Two crucial factors influencing quality of GaAs on Ge substrate

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High-quality GaAs films with fine surfaces and GaAs/Ge interfaces on Ge have been achieved via molecular beam epitaxy. The influence of low temperature annealing and low temperature epitaxy on the quality of the film when GaAs is grown on a (100) 6° offcut towards [111] Ge substrate are investigated by analyzing and comparing the GaAs films that are fabricated via three different processes. A low temperature annealing process after high temperature annealing and a low temperature epitaxy process after the initial GaAs growth play a vital role in improving the quality of GaAs film on a Ge substrate.

Keywords: molecular beam epitaxy, low temperature annealing, low temperature epitaxy

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1. Introduction

Recently there has been a growing research interest in GaAs and Ge metal–oxide–semiconductor (MOS) transistor structures because of their superior semiconductor properties. GaAs and Ge are intrinsically faster semiconductors than Si because of their higher bulk mobilities. In particular, the integration of Ge positive channel metal–oxide–semiconductor (PMOS) with GaAs negative channel metal–oxide–semiconductor (NMOS) is a very attractive replacement for fast Si complementary metal–oxide–semiconductor (CMOS) structures.[1–4] The drive current of the meta–oxide–semiconductor field effect transistor (MOSFET) can be greatly improved by III–V semiconductor material with high electron mobility for the channel. A high-quality GaAs film grown on Ge subsrtare is the main subject of these researches. A GaAs film deposited on Ge substrate via heteroepitaxial growth can be used to fabricate high-efficiency solar cells with light weight, large area, and low cost.[5] In addition, the GaAs/Ge heterostructure is suitable for fabricating a quantum well field effect transistor with p-type channel,[6] photoelectric detector,[7] temperature sensor,[8] device with quantum restriction,[4,9–11] etc.

Although GaAs and Ge have almost the same lattice constants and thermal coefficient of expansion, GaAs is a type of polar semiconductor while Ge is a non-polar semiconductor. When GaAs is deposited on a Ge substrate, measures must be taken to avoid forming an anti-phase domain (APD) which is a very common phenomenon in polar-on–non-polar epitaxy.[12,13] A surface with a mass of double-atom steps that can prevent the APDs from forming effectively on a (100) 6° offcut towards [111] Ge substrate can be obtained by high temperature annealing, but for a high-quality GaAs film a lot of optimization work still needs to be done.[14–17] In addition, the mutual diffusions of the three atoms in the interface cannot be ignored in the case of high epitaxial temperature.[16]

In this work, we investigate the influence of the low temperature annealing and low temperature epitaxy on the quality of the film when GaAs is grown on a (100) 6° offcut towards [111] Ge substrate via three different processes. We find significant differences in GaAs quality among the GaAs films that are prepared in these three ways. The goal of the present study is to show that the low temperature annealing process and low temperature epitaxy process are necessary in order to obtain a high- quality GaAs film on Ge.

2. Experiment

Three Ge (100) substrates (referred to as sample I, sample II, and sample III, respectively) with the same offcut orientations (6° offcut towards [111]) were loaded into a Thermo Semicon V90 MBE system. After pretreatment in an intro-chamber and a buffer chamber under the same conditions, the Ge substrates were all deoxidized by increasing the substrate temperature (440 °C) in the growth chamber, and then covered a GaAs film with the same thickness (700 nm) by means of three different procedures.

Figure 1 shows the three procedures of the Ge substrates in the growth chamber (Fig. 1(a), Fig. 1(b), and Fig. 1(c), respectively, corresponding to sample I, sample II, and sample III). Compared with Fig. 1(a), figure 1(b) replenishes a low temperature epitaxy process, and with Fig. 1(b), figure 1(c) replenishes a low temperature annealing process. After optimization, T_1, T_2, T_3, T_4, and T_5, severally, equal 680 °C, 650 °C, 350 °C, 500 °C, and 620 °C. It must be pointed out that AsH_3 is indispensable in the low temperature annealing process.

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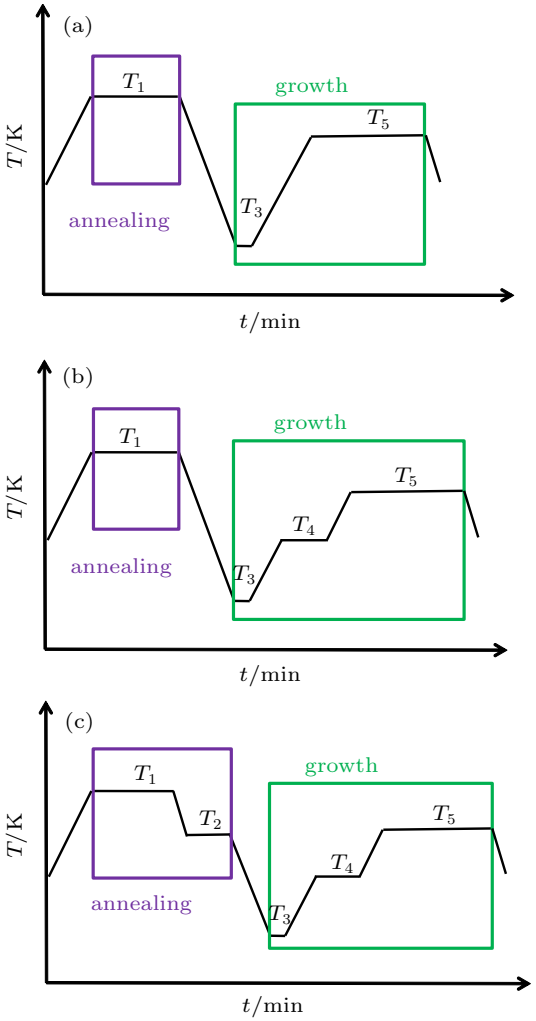


Fig. 1. (color online) Processes of sample I (a), sample II (b), and sample III (c) in the growth chamber; T_1 and T_2 denote the annealing temperatures, and T_3, T_4, and T_5 represent the growth temperatures.

The density of the oval defects and the roughness of surface are significant evaluation criteria of the quality of the GaAs layer.[18–20] Atomic force microscope (AFM) is used to measure the morphologies of the samples in the contact mode. The crystalline qualities of the films and the mutual diffusions of the three atoms (Ge, As, and Ga) in the interface are investigated by four-crystal X-ray diffraction (XRD), transmission electron microscope (TEM), and secondary ion mass spectroscopy (SIMS).

3. Results and discussion

The AFM-images (Fig. 2) for a 10 μm × 10 μm scan field show the surface morphologies of the three samples. Sample I with an unsatisfactory surface roughness (RMS = 5.55 nm) is obviously much more unsmooth than sample II (RMS = 0.83 nm) and sample III (RMS = 0.24 nm). There are three kinds of GaAs growth patterns on Ge: Frank-van der Merwe mode (FM), Volmer–Weber mode (VW), and Stranski–Krastanow mode (SK), among which the FM mode is expected. Without a low temperature epitaxy process, GaAs, as sample I, is deposited on Ge in the SK mode, which results in a rough surface morphology. However, smooth surfaces are obtained in the FM mode, as shown in sample II and sample III.

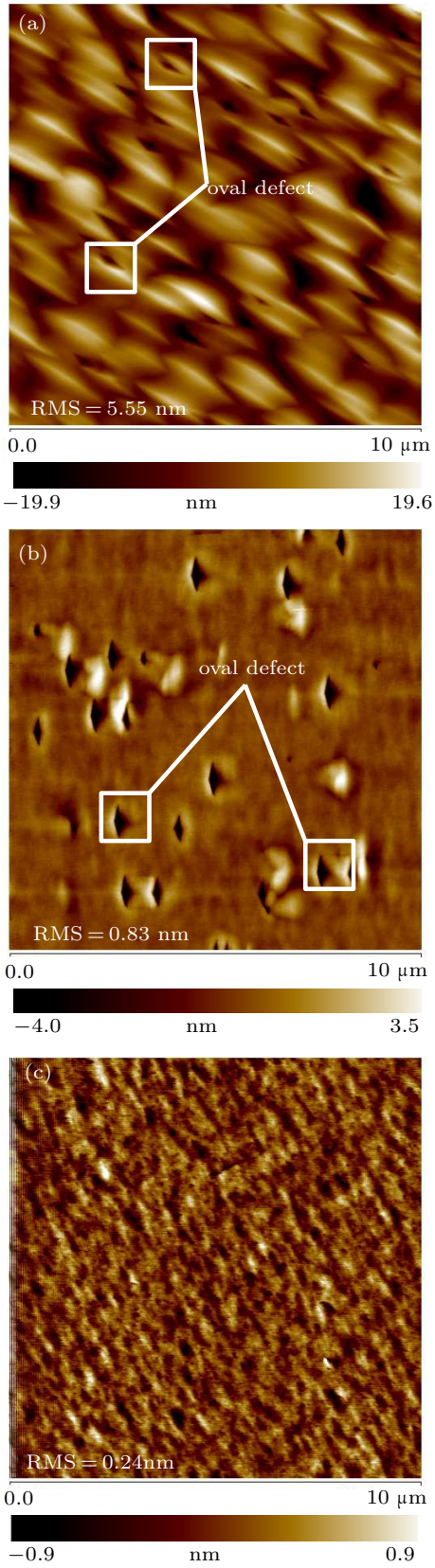


Fig. 2.(color online) AFM-images (10 μm × 10 μm) of the GaAs surface for (a) sample I, (b) sample II, and (c) sample III.

During the deposition of thin films, different growth modes can occur, depending on the change of the total energy ($\Delta\gamma$) of a surface before and after deposition. This can be described by the following equation:

$$\Delta\gamma = \gamma_{\rm F} + \gamma_{\rm S/F} - \gamma_{\rm S}, \tag{1}$$

where $\gamma_{\rm F}$ is the surface energy of the film, $\gamma_{\rm S}$ is the surface energy of the substrate, and $\gamma_{\rm S/F}$ is the interface energy between the film and the substrate. This equation characterizes the interaction between the substrate and the adsorbates. Two limiting cases can be considered: first, the interaction between the substrate and the adatoms is much higher than the interaction between the adatoms, that is $\Delta\gamma > 0$, resulting in a layer-by-layer growth mode or FM growth. Second, if the adatoms are more strongly bound to each other than to the substrate, $\Delta\gamma < 0$, three-dimensional islands will form on the surface. This is called island growth or VW growth. An intermediate case is the SK growth mode, where FM is combined with VW and SK comes into being. At an early time, $\Delta\gamma < 0$, GaAs is deposited on Ge layer by layer. Subsequently, $\Delta\gamma > 0$, the growth pattern turns into VW.[21] The low temperature epitaxy process can keep $\Delta\gamma < 0$, and then GaAs is deposited on Ge in the FM mode.

Sample II owns a barely accepted surface roughness compared with sample III, but has a high density of 2.0×10^{17} cm^{-2} (much higher than 1.0×10^{16} cm^{-2}) of the oval defects which originate from the anti-phase domains (APDs). This shows that the surface of the Ge substrate of sample II needs to be further improved before the GaAs epitaxy. The offcut Ge (100) substrates with an appropriate offcut angle (6° offcut towards [111]) can lead to not only double-atom steps but also single-atom steps on the surface.[22] During high temperature annealing, the Ge atoms have higher thermal active energies to enable them to move from non-double-atom step sites to appropriate sites to form double-atom steps, but only for such a process can a non-defective epitaxial layer not be obtained.[22,23] Meanwhile, a low temperature annealing process with AsH_3 can impel the reconstruction of Ge surface to form double-atom steps and ameliorate the surface. As shown in Fig. 2(c), there is no oval defect in such an 10 μm × 10 μm area, which means that the density of the oval defects is less than 1.0×10^{16} cm^{-2}.

The APDs originate from the single-atom-steps of the Ge substrate surface. Figure 3 shows the cross-sectional TEM images of sample II (Figs. 3(a) and 3(c)) and sample III (Figs. 3(b) and 3(d)). From the figure, the flat GaAs/Ge interface and the APDs can be observed. As mentioned above, sample II shows a higher surface defect density that is derived from the high APD density in Figs. 3(a) and 3(c), but no defect can be found in sample III, as shown in Figs. 3(b) and 3(d) for the low temperature annealing process. This demonstrates that the surface of the Ge substrate is further improved after the low temperature anneling process.

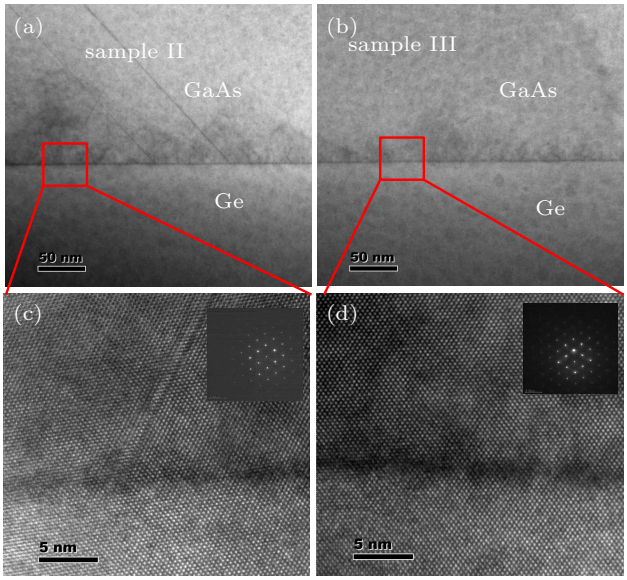


Fig. 3. (color online) TEM images of sample II ((a) and (c)) and sample III ((b) and (d)).

The normalized XRD diffraction curves (radian measure) of sample II and sample III are shown in Fig. 4. The peaks at $\omega/2\theta = 0$ s are caused by Ge substrate and peaks at $\omega/2\theta =$ 150 s by the GaAs films. Distinctly, sample II and sample III possess the subequal half-widths of the Ge substrates (23.06 s for sample II and 25.14 s for sample III), but differ in the GaAs films. Sample III obtains a much smaller half-width (32.85 s) than sample II (40.12 s), which demonstrates that sample III owns higher crystalline quality GaAs film than sample II.[24]

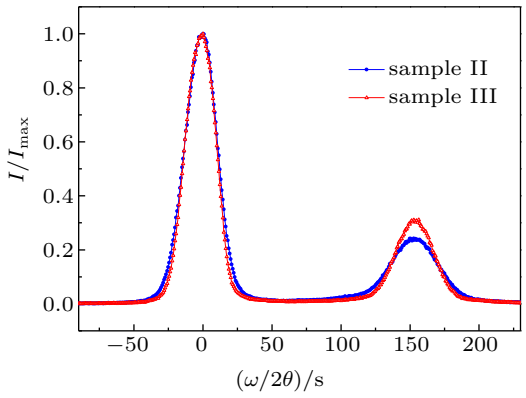


Fig. 4. (color online) Diffraction curves of XRD (004) intensity versus $\omega/2\theta$ of sample II and sample III.

The secondary ion mass spectroscopy (SIMS) profile of sample III is obtained. The Ge profiles, shown in Fig. 5, drop down below the SIMS sensitivity limit of $\sim 3 \times 10^{16}$ cm^{-3} in less than 30 nm which illustrates that the mutual diffusions of the three atoms (Ge, As, and Ga) in the interface are well restricted. For such a 700-nm GaAs film on Ge, the diffusion of Ge atoms in 30 nm does not cause the performance of the device to have any change.

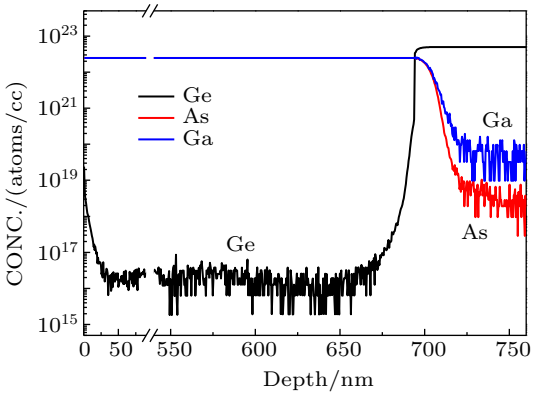


Fig. 5. (color online) SIMS profiles of sample III.

4. Conclusion

The GaAs films grown on Ge substrates via different processes are investigated. A low temperature epitaxy process after the initial GaAs growth plays an essential role in keeping GaAs growth in the FM mode, which is expected, and greatly reduces the roughness of the GaAs surface. A low temperature annealing process after high temperature annealing is found to be a key element in improving the substrate surface to avoid APDs and reducing the density of the oval defects on GaAs surface. High-quality GaAs films with fine GaAs/Ge interfaces on Ge can be obtained by optimizing the growth conditions. Consequently, the low temperature annealing process and low temperature epitaxy process are indispensable to obtain a high-quality GaAs film on Ge. These results provide reference for future research.

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