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# High-resolution transmission electron microscopy study on the growth modes of GaSb islands grown on a semi-insulating GaAs (001) substrate

Y. H. Kim<sup>a)</sup> and J. Y. Lee

*Department of Materials Science and Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305-701, Republic of Korea*

Y. G. Noh and M. D. Kim

*Department of Physics, Chungnam National University, Daejeon 220, Republic of Korea*

J. E. Oh

*Division of Electrical and Computer Engineering, Hanyang University, Ansan 425-791, Republic of Korea*

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The initial growth behaviors of GaSb on a GaAs substrate were studied using a high-resolution electron microscope (HRTEM). Four types of GaSb islands were observed by HRTEM. HRTEM micrographs showed that strain relaxation mechanisms were different in the four types of islands. Although 90° misfit dislocations relieve misfit strain in the islands, additional mechanisms are required to relax the remaining strain. The existence of elastic deformation near the surface related to dislocations and intermediate layers between GaSb and GaAs were demonstrated in island growths. Finally, the generation of planar defects to relieve strain was observed in a specific GaSb growth. © 2007 American Institute of Physics. [DOI: 10.1063/1.2747674]

Heteroepitaxial growth of compound semiconductors has received much attention due to their potential use in electrical and optical devices. For strained heteroepitaxial layers, the coherent growth conserving the two-dimensional (2D) layer-by-layer mode is limited by a critical thickness.<sup>1,2</sup> Theoretical calculation of the critical thickness has been suggested by various researchers, including Matthews and Blakeslee,<sup>1</sup> Fisher *et al.*,<sup>3</sup> and Downes *et al.*<sup>4</sup> The experimental value of the critical thickness can exhibit relatively large discrepancies compared with the value predicted by theoretical calculation due to several factors, including experimental conditions and growth kinetics. Misfit dislocations are always generated in the interface between lattice-mismatched heteroepitaxial layers by exceeding the critical thickness. The transition of the growth mode from a 2D layer-by-layer mode to that of three-dimensional (3D) islands [Stranski-Krastanov (SK) mode] has been normally considered to occur in highly mismatched heteroepitaxial growth.

The heteroepitaxial growth of antimony (Sb)-based materials among compound semiconductors has been studied because of their potential use in the development of extremely high speed and low power electronic devices, optical sources, and sensors.<sup>5-7</sup> The heterostructures of Sb-based compound semiconductors grown on GaAs substrates can exhibit a type-II (staggered) band lineup featuring recombination from spatially indirect excitons. Several research groups have reported studies on the formation and optical properties of type-II Sb-based semiconductors/GaAs systems.<sup>8-11</sup> Recently, Huffaker and co-worker reported the formation and optical characteristics of type-II GaSb/GaAs quantum dots. In their report, the optical properties depended on structural characteristics, especially the microstructure of the interface between the GaSb and the GaAs substrate.<sup>12,13</sup>

Because physical properties depend on microstructural characteristics, a study of the microstructure in the heteroepitaxial growth of highly mismatched systems, such as GaSb/GaAs, is necessary to improve device applications based on these materials.

We demonstrate the existence of specific growth modes in the GaSb/GaAs system, which represents a type of highly mismatched heteroepitaxial growth. Although Rocher reported about misfit dislocations in this system, it is insufficient for a complete understanding of growth behaviors.<sup>14</sup> Various types of growth modes and their microstructural properties involved in relieving the misfit strain caused by lattice mismatch were studied in GaSb islands grown on a GaAs substrate in this letter.

The III-Sb-based compound semiconductors have been grown by molecular beam epitaxy. In this study, Riber 32-PMBE system was used to synthesize compound semiconductors. A semi-insulating GaAs (001) wafer was used as the substrate. A GaAs buffer was deposited to a thickness of 0.2 μm at 550 °C on the GaAs substrate. In this study, very thin GaSb materials were grown to study the initial growth stage. The GaSb was grown to approximately 5 nm in thickness at a growth rate of 3 nm/min. The V/III flux ratio for the GaSb was approximately 8.5.

The high-resolution transmission electron microscopy (HRTEM) studies were performed using JEOL JEM-3010 and JEM-2000EX transmission electron microscopes operating at 300 and 200 kV, respectively. In this study, all of the HRTEM micrographs are acquired through  $[1\bar{1}0]$  zone axis of the zinc-blende structure. All results shown in this letter were generated in the same experiment.

In our experiment, GaSb were grown through 3D island growth mode. The GaSb islands had elongated shapes along the  $[1\bar{1}0]$  direction and were distributed separately on the substrate.

Figure 1 represents the HRTEM micrograph and lattice constant analysis in the micrograph. Figure 1(a) shows a pe-

<sup>a)</sup> Author to whom correspondence should be addressed; Fax: +82-42-869-3310; electronic mail: young.h.kim@kaist.ac.kr

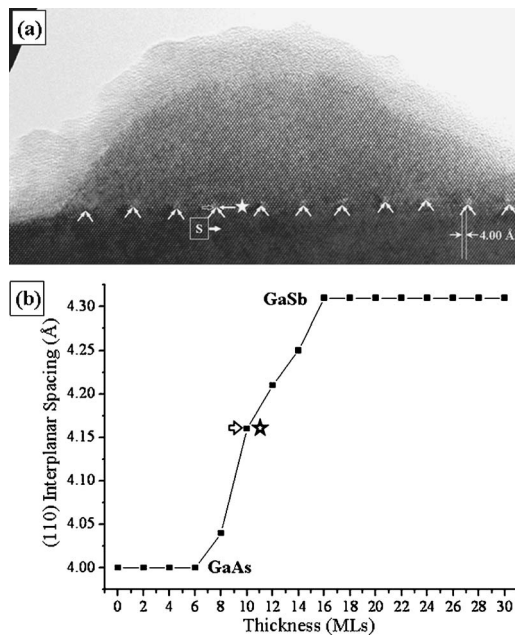


FIG. 1. HRTEM micrograph (a) and the analysis of (110) interplanar spacing (b) taken at the conventional GaSb/GaAs interface. The “S” in the box indicates the starting point to measure the (110) interplanar spacing. The vacant arrow and the star mark show the GaSb/GaAs interface and the generation site of misfit dislocation, respectively.

riodic array of  $90^\circ$  misfit dislocation localized at the GaSb/GaAs interface. The shape of the island approximates a hemisphere. No threading dislocations or other defects were detectable in the bulk material and no misfit dislocations existed at any other location. The misfit separation, measured to be  $\sim 56 \text{ \AA}$ , corresponds exactly to approximately 13 GaSb (110) planes and 14 GaAs (110) planes.

In the system with the relative orientation of the GaSb  $\langle 110 \rangle \parallel$  GaAs  $\langle 110 \rangle$  and GaSb  $\{001\} \parallel$  GaAs  $\{001\}$ , the misfit  $\delta$  between the GaSb layer and the GaAs substrate is defined by

$$\delta = (d_{\text{GaSb}110} - d_{\text{GaAs}110}) / d_{\text{GaAs}110} = 0.078. \quad (1)$$

If  $90^\circ$  misfit dislocations are introduced into the structure for strain relaxation, the average spacing  $S$  of misfit dislocations depends on the misfit  $\delta$  and is of the order of  $d_{\text{GaSb}110} / \delta$ . Therefore, the value of  $S$  is determined as given by

$$S = d_{\text{GaSb}110} / 0.078 = 55.3 \text{ \AA}. \quad (2)$$

If  $90^\circ$  dislocations, the most efficient misfit dislocation for strain relaxation, are inserted into the interface, the theoretical average spacing  $S$  of the misfit dislocations is  $55.3 \text{ \AA}$ . From the discussion above, it was concluded that the average spacing of  $90^\circ$  dislocations ( $\sim 56 \text{ \AA}$ ) observed experimentally in Fig. 1(a) is approximately equal to the theoretical value.

In Fig. 1(b), the (110) interplanar spacing is observed to recover to that of GaSb through the GaSb/GaAs interface. The misfit strain by lattice mismatch is relieved by introducing the  $90^\circ$  misfit dislocations. The arrow and the star in Fig. 1(b) indicate the GaSb/GaAs interface and the generation position of misfit dislocations, respectively. The misfit strain was relieved to a greater extent in the upper region of the misfit dislocations, exactly in the GaSb. The strain relaxation continued through approximately 6 ML in the GaSb.

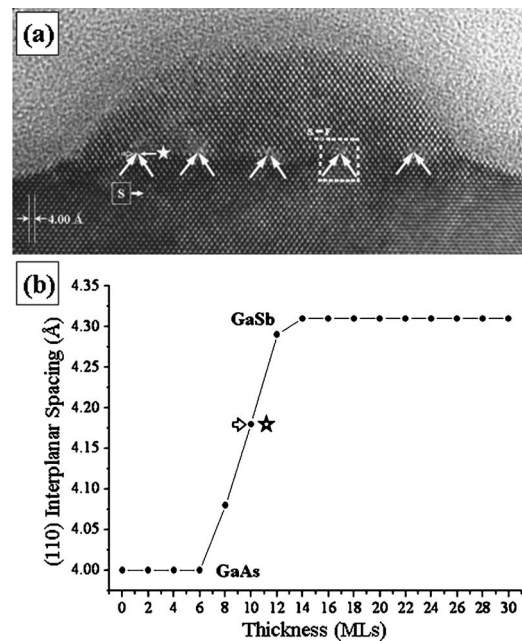


FIG. 2. (a) HRTEM micrograph taken from the GaSb island growth showing elastic deformation near the surface. (b) (110) interplanar spacing analysis in (a).

Figure 2 shows another small island. The small island shows a periodic array of  $90^\circ$  misfit dislocations similar to that shown in Fig. 1. However, the surface of the GaAs substrate, including the GaSb/GaAs interface, is curved as an arch. This island morphology might be explained by the combination of a coherently strained island and strain relaxation by the introduction of misfit dislocations.<sup>15</sup>

When the strain is compressive, the island tends to expand along the interface but is constrained by the substrate. It responds instead by bending, so that the interfacial plane becomes curved. In Fig. 2(a), the average spacing of  $90^\circ$  misfit dislocations is illustrated to be approximately  $50.0 \text{ \AA}$ , which is much smaller than the theoretical value for complete relaxation of the misfit strain. The strain concentration might be caused by a surface bending phenomenon to conserve a coherently strained island. Additionally, in this island growth, the lattice constant of GaSb is observed over the misfit dislocation [Fig. 2(b)]. In Fig. 2(b), the lattice constant of GaSb is rapidly recovered near the misfit dislocations. The misfit strain is primarily relieved in the GaAs buffer layer. From the results reported above, the lattice constant of the GaAs buffer layer is slightly increased near the surface, below the misfit dislocations, by elastic deformation. Although local elastic deformation of near-surface layers in the substrate has been suggested in the dislocation-free SK growth mode, this figure shows that the deformation of near-surface layers can be accompanied by misfit dislocations.

Figure 3 shows a unique growth mode of the GaSb islands. An intermediate layer (IML) is observed between the GaSb island and the GaAs substrate in Fig. 3(a). A few GaSb monolayers with a lattice constant well matched to the GaAs substrate are observed at the bottom of the IML, near the GaSb/GaAs interface. The thickness of the IML is approximately 8 ML ( $\sim 25 \text{ \AA}$ ). The interface between the GaSb and the GaAs substrate is flat and free from surface deformation. The GaSb island in Fig. 3(b) is surrounded by  $\{111\}$  and  $\{112\}$  planes, and another plane which bears little discrepancy.

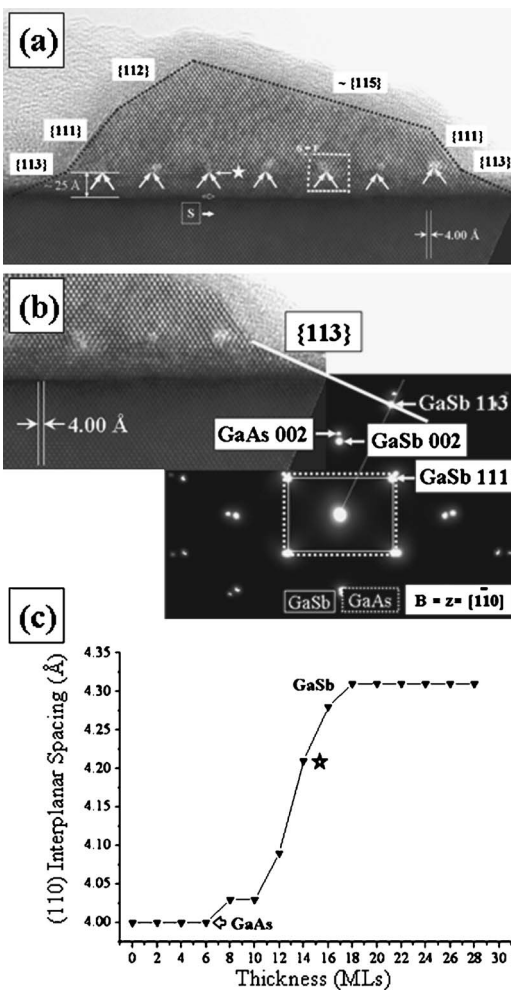


FIG. 3. (a) HRTEM micrograph taken from the GaSb island growth with an intermeditated layer (IML). (b) Selected area electron diffraction (SAED) pattern to determine the basal planes of the island in (a). The zone axis of the SAED pattern is indexed as  $[1\bar{1}1]$  of zinc-blende structure. (c)  $(110)$  interplanar spacing analysis in (a).

ancy from a  $\{115\}$  planes. Figure 3(b) proves that the surface planes of the base tails are  $\{113\}$  planes with an inclination angle of approximately  $27^\circ$  for the  $(001)$  plane. In Fig. 3(c), the lattice constant increased gradually as the thickness in the IML increased. The lattice constant of the GaSb was completely recovered by passing through the  $90^\circ$  misfit dislocations. The misfit dislocations were generated near the top plane of the IML surrounded by the interfaces and  $\{113\}$  planes. Because the average spacing of the periodic  $90^\circ$  misfit dislocations was approximately  $56 \text{ \AA}$ , it is demonstrated to be near the theoretical value for complete strain relaxation. This phenomenon might be explained similarly with the SK growth mode of islands.

In Fig. 4, multiple planar defects generated at the interface are observed in the island. These planar defects play a role for strain relaxation, such as misfit dislocations shown in previous micrographs. A region similar to an IML, named as a quasi-IML in this letter, is also observed in Fig. 4. Specifically, the  $\{111\}$  planes in Fig. 4 are tilted at the interfaces. The tilting angles between the GaSb island and the quasi-IML and between the quasi-IML and the GaAs buffer are  $10^\circ$  and  $4^\circ$ , respectively. These planar defects poorly affect a continuously grown layer. Because the lattice constant of a

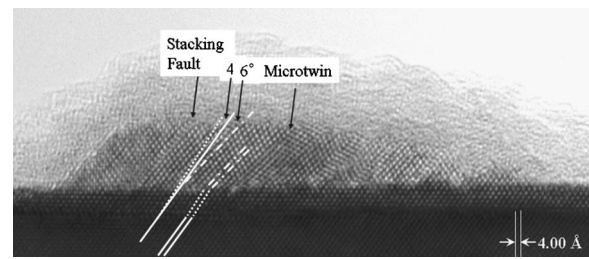


FIG. 4. HRTEM micrograph taken from the GaSb island with many planar defects. The lines show the tilted  $\{111\}$  planes.

GaSb is larger than that of a GaAs, a compressive strain is imparted to a GaSb grown on a GaAs substrate. Partial dislocations for the formation of planar defects for the relief of pseudomorphic strain in the GaSb/GaAs heteroepitaxial growth are determined to be  $30^\circ$  dislocations by the restrictive conditions.<sup>16,17</sup>

In summary, four types of GaSb island growth on a GaAs substrate were discovered using HRTEM. HRTEM micrographs revealed that the strain relaxation mechanisms are, respectively, different in the four types of island growth. Although  $90^\circ$  misfit dislocations relieve misfit strain in the island, additional mechanisms are required to relax the remaining strain. Especially, the existence of elastic deformation near the surface related to dislocations and IMLs between the GaSb and the GaAs substrate were shown in the growth of GaSb islands.

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