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Direct growth of a 40 nm InAs thin film on a GaAs/Ge heterostructure by metalorganic chemical vapor deposition

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In this paper, the authors directly grew an InAs thin film (40 nm) by metalorganic chemical vapor deposition on GaAs/Ge substrates by using flow-rate modulation epitaxy with an appropriate V/III ratio. The growth of a high-quality InAs thin film with periodic 90° misfit dislocations was related to a uniform monolayer In atom distribution at the InAs/GaAs interface. The In monolayer effectively minimized the difference between surface energy and strain energy, producing a stable interface during material growth. The authors also found that a tightly controlled V/III ratio can improve the quality of the InAs islands on the GaAs/Ge heterostructures, though it is not the key factor in InAs thin-film growth. © *2014 American Vacuum Society*.
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I. INTRODUCTION

In recent years, much progress has been made in growing III–V materials on GaAs or Si substrates for high-speed device applications.[1,2] Some III–V compound semiconductors, such as In(Ga)As-based materials, have high electron mobility because of their direct, narrow energy bandgaps. However, the lattice constants of InAs and Ge differ by 7.2%, which generates many InAs islands (Stranski–Krastanov mode, S–K mode) and misfit dislocations at the interface, degrading electron mobility. Some traditional growth techniques executed by molecular beam epitaxy, 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 prevent gliding of 60° misfit dislocations at the interface. Although these approaches can effectively release compressive strain with 90° complete dislocations (90° misfit dislocations), they require thicker buffer layers, from several hundreds of nanometers to several micrometers; it is very difficult to directly form thin InAs epitaxial layers on highly mismatched substrates.

However, thin InAs epitaxy on substitutional substrates has been explored by using the epitaxial transfer method.[5] In particular, Ko *et al*.[5] also pointed out that the electron mobility in InAs field-effect-transistors increases with the increase in InAs thickness, and reaches a maximum with an InAs thickness of 40–50 nm. In our previous work, low-antiphase domain and smooth GaAs epitaxy on a Ge/Si substrate with the graded-temperature arsenic prelayer was demonstrated by metalorganic vapor phase epitaxy.[6] Therefore, the continuous development of an epitaxial technique that can grow a thin InAs layer (∼40 nm) directly on GaAs/Ge or other substitutional substrates without a buffer layer while maintaining high relaxation and a smooth surface is an important criterion for the development of high-speed III–V electronic devices on Ge/Si substrate.

II. EXPERIMENTAL METHODS

All samples in this study were grown by a low-pressure metal organic chemical vapor deposition (MOCVD, EMCORE D180) using trimethylgallium, trimethylindium, and arsine (AsH_3) as the source materials. Ge (100) substrates with six degree off toward the [111] direction were used, and GaAs epitaxy was grown on them using the graded-temperature arsenic prelayer. The detailed description of the growth of GaAs epitaxy on Ge substrate can be found in Ref. 6. Prior to growth, the substrate was annealed in hydrogen at 650 °C for 60 s and then cooled down to the growth temperature of 350 °C in hydrogen. The graded-temperature arsenic prelayer was formed while the substrate temperature increased from 350 to 420 °C. Then, the GaAs epitaxy was grown on the Ge substrate by low-temperature epitaxy (450 °C). The growth temperature for the InAs thin films was kept at approximately 450 °C, similar to the growth temperature of the GaAs epitaxy. Besides, some researchers showed that the control of V/III ratio is an

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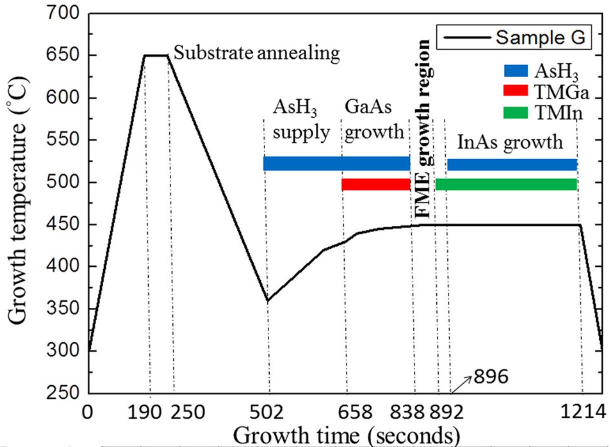

FME growth

In	4s				4s				4s			
As			4s				4s				4s	
H		5s		5s		5s		5s		5s		5s

FIG. 1. (Color online) Schematic illustration of the growth process for the InAs epitaxy (flow-rate modulation epitaxy growth together with an appropriate V/III ratio of 32) on a GaAs/Ge heterostructure.

important parameter for InAs nanostructure growth, specially quantum dots and nanowires.[7–9] The V/III ratio during material growth strongly affects the activation energy of the surface and the coverage of the precursors. Therefore, in order to improve the quality of the InAs grown on the GaAs/Ge heterostructure, the V/III ratio was adjusted in this study from 16 to 225 (samples A–F). To deposit the InAs interfacial layer, we grew some samples with flow-rate modulation epitaxy (FME), whose the gas-flow sequence consists of four steps in one cycle, as shown in Fig. 1. Our results show that using FME growth with an appropriate V/III ratio (sample G) effectively produced InAs thin films with high relaxation and smooth surface morphology on the GaAs/Ge heterostructure. The surface morphology of the InAs thin film on the GaAs/Ge heterostructure was examined using atomic force microscopy (AFM), and the characterization of the InAs/GaAs interface was performed using (scanning transmission electron microscopy, JEOL ARM-200). The crystalline quality and strain relaxation of the grown samples were estimated using high resolution x-ray diffraction.

III. RESULTS AND DISCUSSION

Figures 2(a) and 2(b) illustrate cross-sectional high-resolution transmission electron microscopy (HRTEM) images of an InAs thin film on the GaAs/Ge heterostructure grown by MOCVD (sample G). The epitaxial thicknesses of the GaAs and InAs layers were about 116 and 40 nm, 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,[10] indicating that 90° misfit dislocations could be formed by combining Frank and Shockley partial dislocations. The effect of the atomic arrangement at the interface versus 90° misfit dislocations will be discussed later. Due to the rapid formation of the InAs thin film with periodic 90° misfit dislocations on the GaAs surface, the difference between the surface energy and strain energy could become small when the InAs epitaxial thickness exceeded the critical thickness.[11] This behavior implies that atoms from the precursors were likely deposited uniformly on the GaAs surface, not on the 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, the satellite spots surrounding the primary beam can be clearly seen, as shown in Fig. 2(c). These diffraction spots, close to the primary beam, represent the InAs epitaxial structure, indicating its good crystalline quality.

Figure 3 illustrates the reciprocal space map (RSM) of an InAs thin film on the GaAs/Ge heterostructure (sample G)

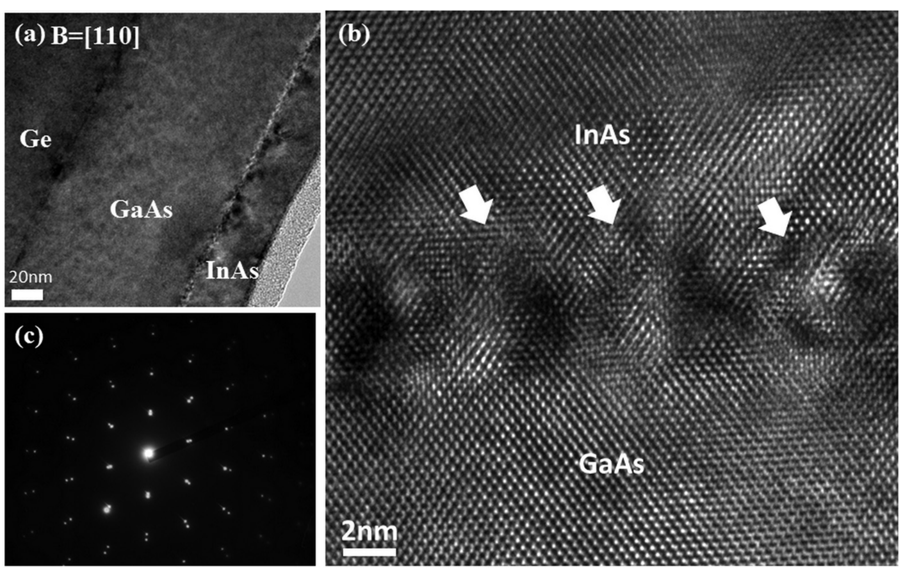

FIG. 2. (a) Cross-sectional TEM image of the InAs thin film on the GaAs/Ge heterostructure, (b) HRTEM image of the InAs/GaAs interface, and (c) selected area diffraction pattern from the InAs/GaAs interface.

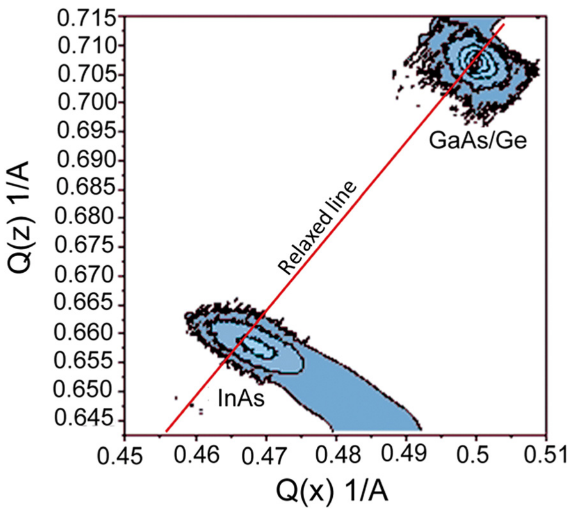

FIG. 3. (Color online) RSM of the InAs thin film on the GaAs/Ge heterostructure measured by using a Ge (224) crystal analyzer scan.

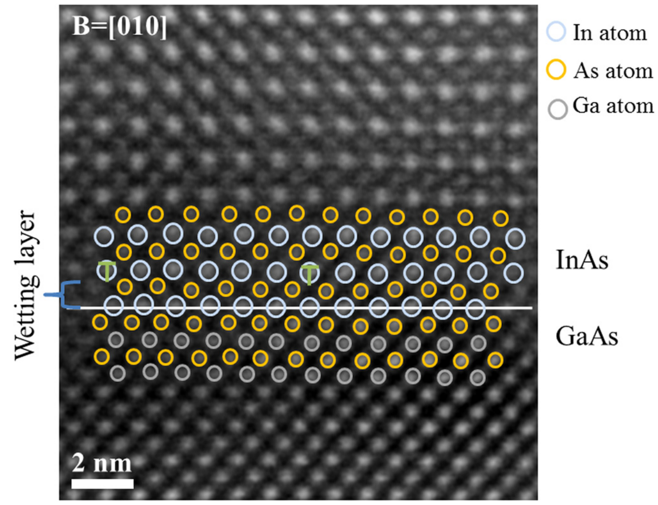

FIG. 4. (Color online) HAADF image of the InAs/GaAs interface taken along the [010] zone axis.

obtained by using a Ge (224) crystal analyzer scan. According to the RSM result, it is very difficult to distinguish between the GaAs and Ge epitaxial structures because of their similar lattice constants and the larger scan range we used in this study. Therefore, the RSM result shows that there are only two regions appearing in the $Q_{(z)}$ direction for the InAs/GaAs/Ge heterostructure. The theoretical values for $Q_{(z)}$ and $Q_{(x)}$ in this RSM can be calculated ($Q_{(z)} = 0.6603$; $Q_{(x)} = 0.4669$), and relaxation line was also generated (shown by the red line in Fig. 3). The core of the InAs peak below the relaxation line indicates compressive strain along the growth direction. The degree of relaxation for an InAs thin film on a GaAs/Ge heterostructure can be defined by the following equation:

$$\text{The degree of relaxation} = \frac{a_{\parallel} - a_{\text{sub}}}{a_{\text{full}} - a_{\text{sub}}} \times 100\%, \tag{1}$$

where a_{sub} is the lattice constant of the Ge substrate (5.658 Å) and a_{full} is the lattice constant of the InAs (6.058 Å). The Bragg angle was determined from the peak position of the InAs epitaxy. The difference of lattice parameters between the in-plane and off-plane was calculated to obtain the exact value of $a_{//} = 6.018$ Å. It can be demonstrated that a high relaxation of 90% for a 40 nm InAs thin film on a GaAs/Ge heterostructure was achieved. As judged from the HRTEM and RSM results, a thin InAs layer (~40 nm) with high relaxation was grown by MOCVD on the GaAs/Ge heterostructure without a buffer layer.

Figure 4 illustrates a high-angle annular dark field (HAADF) image of the InAs/GaAs interface region taken along the [010] zone axis (sample G). The experimental result shows that the InAs/GaAs interface is clearly identified as containing two atomic phases, each made by a different type of atom. The atomic arrangement in the InAs thin film, grown on a ~2 MLs thick wetting layer, was slightly distorted along the growth direction. Because of the distorted atomic arrangement, we assumed that some specific In atoms above the wetting layer filled positions with lower energy,[12] 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 lattice constants between GaAs and InAs epitaxial layers and enhance the InAs epitaxial quality. It implies that the formation of 90° misfit dislocation is closely related to the In atom distribution at the interface when the InAs epitaxial thickness exceeds the critical thickness. As mentioned above, the success of the growth of a thin InAs film on the GaAs/Ge heterostructure depends

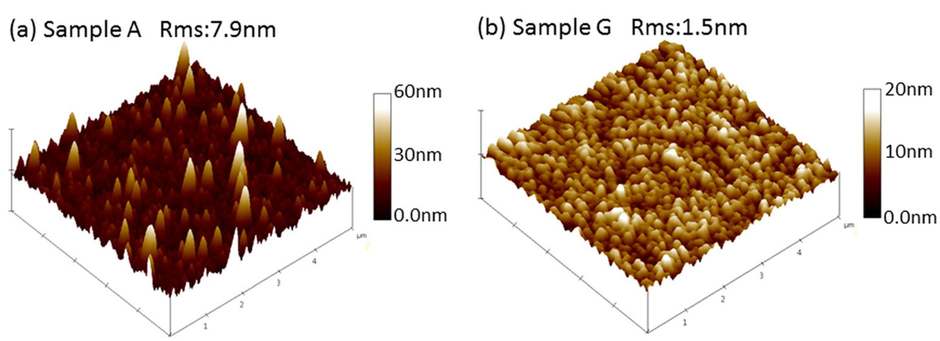

FIG. 5. (Color online) AFM images of the InAs epitaxy with different V/III ratios on a GaAs/Ge heterostructure; (a) V/III: 16, (b) FME together with an appropriate V/III ratio of 32.

TABLE I. Surface roughness of InAs epitaxy with different V/III ratios deposited on a GaAs/Ge heterostructure. (Sample C: InAs islands with a V/III ratio of 32 grown on a GaAs/Ge heterostructure. Sample G: under optimum growth conditions, 40 nm InAs film with periodic 90° misfit dislocations grown on a GaAs/Ge heterostructure.)

Samples	Growth temperature (°C)	Chamber pressure (Torr)	V/III ratios	Surface roughness (nm)
A	450	40	16	7.9
B	450	40	24	6.2
C	450	40	32	4.5
D	450	40	45	5.1
E	450	40	90	8.7
F	450	40	225	7.1
G	450	40	32	1.5

on uniform atomic deposition at the interface during initial growth. Based on the HAADF image, we demonstrated that the high surface mobility of In atoms, leading to more uniform In coverage at the interface, can effectively decrease the surface energy.[13] Since the surface energy is lower than the distorting energy during the InAs/GaAs/Ge heterostructure growth, a stable interface condition without stacking faults between the InAs and GaAs epitaxial layers can be generated.

The effect of V/III ratio on the quality of InAs epitaxy on the GaAs/Ge heterostructure was also investigated. Figure 5 and Table I illustrate the surface morphology and surface roughness with different V/III ratios of InAs epitaxial layers deposited on GaAs/Ge heterostructures as observed by AFM. The optimum V/III ratio of 32 (sample C) can effectively improve the surface roughness (4.5 nm) of the InAs/GaAs/Ge heterostructure. Higher V/III ratios ($\gg$32), implying that more arsenic atoms exist during the InAs growth, lead to poor surface morphology due to 3D growth formation[11,14] where a mixture of 60° and 90° dislocations were generated. At lower V/III ratios ($<$32) and lower growth temperatures, AsH_3 pyrolysis is incomplete under this condition, providing inadequate arsenic atoms during growth. This growth condition will result in liquid–metal droplets on the surface and then increase surface roughness. Actually, we also observed that a distinct link between individual InAs islands was formed under lower V/III ratios of $\leq$32, as shown in Figs. 6(a) and 6(b). It was obvious that InAs island growth and partial islands coalescence occurred. At higher V/III ratios (225), many stacking faults and threading dislocations formed and reached the island surface. These results indicate that producing high-quality InAs islands requires very tight control of the V/III ratio during growth. However, a good V/III ratio alone does not guarantee the formation of an InAs thin film on a GaAs/Ge heterostructure, as shown in Fig. 6.

The smooth surface morphology is necessary for high-speed device applications due to reduced interface carrier scattering. The results of sample G (in Table I) and Fig. 2(b) have shown that the FME growth technique with appropriate V/III ratio can rapidly generate periodic 90° misfit dislocations at

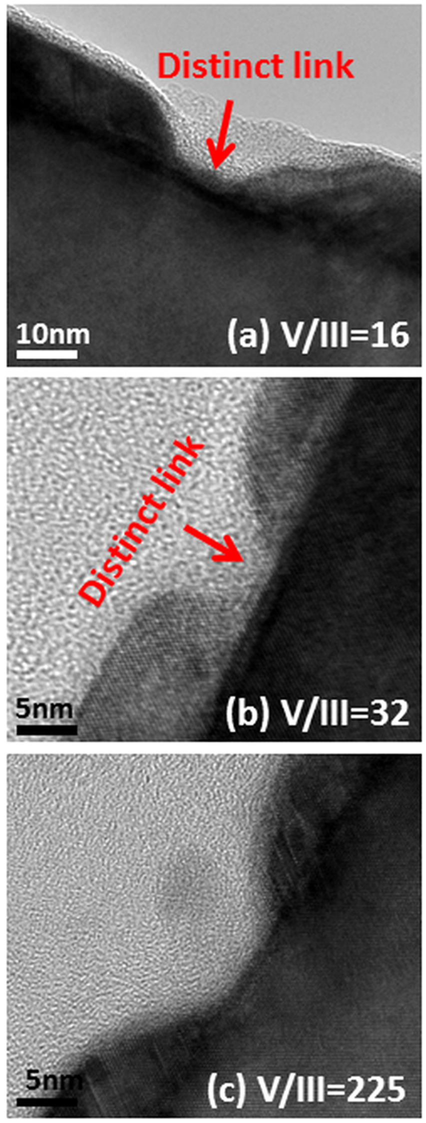

FIG. 6. (Color online) TEM images of the InAs epitaxy with different V/III ratios on a GaAs/Ge heterostructure; (a) V/III: 16, (b) V/III: 32, and (c) V/III: 225.

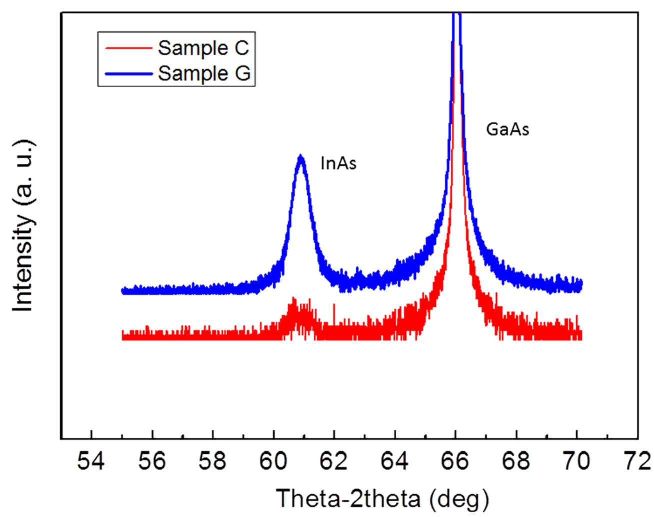

FIG. 7. (Color online) XRD analysis results of the InAs epitaxy without FME (sample C) and with FME (sample G) on a GaAs/Ge heterostructure.

the interface, reducing the surface roughness from 4.5 nm (sample C) to 1.5 nm. Figure 7 illustrates XRD analysis results of InAs thin films with and without FME on the GaAs/Ge heterostructure. The strong XRD peak at about 66° (2θ) is the GaAs/Ge heterostructure, and the InAs peak position is about 61°. The InAs peak of sample G is sharper than that of sample C. This seems to indicate that the crystal quality of InAs epitaxy with periodic 90° misfit dislocations (sample G, FWHM: 500 arc sec) was much better than sample C without FME.

IV. CONCLUSIONS

We have demonstrated that, as compared with traditional growth technique,[3,4] very thin (40 nm) and smooth (1.5 nm) InAs films can be grown directly on GaAs/Ge heterostructures by MOCVD. Under optimum growth parameters, periodic 90° misfit dislocations can be generated at the InAs/GaAs interface to relax the misfit strain (strain relaxation ~ 90%) during the InAs/GaAs/Ge heterostructure growth. We also found that the 90° misfit dislocation formation was closely related to the In atom distribution at the interface when the InAs epitaxial thickness exceeded a critical thickness. Uniform In coverage above the wetting layer promoted the formation of 90° misfit dislocations and produced a stable interface between the GaAs and InAs epitaxial layers. These results demonstrate that high-relaxation InAs epitaxy with periodic 90° misfit dislocations effectively reduces the difference between the surface energy and strain energy during growth, promoting the formation of an InAs thin film on a GaAs/Ge heterostructure. In addition, we also demonstrated that a tightly controlled V/III ratio improves the quality of InAs islands grown on the GaAs/Ge heterostructure; however, it is not the only key factor controlling InAs thin-film growth.

ACKNOWLEDGMENTS

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