Epitaxial growth and formation of interfacial misfit array for tensile GaAs on GaSb

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The authors report the formation of an interfacial misfit (IMF) array in the growth of relaxed GaAs bulk layers on a (001) GaSb surface. Under specific conditions, the high quality IMF array has a period of 5.6 nm and can accommodate the 7.78% tensile GaAs/GaSb lattice mismatch. The misfit site is identified as a 90° edge dislocation using Burger's circuit theory and confirmed by high-resolution cross-section transmission electron microscopy (TEM) images. The resulting GaAs bulk material is both strain-free and highly crystalline. Plan-view TEM images show threading dislocation density of $\sim 3\times 10^6/\mathrm{cm}^2$. This material demonstration will enable novel device structures including an embedded GaSb active region in GaAs device matrix. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2723649]

Exploiting lattice-mismatched GaSb/GaAs and GaAs/GaSb heterojunctions are of considerable interest for III-Sb electronic and optoelectronic devices on a GaAs substrate such as midwave infrared lasers, detectors, and transistors.[1–3] At the compressive GaSb/GaAs interface, popular growth techniques such as metamorphic buffers (MBs) have enabled sufficiently low dislocation densities to realize some of these devices.[4,5] In previous demonstrations, the MB is typically >1 μm in thickness and produces a defect density $<10^7/\mathrm{cm}^2$. To circumvent the MB thickness, a new and novel growth technique involving 90° interfacial misfit (IMF) dislocations has recently been demonstrated by our group at the compressive interface to enable room temperature (RT) lasing at 1.65 μm from a GaSb active region on GaAs.[6] The IMF relieves strain immediately at the compressive heterointerface. The experimental results indicate that the IMF dislocations relieve 98.5% of the strain energy and yields defect density $<10^5/\mathrm{cm}^2$ to enable high quality GaSb materials on a GaAs substrate.[7]

However, there are device applications such as midwave infrared (MWIR) vertical cavity surface emitting lasers that might benefit from the III-Sb active region to be fully embedded in the GaAs matrix. Such a structure exploits the narrow band gap III-Sb materials to access MWIR along with the mature GaAs processing technology, superior electrical contacts, thermal conductivity, and access to a native oxide (Al_xO_y). Such a device requires simultaneous control of the compressive (GaSb on GaAs) and tensile (GaAs on GaSb) interfaces. To date, epitaxy at the tensile GaAs on GaSb interface has not been addressed in the literature. In this letter, we describe the formation of an IMF for strain-relieved, low defect growth of GaAs on GaSb (001) that parallels the IMF formation at the compressive GaSb/GaAs interface.

At the compressive GaSb on GaAs interface, the IMF formation is initiated with an Sb soak during which time, the Sb atoms self-assemble such that each Sb atom forms a single bond with an underlying Ga (001) atom.[7,8] The Sb atoms, however, do not react with the GaAs substrate to displace the As atoms.[9] Strain relief is achieved by a skipped Sb–Ga bond every 13 atomic sites which form the IMF array.[10]

The tensile IMF has a similar atomic structure initiated by a single layer of As (001) atoms bonded to the underlying Ga (001) atomic layer. Strain relief is achieved by a skipped As–Ga bond every 13 lattice sites. However, in contrast to the nonreactive nature of the Sb atom at the GaAs surface, the IMF formation at the tensile GaAs on GaSb interface is more complex since the As_2 specie reacts aggressively with the GaSb surface during an As_2 soak. This reactivity will form nanoscale highly crystallographic pits[11] and makes a reconstructed As layer on the GaSb surface difficult to establish. The surface chemistry is driven by a negative enthalpy of reaction for both the anion exchange reaction and the isoelectronic AsSb compound formation reaction ($\mathrm{GaSb}+\mathrm{As}_2\rightarrow 2\mathrm{GaAs}+\mathrm{Sb}_2$, $\Delta H^\circ=-47.6$ kJ/mol; $\mathrm{GaSb}+\mathrm{As}_2\rightarrow \mathrm{GaAs}+\mathrm{AsSb}$, $\Delta H^\circ=-33.9$ kJ/mol).[9,12] The purpose of this study is to understand the effect of this reaction on the GaAs/GaSb interface.

The samples used in this interfacial analysis are grown on a V80H reactor with valved crackers for both the As and the Sb source. The crackers are operated at 900 and 950 °C, respectively, so that the atomic species from the sources are As_2 and Sb_2. The growth is initiated on a GaSb substrate with a thermal oxide desorption process followed by a GaSb smoothing layer characterized by a 1×3 reconstruction. The smooth GaSb surface is then subjected to an As_2 overpressure with an approximate beam equivalent pressure of 1×10^{-6} mTorr. This overpressure is maintained for 0, 10, or 60 s, respectively. Before the As growth is initiated, the Sb valve is closed allowing Sb atoms to desorb leaving a Ga-rich surface. This process, which is confirmed by reflection

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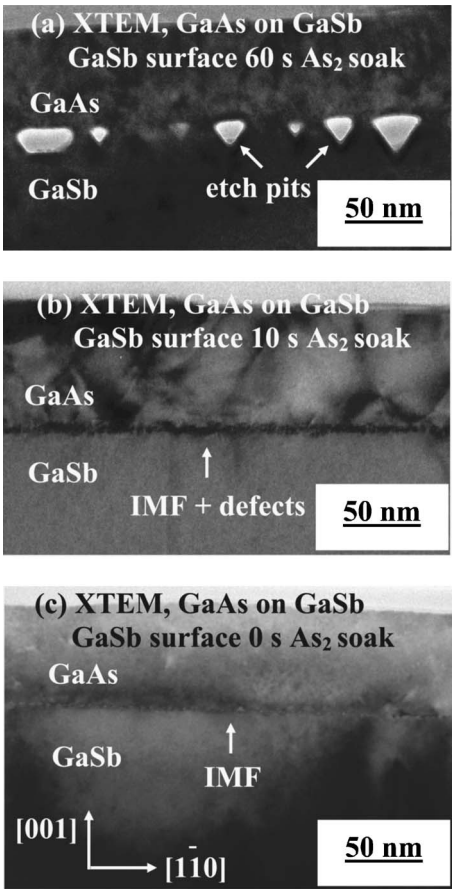

FIG. 1. Cross-sectional TEM images of the tensile GaAs/GaSb interface, GaAs grown on GaSb after GaSb surface (a) 60 s, (b) 10 s, and (c) 0 s As_2 soak.

high electron energy diffraction indicating Ga-rich (4×2) pattern, reduces Sb/As intermixing. Following the As_2 soak, the GaAs growth is initiated without any changes in the growth temperature resulting in a smooth GaAs surface with continued growth.

The resulting misfit array and bulk material have been analyzed carefully using low-resolution and high-resolution transmission electron microscopy (TEM) images. Figures 1(a)–1(c) show the cross-sectional TEM images of a bulk GaAs layers (100 nm) grown on the GaSb surfaces under different As_2 soak times (60, 10, and 0 s, respectively). At 60 s, the As_2 etches nanoscale pits at the GaAs/GaSb interface shown in Fig. 1(a). These pits vary in both size and shape with average dimensions of ~25 nm wide and 10–40 nm high. Subsequent GaAs bulk overgrowth coalescences over the nanopits resulting in nanovoids.[11] The subsequent GaAs bulk material has a significant threading dislocation density ($>10^9/cm^2$). Using a 10 s As_2 soak time, the tensile GaAs/GaSb IMF array of moderate quality forms, shown in Fig. 1(b). Some etch pits also appear along the GaAs/GaSb interface (not shown). The density of threading dislocations in GaAs epilayer decreases two to three orders of magnitude compared to Fig. 1(a), but remains high $(10^7/cm^2)$. If no As_2 soak is used on the GaSb surface prior to the growth of GaAs layer, only tensile GaAs/GaSb IMF array forms at the interface and produce good quality GaAs epilayer, as shown in Fig. 1(c). The limited cross-sectional area sampled by the TEM image indicates no threading dislocations, dark-line defects, or misfit dislocation. While the

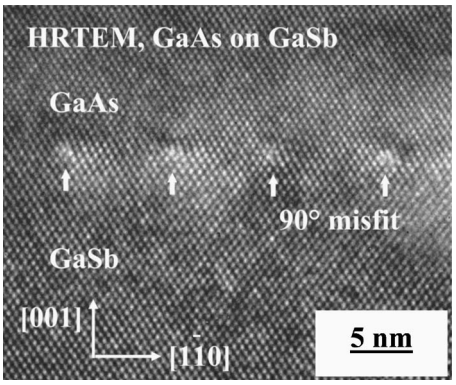

FIG. 2. HRTEM image of the tensile GaAs/GaSb interface, featuring 90° IMF array formed with 0 s As_2 soak.

single As atomic layer seems to form on the Ga atomic layer by ambient As overpressure, it appears to lack long-range uniformity. This leads to a higher defect density than what can be realized in the compressive growth mode, as indicated in plan-view TEM analysis shown below.

Careful examination of the IMF and surrounding atomic lattice is conducted using cross-sectional HRTEM images, as shown in Fig. 2. The misfits appear as bright spots and are arranged in a highly periodic array localized at the tensile GaAs/GaSb interface. Using Burger's circuit theory around a misfit dislocation shows that Burger's vector, i.e., $a/2[1\bar{1}0]$, lies along the interface and identifies this misfit as

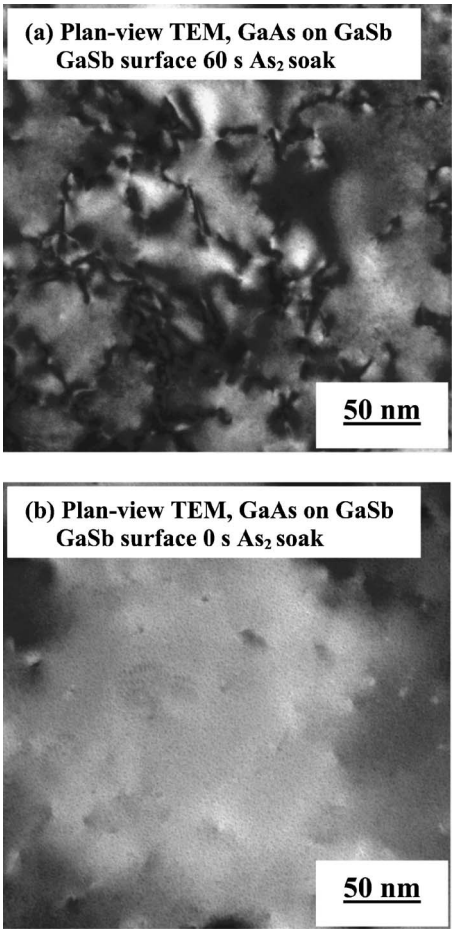

FIG. 3. Plan-view TEM images of the GaAs surface grown on GaSb after GaSb surface (a) 60 s and (b) 0 s As_2 soak, indicating the defect density.

90° pure edge type. The misfit separation, measured to be 5.6 nm, corresponds to exactly 14 GaAs lattice sites grown on 13 GaSb lattice sites. The identical misfit arrays have been observed along both [110] and [1−10] directions, which shows that there is a two-dimensional 90° pure edge dislocation array at the tensile GaAs/GaSb interface.

Figure 3 shows plan-view TEM images of the GaAs surface grown on GaSb after a (a) 60 s and (b) 0 s As_2 soak, respectively. These images indicate threading dislocations which appear as dark, squiggly lines on the shiny GaAs surface and enable the density of threading dislocations to be calculated. The 60 s As_2 soak condition yields a threading dislocation density of $\sim 1\times 10^9$ defects/cm^2. With no As_2 soak, the density of threading dislocation reduces to $\sim 3\times 10^6$ defects/cm^2. This result is consistent with those observed in cross-sectional TEM analysis shown in Fig. 1.

To date, we have used both the tensile and compressive IMFs to embed a III-Sb active region in a vertical cavity light emitting diode (VLED).[13] The VLED emits under RT conditions at 2.0 μm with a turn-on voltage of ~3 V and a differential resistance of ~30 Ω at 8 V. The rather high voltage is due in part to a large *p*-type specific contact resistance of 1×10^{-5} Ω cm^2 caused by unoptimized doping and partially due to a ~1 V drop per IMF. However, to realize high performance electronic devices using the tensile IMF, the defect density of the GaAs on GaSb needs to be reduced $<10^5$/cm^2. To achieve the higher quality GaAs on GaSb, a nonreactive atom can be used either as a surfactant or catalyst. A thin buffer of AlSb, with greater bond strength compared to GaSb, may also reduce the As/surface reactivity enabling long-range uniform IMF formation.

In conclusion, we have demonstrated that a periodic 90° misfit dislocation array can be formed to relieve the high strain energy in tensile lattice-mismatched GaAs on GaSb. The misfit separation, measured to be 5.6 nm, corresponds to exactly 14 GaAs lattice sites grown on 13 GaSb lattice sites. The IMF formation requires the As (001) atomic layer to self-assemble and bond to the underlying Ga (001) atomic layer. However, very specific growth conditions are necessary to achieve this arrangement while minimizing the strong As_2 reaction with GaSb surface. Bulk GaAs material with low dislocation density and strain-relieved properties is generated on GaSb layers by these growth conditions. Control of both tensile (GaAs on GaSb) and compressive (GaSb on GaAs) can lead to new devices based on the novel integration schemes.

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