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Full Length Article

Effects of surface reconstruction on the epitaxial growth of III-Sb on GaAs using interfacial misfit array

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ABSTRACT

The effects of pre-growth Sb reconstruction on a GaAs surface on the epitaxial growth of III-Sb (GaSb and InSb) on a (100) GaAs substrate using interfacial misfit array were investigated. All samples exhibited smooth surface with a root mean square (r.m.s.) roughness below 1.5 nm and nearly 100% relaxation. Modeling indicated that the distribution and types of misfit dislocations can be evaluated using a reciprocal space map (RSM) of the x-ray measurements. The interfacial misfit (IMF) arrays in III-Sb/GaAs samples were characterized by RSMs of high-resolution x-ray diffraction (XRD) and transmission electron microscopy (TEM). The RSM results suggest that all samples exhibited highly uniformly distributed misfit dislocations, and pre-growth (2×8) Sb surface reconstruction promoted the formation of 90° dislocations in an IMF array. Hall measurements of unintentionally doped GaSb and InSb layers also suggested that the highest motilities at both 77 K and 300 K were achieved at the samples grown on GaAs with pre-growth (2×8) Sb reconstruction.

1. Introduction

III-Sb compound semiconductors (GaSb and InSb) have generated much interest due to their potential in high-speed transistors [1], solar cells [2], infrared photodetectors [3] and lasers [4]. Heteroepitaxy of III-Sb on a GaAs wafer decreases the substrate cost and parasite capacitance [5] and enables monolithic integration of III-Sb- and GaAs-based devices on a single platform. Moreover, it is an approach to integrate III-Sb devices on Si for further photonic and electronic application, because growth of GaAs on Ge-buffered Si substrate is available [6,7]. Threading dislocations induced by the large lattice mismatch between the III-Sb layer and GaAs (7.8% for GaSb/GaAs and 14.6% for InSb/GaAs) can be suppressed through the formation of a highly uniform interfacial misfit (IMF) array at the III-Sb layer/GaAs interface [8]. High-quality GaSb and InSb semiconductors on GaAs have been achieved using this method, and it has been shown by transmission electron microscopy (TEM) that the IMF array consists of periodically distributed 90° misfit dislocations (MDs) [9–11]. Moreover, the photodetector [12] and thermophotovoltaic cell [13] are developed using the heteroepitaxial growth of GaSb on GaAs using IMF array. Both modeling and experiments suggest that MDs with uniform spacing entirely relieve the strain energy caused by lattice mismatch [8,14]. Compared with 60° MDs, 90° MDs are capable of relieving higher strain energy per dislocation. These 90° MDs are normally confined at the interface and generally do not lead to the formation of threading dislocations. Therefore, 90° MDs are preferable to 60° MDs to suppress the formation of threading dislocations and thus improve the quality of the epilayers. The pre-growth reconstruction impacts atomic incorporation during growth which is important for heteroepitaxial [15]. Previous studies suggested that a Sb-terminated GaAs surface promoted the formation of 90° MDs compared with an As-terminated GaAs surface in both GaSb layers [14,16] and quantum dots [17] on GaAs. It is worth noting that Sb atoms can be configured in different surface reconstructions on the GaAs surface [18]. Different surface reconstructions, such as (1×3), (2×8) and (2×4) Sb-terminated reconstructions, were observed at different Sb absorption temperatures[9]. Using scanning tunneling microscopy (STM), a long-range ordered arrangement of Sb atoms was found in the (2×8) reconstruction, while the arrangement in the (1×3) reconstruction was long-range disordered [19]. Studies of heteroepitaxial GaSb and Sb_2Te_3 on (111) Si substrates suggested controlling the Sb reconstruction on Si surface is an effective method to increase the quality of GaSb and Sb_2Te_3, respectively [20,21]. Therefore, it is interesting to identify the effect of Sb reconstruction on GaAs, before growth, on the formation of the IMF array in III-Sb-on-GaAs heteroepitaxy.

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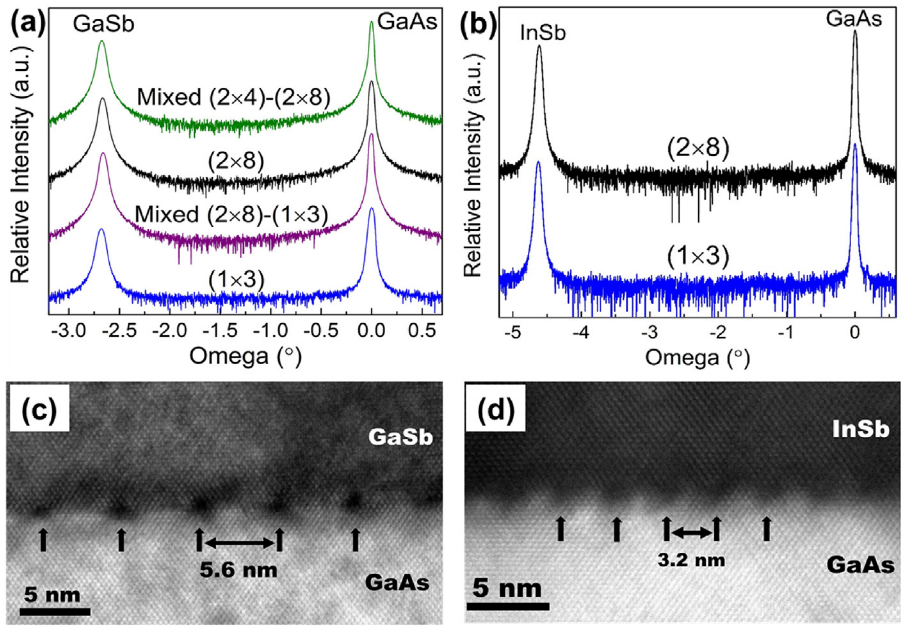

Fig. 1. (a) & (b) symmetric (004) *ω-2θ* scans for GaSb and InSb on GaAs samples, respectively. The Sb reconstructions before growth are indicated; (c) & (d) Cross-sectional TEM of the interfacial misfit dislocations for GaSb and InSb grown on GaAs samples with (2 × 8) Sb reconstruction prior to growth, respectively.

Cross-sectional transmission electron microscope (TEM) is conventionally utilized to observe the types and distributions of MDs. However, due to its limited observation range (only a few micrometers), it is not suitable for measuring threading dislocations, which are not uniformly distributed with a density <10^8 cm^{-2}. MDs result in a non-uniform strain field, which broadens the layer peaks in an x-ray diffraction (XRD) measurement. In an XRD reciprocal space map (RSM), the shape of a layer's peak depends on the types (60° or 90°) and spatial correlations (uniform or non-uniform spacing) of the MDs [22]. Therefore, it is a suitable approach to characterize threading dislocations, 60° MDs and 90° MDs in the macroscopic observation range.

In this study, III-Sb layers were grown on (100) GaAs substrates under different Sb surface reconstructions by changing the substrate temperature at which the Sb was adsorbed (390 °C, 450 °C, 500 °C and 560 °C) before growth. The structures and electrical properties of III-Sb layers were characterized using atomic force microscope (AFM), high resolution XRD, cross-sectional TEM and Hall measurement. Simulation demonstrated the RSMs of GaSb on GaAs with interfaces of pure 60° and 90° MDs respectively. XRD RSMs were used to evaluate the MDs at III-Sb/GaAs interface based on this simulation, and the effect of Sb reconstruction before III-Sb growth was discussed.

2. Experimental procedure

GaSb and InSb layers were grown on (100) GaAs substrates using a solid-source molecular beam epitaxy reactor with valved cracker As and Sb sources. After oxide desorption at 580 °C, a 100-nm-thick GaAs layer was grown to achieve a smooth GaAs surface. Subsequently, the substrate temperature was lowered to 540 °C to desorb excess As on the surface. After the desorption of excess As, the layer exhibited a clear (2 × 4) reconstruction in reflection high-energy electron diffraction (RHEED), indicating an As-terminated surface. Afterward, the samples were exposed to Sb_2 flux with a beam-equivalent flux of about 1.2×10^{-6} Torr for 4 min to form different Sb surface constructions on GaAs surfaces at different temperatures. Two RHEED reconstruction transitions were found between 390 °C and 580 °C. A clear (1 × 3) pattern was observed at 390 °C, while the (1 × 3) pattern began to change to a fuzzy (2 × 8) at 450 °C. A clear (2 × 8) with bright and streaky lines was observed at 500 °C. At 560 °C, (2 × 8) pattern gradually changed to (2 × 4) pattern. Further increase in temperature produced a clear (2 × 4) surface reconstruction pattern.

After the Sb absorption process, the Sb valve was closed and the substrate temperature was lowered to the growth temperature by 30 °C/min. During cooling process, all RHEED pattern remained unchanged. It was necessary to close the Sb valve during temperature cooling because the RHEED pattern was observed to gradually changed from (2 × 8) to (1 × 3) Sb reconstruction if Sb flux was supplied at temperature below 450 °C. Therefore, the Sb valve was closed during the cooling process to maintain the (2 × 8) Sb reconstructions obtained at higher temperature. To avoid the influence of different growth temperatures, the growth temperature of GaSb layers was fixed at 390 °C and that of InSb layers was fixed at 310 °C. Then, a 425 nm GaSb layer and 700 nm InSb layer were grown; further details of the growth process were given elsewhere [9,10]. The XRD *ω–2θ* scans and RSMs of samples were obtained using an x-ray diffractometer with beam collimator and analyzer crystals to achieve sufficiently high resolution. IMF arrays in all samples were examined using cross-sectional TEM and the surface morphology of samples were measured by AFM. The carrier motilities and concentrations of samples were evaluated by Hall/Van der Pauw measurements.

3. Results and discussion

Fig. 1(a) & (b) shows the symmetric (004) *ω–2θ* scans from GaSb and InSb on GaAs, which were grown with different Sb surface reconstructions by changing the Sb absorption temperatures and the corresponding Sb reconstructions have been indicated in images. It can be seen that only layer peaks and substrate peaks were observed. No XRD signal was observed between the layer peaks and the substrate peaks, which indicated that the III-Sb/GaAs interfaces were abrupt and there was no intermediate buffer layer between them. The vertical and parallel lattice constants ($a_\perp$ and $a_\parallel$) were extracted from the symmetric (004) and asymmetric (115) *ω–2θ* scans (not presented) and are listed in Table 1. Using the