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Influence of the lattice mismatch on the lattice vibration modes for InAs/GaSb superlattices

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ABSTRACT

Raman scattering study on a group of InAs/GaSb superlattice (SL) samples where the strain is systematically changed from tensile to compressive regime is presented. The effect of the lattice mismatch between the substrate and the epitaxially grown SL layers on particularly the InSb-like interface phonon frequencies is revealed in the backscattering geometry. The higher order folded longitudinal acoustic (FLA) phonon modes are also observed for samples having different superlattice periodicity. An ideality factor is incorporated into the model used for predicting the FLA phonon frequencies to simply express the deviation in the average acoustic velocity in the SL from the one in the homogeneous medium with abrupt transition in the interfaces.

1. Introduction

The InAs/GaSb type II superlattice (T2SL) structures have been of growing interest due to their ability to localize different type of carriers in different materials and their capability to have tunable effective bandgap over a broad spectral range in the infrared region simply by changing the constituent layer thicknesses. These efficacious properties allowed researchers to design and realize high performance third generation infrared photodetectors with multicolor, multi-band and/or high temperature operation capabilities [1–4]. Because of their unique properties and anticipated high potentials, T2SL structures have been recently proposed as novel devices for like transverse thermoelectrics [5,6], optical switching [7], and radiation thermometry [8]. Studies such as spin polarized [9] and magnetic field dependent [10] photocurrents, carrier transport and recombination channels [11–15] in InAs/GaSb SLs are among the recent studies regarding the fundamental properties of this material system. However, there are still some issues such as the effects of the interfaces, strain, lattice mismatch and vibrational modes that need to be addressed for better understanding in the process of reaching the ultimate device performances. The lack of common atom in the constituent layers of the crystal structure in InAs/GaSb SLs requires optimized growth conditions and controlled net stress for high quality crystal and interfaces that are known to have a profound impact on device performance. Intentionally engineered GaAs and InSb like interfaces are then introduced during the epitaxial growth of the SL layers to control the accumulated strain and the mismatch to the GaSb substrate [16–18]. In addition to the type of the interface, the thicknesses of the interfaces and the consequent layers determine whether the SL is under compressive or tensile strain. These issues are particularly important since the effective bandgap, transport properties, carrier mobilities and scattering mechanisms are drastically affected [19–22]. On this account, it is crucial to have a good understanding about the complex nature of the lattice vibration modes in the SL since (i) they can be used to probe the crystal quality and (ii) the phonon scattering leads to a significant decrease of the electric conductivity especially at high temperatures.

Raman spectroscopy as one of the most efficient experimental tools to probe the phonons in the crystal lattice has been widely employed to SL phonon studies. Yet, there is limited number of Raman scattering studies on InAs/GaSb SL structures [23–31] in comparison to better studied GaAs/AlGaAs SLs. Nevertheless, recent developments in this material system compelled the need to understand all fundamental aspects of the SL and therefore stimulated the Raman studies after many years of inertia. The correct assignment for the observed phonon signatures in the Raman spectrum of InAs/GaSb SLs is particularly difficult: nearly the same densities of InAs and GaSb (5.68 and 5.61 g/cm^3, respectively) cause the overlapping phonon frequencies. Possible phonon modes have been predicted for InAs/GaSb SL, but only a few experimental study show the well-identified phonon modes. A very recent

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Table 1
Targeted layer thicknesses and the results of the HRXRD rocking curve analysis for the studied samples.

Interface	Sample name	InAs (ML)	GaSb (ML)	SL Period (Å)	$\Delta a/a$ (ppm)
InSb changing	SL-1	9	9	57.9 ± 0.1	−3929
	SL-2	9	9	58.6 ± 0.1	−3250
	SL-3	9	9	59.5 ± 0.1	−2687
	SL-4	9	9	59.7 ± 0.1	−1145
	SL-5	9	9	59.9 ± 0.1	−462
InSb fixed	SL-6	9	9	58.4 ± 0.1	0
	SL-7	8	9	54.4 ± 0.1	+945
	SL-8	7	9	51.3 ± 0.1	+1626
	SL-9	7	8	47.8 ± 0.1	+1701
	SL-10	7	7	44.8 ± 0.1	+1791

study reported a comprehensive analysis of the expected different type of phonon modes (confined, quasiconfined, extended and interface) and elaborately labeled them in the optical phonon region of the Raman spectrum [31]. Superlattices also display a unique feature in their spectrum as far as the acoustic phonons are concerned: The observation of folded acoustic phonons, that is also an indication of high structural quality, carries information about the periodicity and the average sound velocity in the SL [27,32]. Beside all the Raman studies in attempt to have a complete understanding of SLs, no clear relationship between the strain (or the mismatch) in the SL and the Raman features has been adequately established yet. In this paper, we present the results of our experimental Raman study on a group of InAs/GaSb T2SL samples where the strain is systematically changed from tensile to compressive regime. The analysis revealed the effects of the lattice mismatch between the substrate and the epitaxially grown SL layers on the InSb like interface phonon frequencies. Additionally, the higher order folded longitudinal acoustic phonon modes were observed and investigated for samples having different superlattice periodicity.

2. Experimental details

Samples presented in this study were grown on 2 inch single side polished n-type Te doped epi-ready (1 0 0) GaSb substrates by Veeco Gen20 molecular beam epitaxy (MBE) system: details of the epitaxial growth can be found elsewhere [18,33]. The InAs/GaSb T2SL photodiodes are designed in p-i-n structure for mid wave infrared (MWIR) detection and have the following layers in growth sequence: 500 nm GaSb buffer, 1000 nm p-GaSb bottom contact, 140 period InAs/GaSb SL active region and a 20 nm n-InAs top contact. The active region consists of 40 periods p-type, 60 periods undoped and 40 periods n-type InAs/GaSb SL layers with InSb-like strain balancing interfaces. GaSb layers in the p-type SL period were doped with Be to a level of 2.3×10^{16} cm^{-3} while the InAs layers in the n-type SL period were doped with Si to a level of 6×10^{17} cm^{-3}. The top and bottom contact layers were doped to a level of 6×10^{17} cm^{-3} with Si and 1.4×10^{17} cm^{-3} with Be, respectively.

Samples were designed in two groups: In the first group of five samples, both the InAs and GaSb layer thicknesses were kept constant at 9 ML but the thickness of the InSb-like interfaces were systematically changed. Interfaces were engineered for strain compensation in a way that the lattice mismatch between the GaSb substrate and the SL was reduced to zero. Details of the applied recipe (the shutter sequence and timing) for controlled interfaces can be found elsewhere [18]. As in the second group of another five samples, both the InAs and GaSb layer thicknesses were changed but this time the InSb-like interfaces were kept fixed: the same interface recipe was applied for GaSb→InAs and for InAs→GaSb transitions for all consecutively grown samples. In a subgroup of these samples, GaSb layer thickness was kept constant at 9 ML and InAs layer thicknesses were changed from 9 ML to 7 ML with 1 ML steps. In the other subgroup, InAs layer thickness was kept constant at 7 ML and GaSb thicknesses were changed from 9 ML to 7 ML with 1 ML steps. Sample codes and the individual targeted layer thicknesses are summarized in Table 1.

For high resolution x-ray diffraction (HRXRD) measurements, Panalytical XPert Pro MRD system was used and all rocking curve measurements were performed around GaSb (0 0 4) symmetry axis with 0.0005° precision. As for the Raman measurements, Bruker Optics FT-Raman Scope III system was used. Measurements were conducted at room temperature with an excitation source of 633 nm laser and 50x microscope objective (NA = 0.75) in a backscattering geometry with no polarizer and/or analyzer in the optical path. The scattered light was collected by a charge-coupled device (CCD) detector with 50×1000 μm aperture. Experiments were conducted under 2, 5 and 10 mW excitation laser power; the Raman signal peak positions shift towards smaller frequencies about 2 cm^{-1} due to the sample heating for 10 mW laser power (compared to 2 mW) [34]. No appreciable shift was observed for 5 mW laser power. All the observed features with respect to one another stays the same for a given excitation power.

3. Results and discussion

The characteristic x-ray rocking curve diffraction pattern obtained from one of the samples (SL-6) is shown in Fig. 1a for a representative purpose. Measurements were performed on each sample to reveal the effect of the changes (in the layer and interface thicknesses) on crystal quality, superlattice period and lattice mismatch between the SL and the GaSb buffer layer. The sharp, well defined and long lasting (in angle) SL peaks around GaSb (0 0 4) substrate peak indicate high crystal quality. From the peak separations for each sample, the superlattice periodicity and the lattice mismatch values were extracted and listed in Table 1. Considering the individual InAs and GaSb layers as well as the interface thicknesses in one period, the extracted periodicity is in good agreement with the targeted thicknesses [18]. Fig. 1b and c focuses on the angular spacing between GaSb (0 0 4) and SL 0th order peaks for each sample in the first and the second groups, respectively. Regarding the entire set of samples, the 0th order SL peak systematically approaches to the GaSb substrate peak from the higher angle side and moves away towards the smaller angle side; i.e. the structures gradually shift from the tensile strain regime to the compressive strain regime. The increased SL period (from 57.9 Å to 59.9 Å) and reduced mismatch (from −3929 ppm to −462 ppm) values obtained for samples SL-1 to SL-5 are due to the increase in the InSb-like interface thickness since the individual layer thicknesses in the SL was kept constant [18]. On the other hand, the decrease in the thickness of individual InAs and GaSb layers disturbs the strain balancing effect of the unchanged InSb-like interfaces that is optimized for 9 ML for each layer (SL-6) and caused to have an increasing compressive strain in the total SL structure (from 0 ppm