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Transmission electron microscopy studies of GaAs nanostructures in InGaAs/InP matrix grown by molecular beam epitaxy

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Self-assembled GaAs nanostructures in $In_{0.53}Ga_{0.47}As$ matrix on (100) InP substrate have been investigated using atomic force microscopy (AFM) and cross-sectional transmission electron microscopy (XTEM). In measured AFM images, dotlike and wirelike GaAs nanostructures were obtained with different deposition thicknesses. The XTEM images clearly showed composition modulation in the overgrown InGaAs matrix. The reason for this composition modulation is explained by strain field compensation and surface energy minimization. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2345031]

I. INTRODUCTION

Semiconductor nanostructures, such as quantum wells, quantum wires, and quantum dots, have attracted much attention in recent years. In these structures, carrier confinement and their energy quantization make them interesting in both physics and device applications. The inverse of these structures, quantum antidots and antiwires, also pose interesting physics but are seldom studied. Several interesting phenomena related to antidots[1–3] and antiwires[4,5] have been observed. However, in these studies, most of the nanostructures were fabricated using external processing techniques, such as e-beam lithography and focused ion beam, or defined with biased metal gates. By depositing a few monolayer GaAs in InAs matrix, the self-assembled growth of antidots was reported.[6] On the other hand, using $In_{0.53}Ga_{0.47}As$ as the matrix material, self-assembled antiwires grown on InP substrate was observed by us recently.[7] In this paper, the cross-sectional transmission electron microscopy (XTEM) characterizations of these GaAs nanostructures in $In_{0.53}Ga_{0.47}As$ matrix will be discussed in detail. Comparing with the case of $In_{0.5}Ga_{0.5}As$ quantum dots (QDs) in GaAs matrix on (100) GaAs substrate, the lattice mismatch between GaAs and $In_{0.53}Ga_{0.47}As$ is about the same but with opposite sign. Hence, it is not difficult to imagine that the elastic energy increases with the deposition of GaAs and then a transition into three-dimensional (3D) morphology must happen in a certain thickness. However, as we have seen previously,[7] although the 3D transition did happen, the morphology of the growth surface behaved quite differently from that of $In_{0.5}Ga_{0.5}As$ QDs on GaAs. Wirelike and dotlike GaAs nanostructures were formed on $In_{0.53}Ga_{0.47}As$ surface at different deposition amounts.

II. SAMPLE GROWTH

The samples were grown on (100) InP substrates by a solid-source Varian Gen II molecular beam epitaxy (MBE) system equipped with an arsenic cracker cell. After the desorption of native oxide at 515 °C under arsenic flux, a 500 nm $In_{0.53}Ga_{0.47}As$ buffer layer was deposited at a rate of 0.9 μm/h before the growth of GaAs nanostructure. According to the measured x-ray diffraction result, the lattice mismatch between the InP substrate and the grown $In_{0.53}Ga_{0.47}As$ buffer layer was less than 0.2%. To understand the evolution of surface morphology by using atomic force microscopy (AFM), several uncapped samples with different numbers of monolayers (MLs) of GaAs were grown under the same growth condition. After GaAs deposition, the uncapped sample was cooled down under arsenic flux. The III/V beam equivalent pressure ratio, the growth temperature, and the growth rate for the GaAs deposition were 10, 500 °C, and 0.1 μm/h, respectively.

III. RESULTS AND DISCUSSIONS

Figure 1 shows the AFM images of the grown samples with 2–6 ML of GaAs. The measurement was performed with the tapping mode by a DI-5000 AFM system in the air. From the image in Fig. 1(a), a nearly flat surface (surface roughness ~0.3 nm) morphology was seen for 2 ML GaAs deposition. Although there is no clear 3D morphology observed in this AFM image, stripe-shape traces somehow emerged. This can be seen clearly in the XTEM image which will be presented hereafter. When the thickness of the deposited GaAs increased to 3 ML, the morphology changed significantly. As shown in Fig. 1(b), a clear wirelike structure was formed. The periodic, wirelike pattern formed along [110] direction with a period around 23 nm. The height of the wires was between 1.2 and 2.0 nm. When the coverage of GaAs increased beyond 3 ML, the wirelike morphology transformed gradually into separate islands with anisotropic shape and distribution, as shown in Figs. 1(c)–1(e).

To get a clearer picture of these GaAs nanostructures, another sample was grown under the same growth condition, which included GaAs from 2 to 7 ML with 1 ML increment. The spacer between each GaAs layer was 50 nm InGaAs. To obtain a clear image, special care was taken in the TEM sample processing to reduce the indium clusters re-deposited

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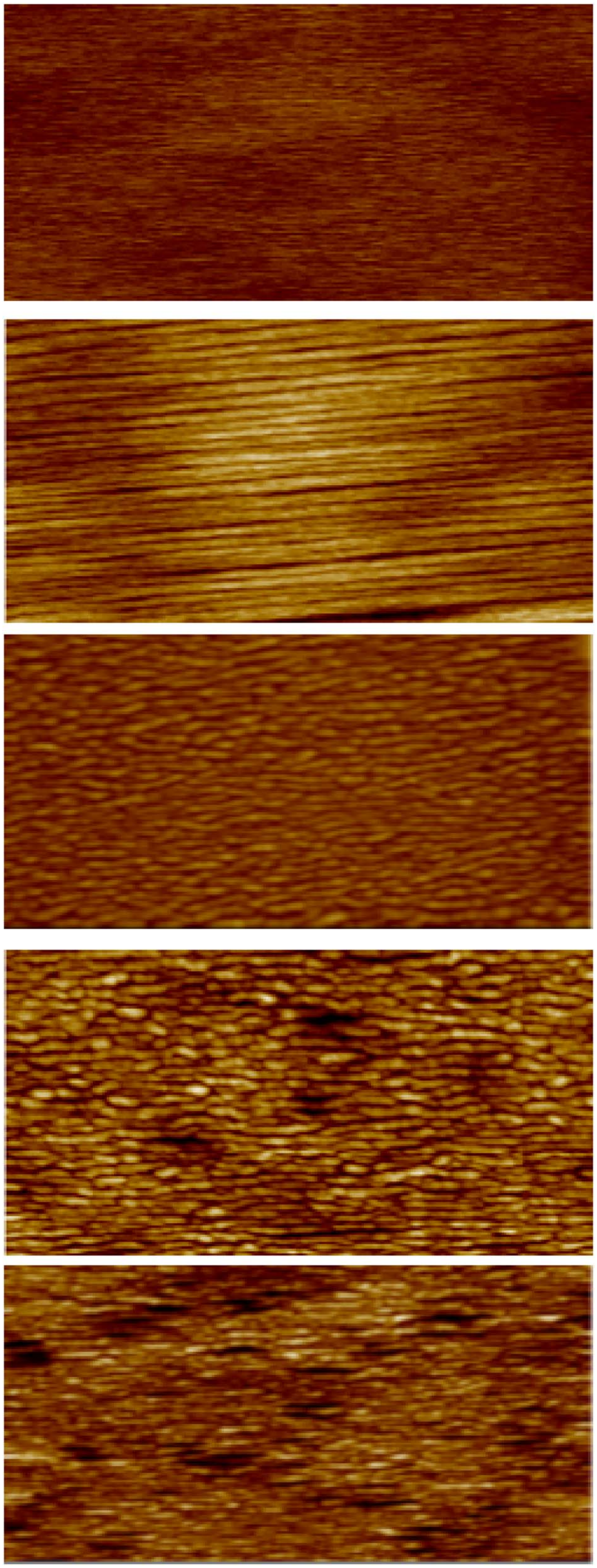

FIG. 1. (Color online) The AFM images of the samples with 2, 3, 4, 5, and 6 ML of GaAs, from the top to the bottom (image size: 1×0.5 μm^2).

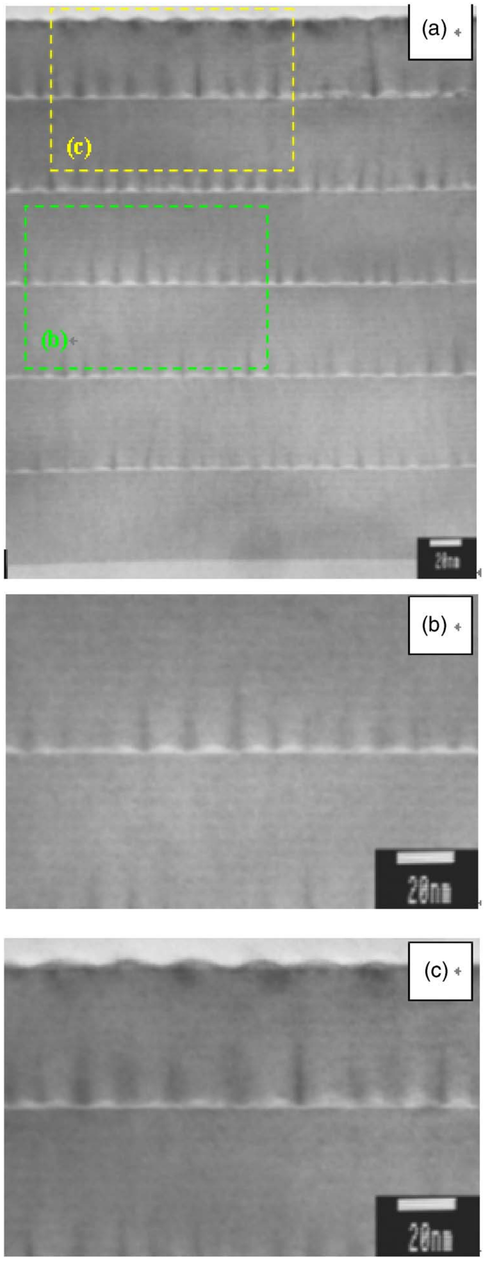

FIG. 2. (Color online) (a) The TEM image of the sample with 2–7 ML GaAs, from the bottom to the top. (b) The magnified picture of the 4 ML GaAs layer. (c) The magnified picture of the 6 and 7 ML GaAs layer.

and contaminated the sample by not using any ion milling during sample thinning. Alternatively, we used a mixture solution of CMP slurry for III-V materials (Rodel Nalco 2350) and diluted hydroperoxide to obtain a transparent foil. The images were taken in a JEOL electron microscope JEM-2010 with beam energy of 200 kV. Figure 2(a) shows the cross-sectional, bright-field TEM image seeing through [110] direction, that is, perpendicular to the wires' direction. Several important features are clearly seen here. First, there are six GaAs layers (the bright thin layers), including the uncapped one on the top, formed in InGaAs matrix (the dark spacers). As each layer contains a different amount of deposited GaAs (from 2 to 7 ML), the progressive change reveals the growth mechanism. If one takes a close look at the shape of the 2 ML GaAs layer, one can find that the growing surface has shown a 3D morphology already. Wirelike GaAs nanostructures had developed at this stage, although it could not be clearly seen in the AFM image above. Comparing these GaAs layers, one can see that the periodic wave form was more perfect on 3 and 4 ML layers, which is consistent with

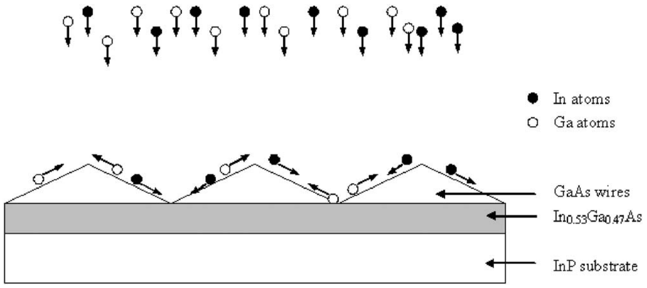

FIG. 3. A schematic figure showing the InGaAs composition modulation on the surface of grown GaAs nanostructures.

the AFM observations. After 3–4 ML growth, some subsequently deposited GaAs went to the valley between the previously formed GaAs wires, and then the periodicity became worse and worse.

Second, from this TEM picture, there are dark lines located between GaAs wires, which go along the growth direction with a length of 10−30 nm. To make the dark lines more visible, one magnified image taken from the 4 ML GaAs layer in Fig. 2(a) is shown in Fig. 2(b). We believe that these dark lines were indium-rich regions rather than caused by the strain field, because the image was taken carefully with the tilting procedure to enhance the compositional contrast.[8] The reason for the formation of these In-rich regions will be stated as follows. Accompanying the formation of GaAs nanostructures, the strain around the top of GaAs relaxed. It can be thought as that the lattice constant around the top of GaAs nanostructures is closer to that of GaAs but that around the valley is closer to that of $In_{0.53}Ga_{0.47}As/InP$. The subsequently deposited In and Ga atoms would see the difference and behave accordingly to minimize the total energy. To reduce the elastic energy due to lattice mismatch, In atoms migrate to the valley of GaAs nanostructures, as shown in Fig. 3 schematically. For the same reason, Ga atoms tend to move to the top of GaAs nanostructures. However, as the diffusion length of Ga is much shorter than that of In at this temperature, only the accumulation of In around the valley happened and thereby the In-rich regions were observed.

There is one more thing which is worth mentioning in the TEM image shown in Fig. 2(a). The top layer with 7 ML GaAs on the surface has a clear difference from other layers, which can be seen more clearly in the magnified picture in Fig. 2(c). The strain induced dark regions located just underneath the uncapped GaAs nanostructures, which do not appear in other capped GaAs layers. We believe that this is because in other layers, the strain was relaxed through the composition modulation of overgrown InGaAs as mentioned above. For the layer of 7 ML GaAs on the surface, there is no subsequent InGaAs, so the strain field stayed underneath the GaAs nanostructures. Based on these TEM results, we can get a clearer picture of the GaAs nanostructure growth. After the GaAs nanostructures are formed, the strain builds up in the InGaAs under the GaAs layer. And then this strain field and the surface construction of GaAs nanostructures cause the composition modulation of the postgrown InGaAs matrix.

IV. CONCLUSION

In conclusion, growth of GaAs nanostructures in $In_{0.53}Ga_{0.47}As$ matrix on InP substrates has been studied. AFM and cross-sectional TEM images reveal the details of these GaAs nanostructures. Composition modulation of the overgrown InGaAs was observed and its reason has been explained. As we have seen in this report, in the growth of GaAs nanostructures, the strain field due to lattice mismatch can play a key role in growth and, even more importantly, for structure engineering.

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