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Investigation of crystallographic tilting in GaSb/GaAs heteroepitaxial structure by high-resolution X-ray diffraction

Yongxin Qiu[a], Meicheng Li[a,*], Guojun Liu[b], Baoshun Zhang[b], Yong Wang[b], Liancheng Zhao[a]

[a]*Department of Materials Physics and Chemistry, Harbin Institute of Technology, Harbin 150001, China*
[b]*National Key Laboratory High Power Semiconductor Lasers, Changchun University of Science and Technology, Changchun 130022, China*

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Abstract

GaSb epilayers were grown on GaAs(0 0 1) vicinal substrate misoriented towards (1 1 1) plane by solid-source molecular beam epitaxy (MBE). The relative tilt between GaSb epilayer and GaAs substrate was studied using high-resolution X-ray diffraction (HRXRD). It was demonstrated that the tilt of the 30 nm thick GaSb film was 0.32°, which was a simple geometrical consequence of 7.8% lattice mismatch. For the 1000 nm thick film, tilt rose to 0.45°, and the increase of tilt was the result of the forming of 60° misfit dislocations (MDs). In contrast to the phenomenon in low-misfit heteroepitaxy system, tilts induced by 60° MDs in our samples were positive (i.e. away from the surface normal) and we attributed the diversity to the different formation mechanisms of 60° MDs. The tilt study gave us another way to investigate the type and the formation mechanism of the MDs.

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Keywords: A1. High-resolution X-ray diffraction; A3. Molecular beam epitaxy; B1. Antimonides; B2. Semiconducting materials

1. Introduction

In recent years, there has been considerable interest in the GaSb/AlSb/InAs semiconductor heterostructures which are called "6.1 Å" family of III–V semiconductors [1–3]. They are near lattice-matched ($a = 6.1$ Å) and are useful as the basis of field effect transistors, semiconductor lasers and detectors due to their electrical and optical characteristics. It is desirable to grow epitaxial layers on a lattice-matched substrate, but the lack of suitable lattice-matched semi-insulating substrates has made for the growth of GaSb film on highly mismatched substrates, such as GaAs. However, the large lattice mismatch (~7.8%) existing between GaSb and GaAs results in the production of a misfit dislocations (MDs) array at the GaAs/GaSb interface. MDs have been verified to exist along both [1 1 0] and [1 $\bar{1}$ 0] crystal directions and form 2D misfit arrays [4]. Transmission electron microscopy (TEM) analysis has shown that the dislocations have a Burger's vector $a/2\langle 1\,1\,0\rangle$ [5], and the majority of MDs are pure 90° edge Lomer type dislocations [6,7], but 60° MDs arrays having the same orientation have been found as well [4,8].

For a lattice-mismatched heteroepitaxy on a stepped surface, the epilayer generally tilts with respect to the substrate [9–11]. But, to our knowledge, the tilt in GaSb/GaAs heterosystem has not been reported in detail. In the relaxed epitaxial layers, the MDs play an important role on the tilt formation. The study of tilt in GaSb/GaAs can provide us more information about the formation and the distribution of the MDs. In this paper, we present a detailed high-resolution X-ray diffraction (HRXRD) study on the tilt in GaSb epilayer grown on GaAs(0 0 1) vicinal substrate.

*Corresponding author. Tel.: +86 451 86418745; fax: +86 451 86415776.
E-mail address: mcli@hit.edu.cn (M. Li).

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2. Experiments

The GaSb epitaxial layers were grown by a Vacuum Generators V80H solid-source molecular beam epitaxy (MBE) system. The substrates were n-type epi-ready GaAs(0 0 1) misoriented by 4° towards (1 1 1) plane (or, in other words, towards [1 1 0] directions). The miscut in this direction created steps on the surface running along [1 1 0] directions. At first, a 300 nm thick GaAs buffer layer was grown at 600 °C on the substrate with a (2 × 4) reconstruction observed by reflection high energy electron diffraction (RHEED). Then the substrate was cooled to 500 °C under As_4 flux and the GaSb layer was grown at a growth rate of 1 ML/s. The V/III beam equivalent pressure (BEP) flux ratio was 3:1. The samples discussed here were sample A, B and C, with thicknesses of 30, 1000 and 2000 nm, respectively.

HRXRD measurements were performed with a double-crystal X-ray diffractometer using a Cu K_α radiation. A well-collimated monochromatic X-ray beam was obtained by means of an asymmetrically cut Ge crystal in the (0 0 4) reflection. The reflected beam was detected with a scintillation detector without slit. Two sets of reflections, the symmetric (0 0 4) and (2 2 4), were measured in order to determine the lattice constant in the plane $a_\parallel$ in each [1 1 0] direction. The percentage of relaxed strain, or strain relaxation R in each [1 1 0] direction was calculated from the following equation:

$$R = 100 \times \left(\frac{a_\parallel - a_s}{a_e - a_s}\right), \tag{1}$$

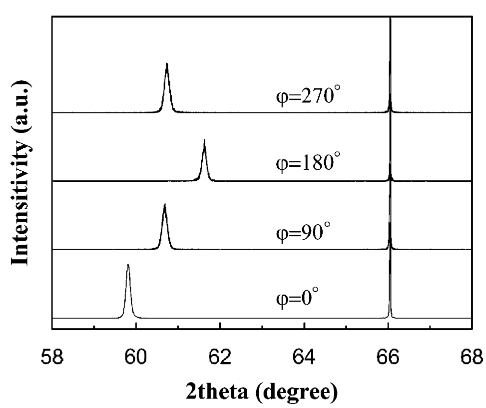

Fig. 1. (0 0 4) rocking curves of the GaSb film on GaAs substrate collected at four azimuthal angles of 0°, 90°, 180° and 270°.

where a_e and a_s are the lattice constants of GaSb film and GaAs substrate, respectively.

In order to determine the tilt, the (0 0 4) rocking curves were recorded at four azimuth angles in 90° increments from 0° to 270°. Those azimuth angles are corresponding to [1 1 0], [$\bar{1}$ 1 0], [$\bar{1}$ $\bar{1}$ 0] and [1 1 0] directions, respectively. One of the HRXRD measurement results was shown in Fig. 1. From these rocking curves, we measured the angular separation $\Delta\omega$ between the epilayer peaks and substrate peaks for different azimuth angles. And then we determined the epilayer tilt by plotting $\Delta\omega$ versus azimuth angle φ and fitting the data with a sine function. The resulting amplitude of the sine curve indicates the magnitude of epilayer tilt.

3. Results and discussions

The HRXRD measurement results were summarized in Table 1, including the lattice constant in the plane $a_\parallel$, the residual strain $\varepsilon_\parallel^{res}$, the strain relaxation R of the GaSb layer and the tilt $\Delta\alpha$, both in [1 1 0] and [1 $\bar{1}$ 0] directions. Table 1 shows that the relaxation of sample A is 94.2% in the [1 1 0] direction and 86.6% in [1 $\bar{1}$ 0] direction. The relaxation of the strain along the two perpendicular directions, [1 1 0] and [1 $\bar{1}$ 0], is anisotropy. When the thickness of the epilayer increased, the strain was further relaxed. For samples B and C, the relaxation is almost complete in both directions.

From Table 1, we can see that all the samples have positive tilts (i.e. tilt away from the surface normal) and the tilt axis is along [1 1 0] direction. Furthermore, the tilt is affected by the layer thickness. For sample A, the tilt was 0.32°. As the film thickness increased to 1000 nm, the tilt added to 0.44°, but the tilt does not change obviously when the thickness increased to 2000 nm.

In order to explain the experiment results, it is reasonable to explore the formation mechanism of the tilt. The origin of the tilt can be analyzed taking into account both the Nagai's tilt [12] and the MDs tilt [9]. The Nagai's tilt is caused by the elastic strain exerted by the substrate surface steps. When a lattice-mismatched epilayer grows on the substrate, the lattice constant in the growth direction changes from a_s (the substrate lattice constant) to $a_\perp$ (the epilayer lattice constant in the growth direction) over the width of the step. The lattice constant difference gives rise to a small tilt of the GaSb epitaxial layer in respect of

Table 1
HRXRD measurement results including the residual strain $\varepsilon_\parallel^{res}$, the strain relaxation R, both in the [1 1 0] and [1 $\bar{1}$ 0] directions and the epilayer tilt $\Delta\alpha$

Sample	Thickness (nm)	Direction	$\alpha_\parallel$ (nm)	$\varepsilon_\parallel^{res}$ ($\times 10^{-3}$)	ε ($\times 10^{-2}$)	R (%)	FWHM (°)	$\Delta\alpha$ (°)	Nagai tilt (°)
A	30	[1 1 0]	0.6062	−4.11	8.11	94.2	0.279	0.32	0.325
		[1 $\bar{1}$ 0]	0.6004	−8.96	8.12	86.6	0.252	0	
B	1000	[1 1 0]	0.6096	−0.08	7.85	99.9	0.079	0.44	0.315
		[1 $\bar{1}$ 0]	0.6093	−0.30	7.85	99.5	0.102	0	
C	2000	[1 1 0]	0.6096	−0.07	7.83	99.9	0.057	0.45	0.314
		[1 $\bar{1}$ 0]	0.6093	−0.30	7.84	99.6	0.068	0	