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Role of monolayer Indium atom distribution in metalorganic chemical vapor deposition of InAs/GaAs epitaxy on Ge substrate

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Abstract

The growth of InAs/GaAs epitaxies by metalorganic chemical vapor deposition (MOCVD) on Ge substrates using flow-rate modulation epitaxy (FME) growth technique together with appropriate V/III ratio is demonstrated. High-quality InAs epitaxy was related to uniform monolayer In atom distribution at the InAs/GaAs interface, which can effectively lower the difference between surface energy and strain energy and produce stable interface condition during material growth. It is also demonstrated that accurate V/III ratio control can improve the quality of InAs epitaxy on GaAs/Ge heterostructure, though it is not the key factor in InAs epitaxial growth.

Introduction

Significant progress has been made in development of III-V material growth on GaAs or on Si substrates for high-speed device applications in recent years.[1,2] Some III-V compound semiconductors, such as In(Ga)As-based materials, possess high electron mobility due to their direct bandgap and low electron effective mass. However, large lattice constant difference of 7.2% between InAs and Ge generates many InAs islands (Stranski-Krastanov mode, S-K mode), and misfit dislocations at the interface, leading to electron mobility degradation. Some traditional growth techniques performed by molecular beam epitaxy (MBE), including linearly graded, step-graded and direct growth, were used to suppress stacking fault formation, mixing with 60° and 90° misfit dislocations at the interface.[3,4] In general, the above-mentioned methods induce 90° complete dislocation formation, and avoid the gliding of 60° misfit dislocations at the interface. Although these approaches can effectively release contractive strains by 90° misfit dislocations, thicker buffer layers from several hundreds of nanometers to several micrometers are required, and it is very difficult to form directly thin InAs epitaxy on high-mismatched substrates.

In our previous work, high-quality and smooth GaAs epitaxy on Ge/Si substrate with graded-temperature arsenic prelayer has been demonstrated by MOCVD.[5] Therefore, the continuous development of an epitaxial technique that can grow thin InAs layer directly on GaAs/Ge or other substitutional substrates without any buffer layer while maintaining higher relaxation and smooth surface morphology is an important criterion for the development of high-speed III-V electronic devices on Ge/Si substrate.

Experiment

All samples in this study were grown by a low-pressure metal organic chemical vapor deposition (MOCVD, EMCORE D180) using trimethylgallium (TMG), trimethylindium (TMIn) and arsine (AsH_3) as the source materials. Ge (100) substrates with 6 degree off toward the [111] direction were adopted, and then GaAs epitaxy was grown on Ge using graded-temperature arsenic prelayer. The detailed description of the growth of GaAs epitaxy on Ge substrate can be found in reference [5]. The growth temperature for InAs thin film was kept at approximately 450℃, which was similar to that of the GaAs growth. The growth processes of InAs epitaxy on GaAs/Ge heterostructure were schematically illustrated in Fig.1. FME growth region was performed by adjusting alternate supply of TMIn and AsH_3 sources to the GaAs epitaxial surface.

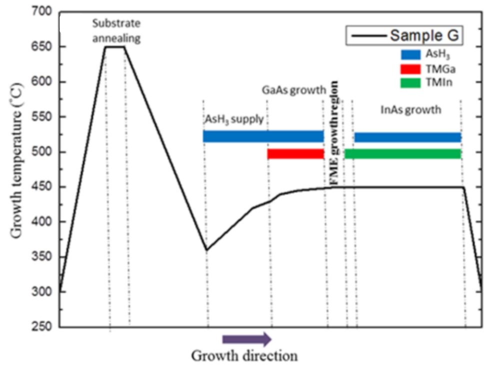

Figure 1. The schematic illustration of InAs epitaxy on GaAs/Ge heterostructure using flow-rate modulation epitaxy (FME) growth together with appropriate V/III ratio of 32

Results and discussion

Figure 2(a) and (b) show the high resolution transmission electron microscopy (HRTEM) images of InAs/GaAs epitaxies on Ge substrate grown by MOCVD (sample G). The epitaxial thicknesses of GaAs and InAs layers were about 116 and 40nm, respectively. It can be seen that periodic 90° misfit dislocations (arrowed) were formed at the InAs/GaAs interface, as shown in Fig. 2(b). A model for the formation of 90° misfit dislocation was established, indicating that a 90° misfit dislocation could be formed by the combination of a Frank partial and a Shockley partial dislocation. Due to rapid formation of the InAs epitaxy with periodic 90° misfit dislocations on GaAs surface, the difference between surface energy and strain energy could become small when InAs epitaxial thickness exceeded the critical thickness. It implies that atoms from precursors are probably deposited uniformly on the GaAs surface, not on distorting atomic structure, and eventually form a continuous InAs thin film on the GaAs/Ge heterostructure. On the other hand, from the selective-area diffraction pattern taken from the InAs/GaAs interface region, the satellite spots surrounding the primary beam can be clearly seen, as shown in Fig. 2(c). The diffraction spots, which are close to the primary beam, represent the InAs epitaxial structure, indicating a good InAs crystalline quality.

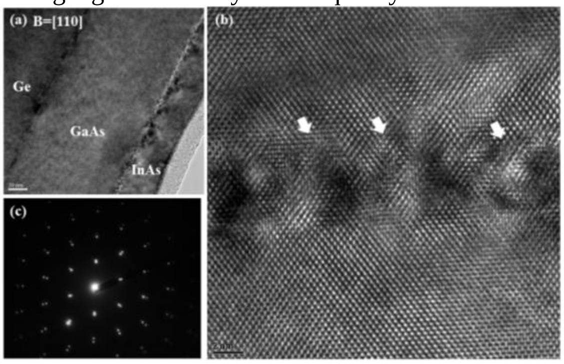

Figure 2. (a) the cross-sectional TEM image of InAs thin film on GaAs/Ge heterostructure, (b) HRTEM image taken from the InAs/GaAs interface region, (c) the selected area diffraction pattern taken from the InAs/GaAs interface region.

Figure 3 illustrates the reciprocal space map (RSM) of InAs/GaAs epitaxies on Ge substrate obtained by using a Ge (224) crystal analyzer scan. According to the RSM result, it is very difficult to distinguish between GaAs and Ge epitaxial structures because of similar lattice constant and larger scan range used in this study. Therefore, the RSM result shows that there are only two regions appearing in $Q_{(z)}$ direction for the InAs/GaAs/Ge heterostructure. The core of InAs peak appearing below relaxation line indicates compressive strain along growth direction. It can be demonstrated that high RD of 90% for InAs/GaAs epitaxies on Ge substrate was achieved. As judged from HRTEM and RSM results, a thin InAs layer (~40nm) with high RD was grown on GaAs/Ge heterostructure without any buffer layer by MOCVD.

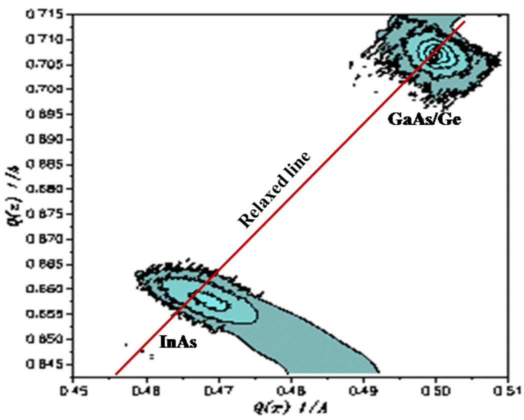

Figure 3. The reciprocal space map (RSM) of InAs epitaxy on GaAs/Ge heterostructure measured by using a Ge (224) crystal analyzer scan.

Figure 4 illustrates the high-angle annular dark field (HAADF) image of InAs/GaAs interface region taken along [010] zone axis. The experimental result shows that the interface of InAs/GaAs is clearly identified as containing two atomic phases each made by a different type of atoms. The atomic arrangement in InAs thin film, grown on a ~2MLs thick wetting layer, was slightly distorted along the growth direction. Furthermore, we also found that, due to the distorted atomic arrangement, some specific In atoms above the wetting layer filled in the preferred positions with lower energy where each In atom sits in the middle region of the regular In and As column as shown in Fig.4. This behavior can effectively reduce the difference in the lattice constants between GaAs and InAs epitaxies and enhance the InAs epitaxial quality.

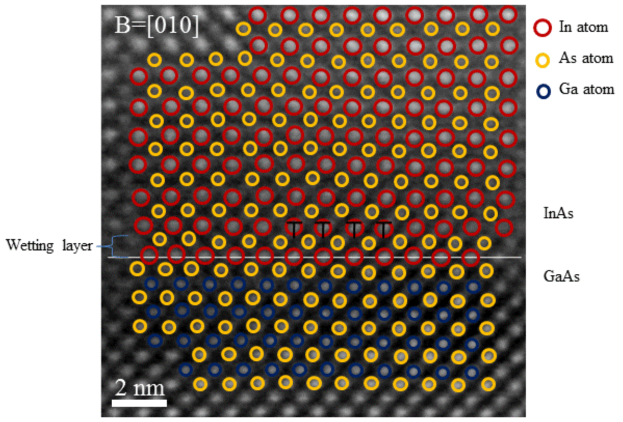

Figure 4. The high-angle annular dark field (HAADF) image of InAs/GaAs interface region taken along [010] zone axis.

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