.

Many studies have been undertaken to solve the T2SL lifetime problem. The effect of growth parameters on lifetime including interfaces [8,10], InSb strain compensation layer thickness [11], growth rates [10], and growth temperatures [8] have been reported. Varying the number of interfaces per unit volume or growth rate did not have a drastic impact on measured minority carrier lifetimes and the InSb layer thickness showed a ~100 ns improvement in hole lifetime only (from 48 ns to 157 ns). A study of the growth temperature's effect on bulk InAs and GaSb showed that GaSb has about the same lifetime as T2SL if it is grown at T2SL growth temperatures, while at higher temperatures, its lifetime increases [8]. This points to GaSb as a potential cause of the short lifetimes, yet simply increasing growth temperature is not a viable solution because of T2SL crystallographic degradation at higher growth temperatures. Further evidence that GaSb causes the low lifetimes is seen by simply removing it; Ga-free InAs/InAsSb superlattices have shown an order of magnitude improvement in minority carrier lifetimes [12,13]. With this information, it is clear that the key to improving T2SL lifetimes lies in improving the lifetime of GaSb. One of the ways this can be done is by studying the defects in GaSb.

Defects levels in GaSb is not a new topic; numerous defect levels have already been identified [14]. However, from the perspective of trying to reduce T2SL defects through the improvement of GaSb, there is still much to learn. In this report, steady-state photocapacitance measurements are used to determine defect levels in the T2SL. Previously, steady-state photocapacitance has been

* Corresponding author.
E-mail address: bklein01@unm.edu (B. Klein).

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applied to such materials as GaAs [15,16], InGaAs [17], GaP [18], and GaAsN [19]. This method exploits the relationship between space-charge region capacitance (C) and the density of ionized impurities (N_{SCR}) to discern trap energy levels [20]: $C \propto \sqrt{N_{SCR}}$. Steady-state photocapacitance works by scanning through a range of wavelengths incident on the sample while monitoring capacitance, the resulting filling or emptying of traps and their corresponding energies relative to the valence or conduction band can be observed.

2. Experiment

All samples were grown in a solid source molecular beam epitaxy (MBE) VG-80 system equipped with valved cracker sources for the group V Sb_2 and As_2 fluxes, and Ga/In SUMO® cells. A list of the structures, numbered 1–4, is shown in Table 1 and an illustration of the growth structures is given in Fig. 1. The GaSb and T2SL samples were grown on undoped (residually p-type, $\leqslant 2 \times 10^{17}$ cm^{-3}) GaSb substrates and all epitaxial layers were 4 μm thick.

The GaSb samples were grown using conditions as close as possible to what the GaSb in each superlattice layer would be subjected to during a typical T2SL growth. Therefore, the growth temperature was approximately 25 °C less than the GaSb RHEED (reflection high-energy electron diffraction) reconstruction transition temperature [21]. Sample 1 was a control sample grown at T2SL temperatures, without indium or arsenic incorporation. For Sample 2 the arsenic shutter was closed during the entire growth but the valve was opened to a typical setting for the InAs layers of the T2SL, while for Sample 3 the indium was heated to a temperature that would produce an InAs growth rate of 0.3 ML/s but with the shutter closed. The T2SL sample 4 was also grown at approximately 25 °C less than the GaSb RHEED reconstruction transition temperature with growth rates of 0.3 ML/s for both indium and gallium.

After growth, each sample was characterized with Nomarski interference microscopy and X-ray diffraction (XRD) to examine surface defects and crystallographic quality, respectively. Nomarski images revealed cross-hatching on the GaSb samples 2 and 3, suggesting a large amount of both arsenic and indium incorporation had occurred. The XRD (shown in Fig. 2) was also effected by the incorporation; for the As-incorporated sample (2) the full-width half-maximum (FWHM) of the epitaxy peak was broadened, and for the In-incorporated the epitaxy peak was separated from the substrate peak (see Table 1). Sample 2 had to be re-grown for the sake of determining As incorporation, with a thinner layer of epitaxy (500 nm) so that the epitaxy peak could be distinguished from the substrate peak (this is the XRD plot shown in Fig. 2). RADS Mercury simulation software was used to approximate the amount of incorporation of As and In based on the XRD data, which was 2.2% and 1.2%, respectively. The GaSb control sample (1) showed no unusual surface features and the FWHM of the XRD was low, a sign of normal GaSb growth.

Each sample was processed into Schottky photodiodes using a Schottky diode mask set (see Fig. 3). Standard contact lithography defined mesas with AZ4330 photoresist and inductively-coupled plasma etching with BCl_3 gas. Then, two metal layers, defined by

Table 1
List of samples in this study. The FWHM is for the epitaxy peak separated from the substrate peak. The FWHM of the regrowth of Sample 2 was 46 arc seconds.

	Sample	Description	FWHM (arcsec)
1	GaSb	Control sample (Grown at ~400 °C)	25.82
2	GaSb: As	GaSb with arsenic incorporation	119.87
3	GaSb: In	GaSb with indium incorporation	35.58

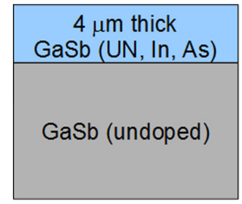

Fig. 1. Illustration of each sample structure grown for this study.

AZ5214-IR photoresist were deposited. The first metal layer was wire bond pads which consisted of 500 Å Ti/500 Å Pt/1000 Å Au. The second layer, the Schottky metal contact [22], has to be thin enough to transmit light, but thick enough that it does not have a high series resistance [23]. Therefore, 150 Å of Au was selected. Prior to metalization, all samples were dipped in a HCl : H_2O (1:10) solution for 30 s to remove surface oxides. Each sample was then mounted onto a chip carrier and wire bonded. Current–voltage measurements were used to confirm that a Schottky diode had been made.

The steady-state photocapacitance measurement setup consisted of a tunable IR source (Hawkeye IR-18 source and a CM110 1/8 m monochromator), a cryostat to cool the sample to 77 K (Janis VPF-100 liquid nitrogen pour-filled), a temperature controller (LakeShore 330), and a capacitance meter (Agilent 4263B LCR meter, AC test frequency 10 kHz, AC bias 400 mV). The reverse bias voltage, that provided the maximum capacitance change when incident light (broad spectrum) was blocked or allowed on the sample, was used. This was typically around −1 V. Photocapacitance measurements were taken by aligning the sample under a broad-spectrum of light (to where the difference in capacitance between light and dark was maximized), setting the monochromator to a maximum wavelength (minimum energy), and scanning from higher to lower wavelengths while recording the capacitance of the diode under test.

3. Results and discussion

The photocapacitance results for the GaSb control sample (1) are presented in Fig. 4. To determine which peaks were artifacts of the monochromator, the spectrum was taken with both 800 and 2500 nm long-pass filters in front of the monochromator. The entire spectrum of Fig. 4 was visible with the 800 nm filter, while it disappeared entirely with the 2500 nm filter, indicating that all non-artifacts were between these two filter wavelengths. This is plotted in detail for Samples 1–3 in Fig. 5. No changes in photocapacitance were observable at energies less than 0.4 eV, while utilizing the 2500 nm long-pass filter. This is probably related to the sample temperature; by further reducing the temperature during measurement, it may be possible to observe capacitance changes at lower energies. Note that this plot is normalized photocapacitance values. This was done by defining a maximum and minimum in the data, subtracting the offset from zero for the minimum data point, and then dividing by the new maximum to set the maximum to one. In this way the maximum equals one and the minimum is at zero.

For the GaSb and GaAsSb samples, from ~0.45 eV to 0.60 eV there is an increase in capacitance (labeled as feature A), caused by an increase in the density of ionized impurities in the space-charge region; this implies that this feature is due to either a complimentary transition from an electron trap at about 0.23 eV or a hole trap at 0.55 eV. Previously, deep level traps with activation energies of 0.63 eV (attributed to Te) and 0.25 eV (attributed to a native defect such as Ga_{Sb}–V_{Ga}) had been reported for undoped GaSb [24]. Therefore, it is possible that the feature A can be attributed to either the 0.63 eV or 0.25 eV defect levels.