Strucrural Properties of GaSb Layers Grown on InAs, AlSb, and GaSb Buffer Layers on GaAs (001) Substrates

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The strain-relief and the structural properties of GaSb films with thin InAs, AlSb, and GaSb buffer layers grown on GaAs (001) substrates at low temperature (LT) by molecular beam epitaxy were investigated using atomic force microscopy, transmission electron microscopy, and X-ray diffraction. The strain arising from depositing the thin buffer layer onto the GaAs substrate was relieved by a periodic array of 90° misfit dislocations with a Burgers vector of 1/2a<110> for the AlSb/GaAs and the GaSb/GaAs systems, but by both 60° and 90° misfit dislocations for the InAs/GaAs system. The 90° misfit dislocation arrays at the AlSb/GaAs and GaSb/GaAs interface had average spacing of 4.80 nm and 5.59 nm, respectively. The mean roughnesses and the full widths at half maximum of the rocking curves of the GaSb films on the thin AlSb and GaSb buffer layers were found, respectively, to be less than 1 nm and about three times lower than the corresponding values for the system with an InAs buffer layer. These results clearly demonstrate that the presence of a thin, low-temperature AlSb or GaSb buffer layer is very useful for improving the quality of GaSb crystals grown on GaAs substrates.

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I. INTRODUCTION

Antimony-based compounds offer a wide range of electronic band gaps, band-gap offsets, and electronic barriers along with extremely high electron mobility, thereby enabling a variety of devices that are much faster and have lower power consumption than equivalent InP- and GaAs-based devices [1] and infrared light sources [2, 3]. Lattice-mismatched epitaxy of Sb-based materials on GaAs and Si substrates has attracted considerable attention due to the numerous advances in optoelectronic devices, such as laser diodes [4–6], detectors [7], and transistors [8]. Therefore, much effort has been devoted to growing high-quality Sb-based layers on GaAs and Si substrates.

In spite of the performance advantages offered by Sb-based layers on GaAs and Si substrates, growing III-Sb-based compound semiconductors on GaAs and Si substrates is problematic due to the large difference in lattice constants between the epitaxial layer and the substrate, which leads to stress and dislocations in the epitaxial film. Thus, epilayers of these types are limited to a critical thickness, beyond which the material relieves the strain energy by forming misfit and threading dislocations [9]. To overcome this problem, various buffer layers, such as As- and Sb-terminated layers, have been used, and growth techniques with low-temperature (LT), and compositionally graded buffers have been implemented to reduce the density of threading dislocations [10–13]. However, although arsenic and phosphorus material systems have been widely studied, relatively little work has been done on the interface between antimony-based materials and GaAs substrates. In the development of high-quality device structures, it is important to understand the source of confinement of misfit dislocations at hetero-interfaces.

In the present work, we compared the strain relief in thin InAs, AlSb, and GaSb buffer layers grown on
GaAs (001) substrates at LT. We investigated the dependence of the microstructural properties of unintentionally doped p-GaSb films grown on thin InAs, AlSb, and GaSb buffer layers. The effects of the buffer materials were investigated using atomic force microscopy (AFM), high-resolution transmission electron microscopy (TEM), and X-ray diffraction (XRD) measurements. In these studies, the use of high-resolution TEM and XRD proved useful in characterizing the interface.

II. EXPERIMENT

The samples used in this work were grown on semi-insulating (001)-oriented GaAs substrates by using conventional solid source molecular beam epitaxy (MBE). First, a 200-nm GaAs buffer layer was grown on the GaAs substrate at 530 °C. The substrate temperature was then lowered to 440 °C for the growth of the LT InAs and GaSb buffer layers or to 460 °C for the growth of the AlSb buffer layer. The As/In, Sb/Ga, and Sb/Al flux ratios during the growth were 20, 8, and 10, respectively. The InAs, AlSb, and GaSb growth rates per second were set to 0.08, 0.3, and 0.7 monolayers (ML), respectively, and the growth process was monitored in situ by using reflection high energy electron diffraction (RHEED). The RHEED patterns of the InAs, AlSb, and GaSb buffer layers became slightly streaky during the initial stage of growth, but subsequently underwent an abrupt change to a spotty pattern. These series of patterns can be attributed to the formation of islands during the initial stage of growth, but subsequently underwent an abrupt change to a spotty pattern. These series of patterns can be attributed to the formation of islands during the initial stage of growth, but subsequently underwent an abrupt change to a spotty pattern. These series of patterns can be attributed to the formation of islands during the initial stage of growth, but subsequently underwent an abrupt change to a spotty pattern.
Structural Properties of GaSb Layers Grown on InAs,· · · – Y. K. Noh et al.

The lattice parameters, and island coalescence [14]. The lattice mismatch between the buffer layer and the GaAs substrate. A spaced array of misfit dislocations at the interface between the substrate and buffer layer. The average distance between the misfit dislocations in the InAs buffer layer is 3.998 Å.

Fig. 3. Cross-sectional high-resolution TEM images along the [110] zone axis of thin (a) InAs, (b) AlSb, and (c) GaSb buffer layers grown on GaAs. Arrows indicate 60° and 90° misfit dislocations at the interface between the substrate and buffer layer. The lattice spacing of GaAs is 3.998 Å.

Table 1. The lattice constants, strains, and FWHM values for the GaSb films with InAs, AlSb and GaSb buffer layers on GaAs substrates.

<table>
<thead>
<tr>
<th>Layer Type</th>
<th>Lattice Constant (Å)</th>
<th>Strain (%)</th>
<th>FWHM (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaSb lattice</td>
<td>6.0787</td>
<td>7.572</td>
<td>1296</td>
</tr>
<tr>
<td>InAs buffer</td>
<td>6.0953</td>
<td>7.820</td>
<td>517</td>
</tr>
<tr>
<td>AlSb buffer</td>
<td>6.0960</td>
<td>7.832</td>
<td>468</td>
</tr>
</tbody>
</table>

Fig. 3 shows HR-TEM micrographs of the interfaces between the buffer layers and the GaAs (001) substrates. A regular array of misfit dislocations is observed at the interface between each buffer layer and the GaAs substrate. Each of these dislocations, indicated by arrows in the figure, coincides with a {111} plane of GaAs. The relative orientations of the InAs, the AlSb, and the GaSb buffer layers with respect to the GaAs substrates are [110] buffer layer // [110]GaAs substrate and (001) buffer layer // (001)GaAs substrate, respectively. Figure 3(a) shows an HR-TEM image of the interface between the InAs buffer layer and the GaAs substrate. A spaced array of 60° and 90° misfit dislocations, which have Burgers vectors of 1/2 a[011] (or 1/2 a[101]) and 1/2 a[110], is observed along the [110] directions. The driving force for the generation of these 60° and 90° dislocations is the lattice mismatch between the buffer layer and the GaAs substrate. At present, the precise source of the 60° misfits is unclear, although they presumably arise due to factors such as the degree of mismatch, the growth parameters, and island coalescence [14]. The lattice mismatch between the buffer layer and the GaAs substrate is also known to cause threading dislocations in the GaSb layer. The 90° misfits appear every 13 lattice spacings in the GaAs substrate. The average distance between the misfit dislocations in the InAs buffer (≈5.20 nm) is less than the theoretical value of 5.83 nm derived using the formula $S = b/f$ [15], where $b$ is the Burgers vector ($b = 4.17$ Å) and $f$ is the lattice mismatch ($f = 7.16 \times 10^{-2}$). Figures 3(b) and (c) show HR-TEM images of the interfaces between the AlSb and GaSb buffer layers, respectively, and the GaAs substrates. The images show small AlSb and GaSb distortions, manifesting as characteristic dark and bright contrasts, mainly bound in the interface. An array of 90° misfit dislocations with a spacing of 12 is observed at the AlSb/GaAs interface. The average distance between the misfit dislocations in the AlSb buffer is about 4.80 nm, which is quite close to the theoretical value of 4.95 nm. This result means that in the AlSb buffer layer, the mismatch strain between the epilayer and the substrate should be almost completely compensated for by the misfit dislocations at room temperature and that the confinement of the misfit dislocations at the heterointerface should enable the formation of a smooth growth surface free of distortions. In the case of GaSb/GaAs interface, the average spacing of 90° misfit dislocations is 14. The average distance between the misfits dislocations in the GaSb buffer (≈5.59 nm) is very close the theoretical value of 5.53 nm. The 90° dislocations are the most efficient misfit dislocations for strain relaxation because the length of the Burgers vector edge component projected onto the interface, $b_e$, is $a/\sqrt{2}$. Therefore, it is of great importance to clarify the microscopic mechanism by which these dislocations arise, although the growth mode is very sensitive to variables such as the growth temperature, the growth rate, and the V/III flux ratio.

Figure 4 shows the high-resolution XRD rocking curves of the 500-nm-thick GaSb layers grown on the InAs, AlSb, and GaSb buffer layers. The peaks corresponding to the (004) planes are sharp for the GaSb buffer layer (Figure 4(c)), but broad for the InAs buffer layer (Figure 4(a)). The broadness of this peak when the GaSb layer is deposited on a InAs buffer layer is attributed to the generation of threading dislocations resulting from strain relaxation. These results are in agreement with the AFM and the TEM results. The full width at half maximum (FWHM) of the XRD rocking curve for GaSb on a GaSb buffer layer (Figure 4(b)) is 468 arcsec, which is much smaller than the FWHM of 1296 arcsec obtained for the sample with an InAs buffer layer. In addition, the samples containing the AlSb and the GaSb...
buffer layers were found to exhibit mirror-like surfaces after GaSb growth. The strains and the FWHM values of the three samples, as determined from the XRD measurements, are summarized in Table 1. As Table I shown, the GaSb epilayers on the AlSb and the GaSb buffer layers have the same characteristics as fully relaxed bulk GaSb. These results clearly demonstrate that the presence of a thin, LT AlSb or GaSb buffer layer is very useful for improving the quality of GaSb crystals grown on GaAs substrates.

IV. CONCLUSION

The microstructural properties of GaSb films grown on thin InAs, AlSb, and GaSb buffer layers deposited at LT by using MBE were investigated using AFM, HR-TEM, and XRD measurements. HR-TEM of the GaSb layer grown on the thin LT AlSb and GaSb buffers revealed 90° misfit dislocations with a Burgers vector of 1/2a[110] at the AlSb/GaAs and the GaSb/GaAs interfaces. These defects represent the most efficient type of dislocation for misfit relaxation. By contrast, both 60° and 90° misfit dislocations were observed at the interface between the InAs layer and the GaAs substrate. Taken together, the present findings for the GaSb layer grown on a thin LT AlSb or GaSb buffer - mean roughness less than 1 nm, 90° misfit dislocations, and low FWHM value by XRD - confirm that the LT AlSb or GaSb buffer layer plays a key role in the growth of high quality GaSb layers. These observations can be used to improve the crystal quality of large mismatch heteroepitaxy structures.

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