Growth of ultrathin GaSb layer on GaAs using metal–organic chemical vapor deposition with Sb interfacial treatment

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Abstract

As complementary metal–oxide–semiconductor (CMOS) device scaling approaches the physical limit, III–V high-mobility materials have been proposed as channel materials for future device scaling. To avoid short-channel effects (SCEs), ultrathin-body metal–oxide–semiconductor field-effect transistors (UTB-MOSFETs) have been proposed to electrostatically control the channel potential better and to minimize the junction capacitance. Among the III–V materials, GaSb is an attractive material for p-type channel MOSFETs because of its high hole mobility (∼850 cm² V⁻¹ s⁻¹), which is at least two times those of silicon and GaAs. GaSb also has an electron mobility that is twice higher than that of silicon. The fabrication of a high-quality dielectric on the GaSb surface is crucial to the achievement of high-performance MOSFETs. Research studies on MOSFETs show that the surface roughness and vertical field induce additional carrier scattering at the interface. The interface trap states cause the gate-channel coupling efficiency to deteriorate; also, the bulk strain plays an important role in the structure formation of the semiconductor surfaces. Furthermore, the close correlation between the misfit dislocation (MD) network at the interface and the surface morphology indicates that the development of cross-hatching primarily results from the generation of MDs. The statistical analysis of the surface roughness revealed that the anisotropy in the strain relaxation of the epitaxial layers results from the asymmetry due to the formation of MDs.

A high lattice mismatch (−7.8%) between GaSb and GaAs complicates the epitaxial growth of the GaSb layer on GaAs. Recently, a fundamentally different growth mode with an interfacial misfit dislocation (IMF) has been introduced. The strain due to the high mismatch at the interface between GaSb and GaAs is relieved by the formation of 90° MDs in the [110] and [110] crystallographic directions. To facilitate the direct growth of low-defect-density GaSb on GaAs substrates without buffer, it is essential to grow GaSb epitaxial layers in the IMF mode. The IMF growth mode can be conducted by optimizing the growth temperature; a growth temperature of 520 °C favors 90° misfits and that of 560 °C favors 60° misfits. In addition to the growth temperature, the lattice mismatch was shown to be critical to the formation of 90° misfits; low-strain (<2%) systems typically produce 60° MDs, moderate-strain (3–4%) systems produce a mixture of 90 and 60° MDs, and high-strain (>6%) systems favor 90° MD formation.

In this study, we demonstrated a chemical vapor deposition method with Sb interfacial treatment to grow quasi-two-dimensional (quasi-2D) GaSb islands in the IMF growth mode. For the growth at 520 °C, the mismatch strain was primarily accommodated by periodic 90° dislocations, which requires the balance between strain energy and adatom migration, and can be controlled through optimized growth conditions. By modulating the V/III ratio, the surface roughness of the ultrathin (10-nm-thick) GaSb layer on GaAs can be improved and the surface roughness scattering can be reduced. By optimizing the V/III ratio, the surface roughness was decreased and the hole mobility of the thin film was increased by 78.5%.

All GaSb samples were grown on semi-insulating GaAs(100) substrates using a metal–organic chemical vapor deposition rotating-disk reactor (AIXTRON 2400). Trimethylgallium was used as the Group III source, arsine and trimethylantimony were used as Group V sources, and H₂ was used as the carrier gas. To investigate the effect of interfacial treatment at the GaSb/GaAs interface, the surface was exposed to different interfacial treatments for 20 s prior to the growth of the GaSb epitaxial layer. The GaSb/GaAs heterostructures were grown in the IMF growth mode at temperatures between 490 and 550 °C. An ultrathin (10-nm-thick) GaSb layer was grown on a GaAs buffer layer with a V/III ratio from 0.625 to 2.5 for ultrathin-body device application. The interface between GaSb and GaAs was examined by high-resolution transmission electron microscopy (HR-TEM), and the surface morphology and root-mean-square (RMS) roughness were investigated by atomic force microscopy. Hall measurements were performed at room temperature at a 0.5 T magnetic field using the standard van der Pauw geometry pattern.
Figures 1(a)–1(c) show the HR-TEM images of the single-crystal islands formed with different interfacial treatments, i.e., with Ga (sample A) and Sb (sample B), and without interfacial treatment (sample C); these treatments resulted in 3D, quasi-2D, and 2D growth modes for the GaSb island growth on GaAs substrates, respectively. These different growth modes can be attributed to the different interfacial treatments, which result in the modifications of the growth kinetics and thermodynamics of the epitaxial layers. Owing to the kinetically limited growth, 3D island formation was suppressed after the Sb interfacial treatment.\(^{10}\) In addition, from the perspective of thermodynamic effect, the Sb interfacial treatment promotes the formation of strong Ga–Sb bonds in the initial stage of GaSb/GaAs heteroepitaxial growth.\(^{11}\) With the Ga interfacial treatment, the Ga diffusion length increases, thus promoting 3D island formation at the GaSb/GaAs interface. With the Sb interfacial treatment, the diffusion length of Ga decreases, thus suppressing 3D island formation. Because of the small diffusion length, 3D island growth no longer exists.\(^{12}\)

Table I shows that the three different interfacial treatments (Ga, Sb, and without) resulted in three different island growth modes, i.e., 3D, quasi-2D, and 2D, with island densities of \(5.05 \times 10^9\), \(1.9 \times 10^9\), and \(2.75 \times 10^8\) \(\text{cm}^{-2}\), respectively. The interfacial treatments also affected the mean aspect ratio of \(((001)/[110])\) for the GaSb islands; the aspect ratios were 0.162, 0.014, and 0.031 for different interfacial treatments (Ga, Sb, and without, respectively). Sb interfacial treatment resulted in decreases in island density and aspect ratio, which is typically observed during quasi-2D growth with elongation in the [110] direction.\(^{13,14}\) This outcome is reasonable, because Sb interfacial treatment increases the sticking coefficient of the Group III adatoms at the [110] step edges owing to the occupation of the dangling Group V sites at the step edge by Sb. Since Sb has a far lower volatility, and it has also been observed to increase the step velocity,\(^{15,16}\) Sb interfacial treatment caused quasi-2D growth with a low defect density, resulting in a GaSb layer superior to those obtained with and without Ga interfacial treatment.

| Table I. Growth mode, island density, and aspect ratio of the samples with different interfacial treatments. |
|----------------------------------------|-------------|-------------------|-----------------|
| Interfacial treatment | Growth mode | GaSb island density \((\times 10^9 \text{cm}^{-2})\) | Aspect ratio \((\text{height/width})\) |
| Sample A with Ga | 3D | 5.05 | 0.162 |
| Sample B with Sb | quasi-2D | 1.9 | 0.014 |
| Sample C without | 2D | 2.75 | 0.031 |

Figures 2(a)–2(c) show the TEM images of the GaSb/GaAs interface regions of samples D, E, and F, which were grown at 550, 520, and 490 °C, respectively. This evolution of the morphology seems to agree with the kinetics of material growth: at lower temperatures, the small diffusion length of Ga adatoms induces a high density of small GaSb islands.\(^{15,16}\) This implies an increase in Ga adatom diffusion length when the growth temperature is decreased.\(^{17}\) Figure 2(d) shows the strain relaxation and average distance of 90° MDs as functions of growth temperature in quasi-2D growth mode.

\[ S = \frac{b}{f} = \frac{a_{\text{epi}} \cdot a_{\text{sub}}}{\sqrt{2(a_{\text{epi}} - a_{\text{sub}})}}. \]
Figures 3(a)–3(c) show the effect of V/III ratio on the surface roughness of the GaSb/GaAs heterostructure epilayers. The samples grown at 520 °C under different V/III ratios exhibited different surface morphologies. Samples H, I, and J (thickness = 10 nm) that were grown at V/III ratios of 2.5, 1.25, and 0.625 exhibited RMS roughnesses of 3.5, 2.6, and 0.5 nm, respectively. Thus, the V/III ratio of 0.625, which resulted in the smallest surface roughness, was selected as the optimum value for the GaSb/GaAs heteroepitaxial layers formed at various V/III ratios of (a) 2.5, (b) 1.25, and (c) 0.625.

Table II shows the qualitative relationships among the RMS roughness, the hole mobility $\mu_h$, and the hole density $p$ for the GaSb epilayer. It also shows that when the V/III ratio decreases, the hole density increases as the number of Sb vacancies increases, which allows the incorporation of more carbon particles.\textsuperscript{19,20} Moreover, it shows that, when RMS is reduced, the hole mobility is increased. Normally, as the hole density increases, the hole mobility decreases; however, the opposite is observed in our case, because the RMS effects offset the ionized impurity scattering effects. The hole mobility was further affected by the surface roughness.\textsuperscript{21} The hole mobility effect due to surface roughness scattering can be extracted following Matthiessen’s rule, where the decrease in hole mobility with increasing surface roughness is described by

$$\mu_h \propto \frac{1}{(\Delta - L)^2}.$$  

where $\Delta$ and $L$ are the mean asperity height and correlation length of the surface roughness, respectively.\textsuperscript{22} At the optimum V/III ratio of 0.625, sample J exhibited a high hole mobility of 241 cm$^2$ V$^{-1}$ s$^{-1}$ and a hole density of $7.4 \times 10^{17}$ cm$^{-3}$ with a small surface roughness of 0.5 nm; this hole mobility was 78.5% greater than that of sample H with a surface roughness of 3.5 nm ($\mu_h = 135$ cm$^2$ V$^{-1}$ s$^{-1}$ and $p = 2.9 \times 10^{17}$ cm$^{-3}$; Table II).

Table II. Hole mobility, hole density, and root-mean-square (RMS) roughness of samples grown at various V/III ratios.

| Sample | Thickness (nm) | V/III ratio | RMS roughness (nm) | Hole mobility (cm$^2$ V$^{-1}$ s$^{-1}$) | Hole density ($10^{17}$ cm$^{-3}$) |
|--------|---------------|-------------|--------------------|----------------------------------------|---------------------------------|
| Sample G | 50 | 2.5 | 1.9 | 401 | 2.8 |
| Sample H | 10 | 2.5 | 3.5 | 135 | 2.9 |
| Sample I | 10 | 1.25 | 2.6 | 190 | 5.6 |
| Sample J | 10 | 0.625 | 0.5 | 241 | 7.4 |

Fig. 4. (a) Cross-sectional HR-TEM image of an ultrathin (10-nm-thick) GaSb layer on GaAs grown at the optimum V/III ratio of 0.625. (b) Highly periodic 90° MDs at the GaSb/GaAs interface. (c) Selective-area diffraction pattern of the scan area.
MDs with a period of 5.67 nm. The 90° MDs at the interface not only relieved the strains but also reduced the dislocation density in the epitaxial layer, improving the surface morphology and crystal quality. By optimizing the V/III ratio, the surface roughness of the ultrathin (10-nm-thick) GaSb/GaAs heterostructure was improved and the carrier scattering due to the surface roughness was effectively reduced. Overall, GaSb film growth at 520 °C with an optimal V/III ratio of 0.625 showed a small surface roughness of ∼0.5 nm and that the hole mobility in the film increased by 78.5% to 241 cm² V⁻¹ s⁻¹.

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