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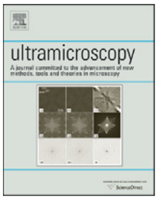

Quantitative analysis of interfacial strain in InAs/GaSb superlattices by aberration-corrected HRTEM and HAADF-STEM

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ABSTRACT

The strain distribution across interfaces in InAs/GaSb superlattices grown on (100)-GaSb substrates is investigated by aberration corrected transmission electron microscopy. Atomic resolution images of interfaces were obtained by conventional high resolution transmission electron microscopy (HRTEM), using the negative spherical-aberration imaging mode, and by scanning transmission electron microscopy (STEM), using the high-angle annular dark-field (HAADF) imaging mode. The local atomic displacements across interfaces were determined from these images using the peak pair algorithm, from which strain maps were calculated with respect to a reference lattice extracted from the GaSb substrate region. Both techniques yield consistent results, which reveal that the InAs-on-GaSb interface is nearly strain balanced, whereas the GaSb-on-InAs interface is in tensile strain, indicating that the prevalent bond type at this interface is Ga–As. In addition, the GaSb layers in the superlattice are compressively strained indicating the incorporation of In into these layers. Further analysis of the HAADF-STEM images indicates an estimated 4% In content in the GaSb layers and that the GaSb-on-InAs interface contributes to about 27% of the overall superlattice strain. The strain measurements in the InAs layers are in good agreement with the theoretical values determined from elastic constants. Furthermore, the overall superlattice strain determined from this analysis is also in good agreement with the measurements determined by high-resolution X-ray diffraction.

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1. Introduction

InAs/GaSb superlattices have attracted much interest as future device materials for a variety of optoelectronic applications, such as tunable infra red detectors [1–3] and lasers [4–6]. The band alignment in these superlattices is type II, wherein the conduction band of InAs is about 150 meV below the valence band of GaSb, which permits the tunability of properties through proper design and control of the constituent layer thicknesses [7]. Although the lattice mismatch between individual layers in the superlattice is relatively small due to the closeness in the lattice constants of InAs ($a_{\mathrm{InAs}}=0.6059$ nm) and GaSb ($a_{\mathrm{InAs}}=0.6095$ nm), the mismatch at interfacial regions can be significant since the interfacial bonds are of the type Ga–As and In–Sb. The two interfacial bond types result because both cations (In/Ga) and anions (As/Sb) change across each interface. Considering typical growth on a (100)-GaSb substrate, the strain state at an interface is then strongly dependent on its dominant bond type, being tensile for a GaAs-like interface ($a_{\mathrm{GaAs}}=0.565$ nm) and compressive for an InSb-like interface ($a_{\mathrm{InSb}}=0.639$ nm). As a result, interfaces have a strong influence on the structural and optoelectronic properties of the superlattice, as reported in many experimental and theoretical studies [8–10]. Indeed, tailoring of interfacial strain by controlled modification of interface composition is a growth strategy that is presently being explored in many studies for optimizing properties and balancing the overall strain in the superlattice [11–15]. An important requirement in these efforts is the capability for examining the composition and strain at interfaces. Detailed investigations on the composition of interfaces have been reported in earlier studies, which show that surface segregation of In and Sb due to cation (Ga/In) and anion (As/Sb) exchange processes lead to asymmetric composition profiles at interfaces [15–17]. However, corresponding studies on interfacial strain profiles are rather limited. As noted in recent studies, these measurements are important not only in the understanding of growth phenomena, but also in the refinement of existing theoretical models to accurately predict the band structure and related properties of the superlattice [5].

The objective of this paper is to perform a quantitative study of the strain distribution across interfaces in InAs/GaSb superlattices, using recent techniques based on transmission electron microscopy (TEM). The approach employed utilizes the enhanced spatial resolution achieved in aberration corrected transmission

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electron microscopy, which is essential for measuring local lattice displacements of the order of 10 pm across thin layers (2–5 nm) in the superlattice. The superlattices are examined using two techniques: conventional high-resolution transmission electron microscopy (HRTEM) and high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM). Whereas HRTEM has been used extensively in many strain mapping studies over nearly two decades [18–22], the use of HAADF-STEM is relatively recent [23–25]. The present study thus provides a means also for comparing the two techniques. In addition, high-resolution X-ray diffraction (XRD) is used as a common standard to further evaluate results from both techniques.

2. Experimental

The superlattices investigated in this study were grown on (100) GaSb substrates by molecular beam epitaxy, under growth conditions described in detail in a recent report [14]. The intended superlattice period was 7 nm, with individual layer thickness being 4.9 nm for InAs and 2.1 nm for GaSb. The interfaces in the structure were grown under nominal conditions, with no pre-deposition or growth interruption. Cross-sectional samples for TEM observations along the orthogonal [011] and [0 − 11] zone axes were prepared by conventional methods, involving mechanical grinding and polishing followed by liquid nitrogen cooled ion-milling. The HRTEM observation of the superlattices was performed using a Titan 80-300 TEM equipped with a spherical aberration (image) corrector. The interfaces were examined using the negative spherical aberration (C_s) imaging (NCSI) method [26], wherein the nominal value of C_s was set to -20 μm and the images acquired at over-focus in the range of 6–10 nm, so that the projected atomic sites appear bright over a dark background. As noted in a recent publication [27], this imaging method provides optimal contrast for imaging light atoms in the vicinity of heavy atoms which in the present case aids in precisely locating the lighter As/Ga sites adjacent to the heavier In/Sb sites in the superlattice. The HAADF-STEM observations were performed using the TEAM 0.5 instrument (NCEM, Berkeley, CA). In both HRTEM and HAADF-STEM experiments, the images were acquired with the TEMs operated at an accelerating voltage of 300 kV. To aid in the TEM studies, structural characterization of the superlattices was also performed by high resolution X-ray diffraction (XRD), wherein the strain measurements deduced from the XRD profiles were used as a reference for further analyzing the TEM results.

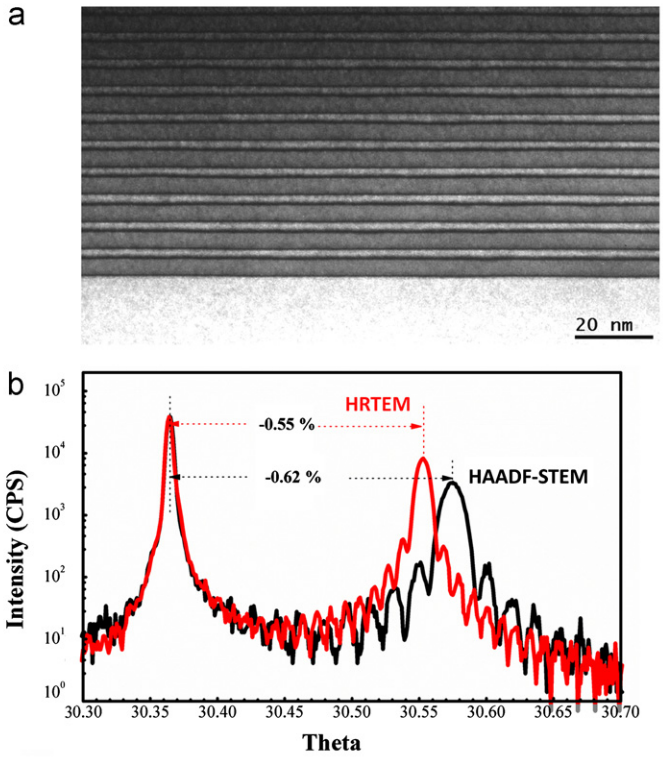

Fig. 1. (a) (200) Dark-field image of an InAs/GaSb superlattice where the InAs and GaSb layers appear dark and bright, respectively. (b) X-ray diffraction profiles of the two InAs/GaSb superlattices around the (400) reflection of the GaSb substrate. The numerical values inside the plot indicate the superlattice strain along the growth direction as determined from the separation between the peaks corresponding to the substrate (left) and the superlattice (right). The samples chosen for HRTEM and HAADF-STEM are also indicated.

To determine the strain profiles, digital analysis of HRTEM and HAADF-STEM images was performed using peak pair algorithm (PPA) developed by Galindo et al. [22]. This method was implemented using a commercial version available from HREM Research, Inc., as a plug-in to the software Digital Micrograph marketed by Gatan, Inc. The analysis was performed somewhat differently from procedures described in the original publication by Galindo et al. [22], in that the Bragg filtering step described therein was not adopted in the present study. The HAADF images were not corrected for STEM distortions to maintain consistency with analysis applied for HRTEM images. Prior to applying the PPA method, the background subtraction filter [28] was applied to all images in order to remove sample preparation artifacts. The analysis was performed such that the strain components ε_{xx} was parallel to the interface (along [011]) and ε_{yy} along the growth direction ([100]).

3. Results and discussion

Fig. 1(a) is a representative (200) dark-field TEM image of the superlattices examined in this study where the dark and bright regions correspond to the InAs and GaSb layers, respectively. The interfacial region between the two layers is well defined and exhibits darker contrast, in comparison to the InAs layers. Fig. 1(b) is the X-ray diffraction profile of the (400) reflection

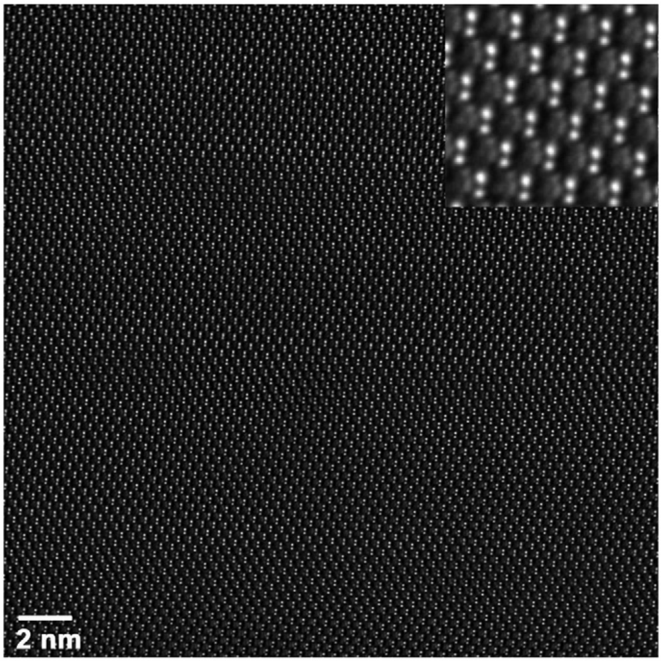

Fig. 2. HRTEM image of an InAs–GaSb superlattice along the [011] zone axis. The inset is a magnified image showing the resolved atomic positions.

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