Formation of GaAs hollow above InAs quantum dots

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ABSTRACT

GaAs hollow nanostructure is constructed above low-temperature (250 °C) InAs quantum dots after a thin GaAs layer capping at 480 °C. The hollows mostly disappeared after the high temperature annealing at 580°C. The formation mechanism is simply discussed.

Keywords: micro hollow, nanostructure, InAs QDs, MBE

1. INTRODUCTION

Great efforts are made in the construction of microstructures in nano scale in past decades. Many positive microstructures like bars, grains, and some complicated structures studied earlier were constructed on semiconductor thin films. The negative structures like tubes and hollows also attracted intensive attention for their unique character contrast to the positive structures. However, it is seldom reported about large amount of self-assembled hollows on high quality GaAs thin films.

Recently we had successfully constructed self-assembled InAs quantum dots (QDs) on GaAs substrates by molecular beam epitaxy (MBE) at low temperature (LT: 250 °C) [1]. The LT InAs QDs are supposed to be of both high optical nonlinearity [2-5] and fast responsibility [6-7]. We noticed the formation of micro hollows after a thin capping layer at moderate temperature (MT: 480°C) above the LT InAs QDs, which are no longer observed after a high temperature (HT) annealing procedure at 580 °C. This phenomena also happened for the samples grown on GaAs(311)A&B substrates. The observation thus inspires our interest to carry on a more comprehensive study of these hollows.

2. GROWTH DETAIL AND CHARACTERIZATION

A solid-source MBE system is used for the epitaxial growth of samples. The GaAs and InAs growth rates were 0.15 and 0.04 nm/s, respectively, and the As_4 beam equivalent pressure was 1.0×10^{-5} torr. The layer sequences were initiated by a 500 nm GaAs buffer layer at 580 °C followed by a 500 nm at LT (250 °C) grown GaAs bottom layer. For the formation of Stranski-Krastanov (SK) QDs, 2 monolayers (MLs) InAs were deposited at LT (250 °C) on the LT GaAs bottom layer, then annealed for several minutes at MT (480 °C) before a 3 nm thin GaAs inter-layer was grown at the same temperature. The observation on samples terminated at this moment exhibited a number of hollow nanostructures. The samples then experienced the 580 °C annealing for further LT GaAs overgrowth of LT GaAs, after which the hollow nanostructures disappeared, and most large InAs clusters are believed to evaporate, keeping the InAs dots under the thin film GaAs interlayer safely. The morphological characterization is carried out by high sensitivity atomic force microscopy.

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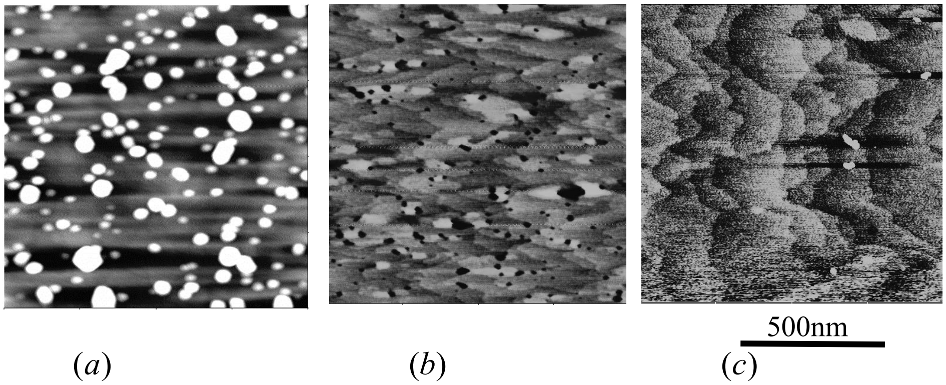

Figure 1 (a) AFM images of the SK-InAs QDs on GaAs (100), height contrast 10 nm; (b) corresponding micro hollows after thin film capping at MT (480°C); and (c) the smooth terrace MLs structure after high temperature at HT(580°C), height contrast 1nm.

3. RESULTS AND DISCUSSION

For the samples grown on GaAs (100), Fig.1 (a) shows the atomic force microscopy (AFM) images of the LT-InAs QDs, (b) with thin GaAs capping at 480 °C and (c) after the annealing at 580 °C. The LT-InAs QDs on GaAs (100) in Fig. 1(a) are characterized by 30 nm × 50 nm ± 25 % lateral size, 2.2 nm average height, and 1.5×10^{10} cm $^{-2}$ density. Additionally there are large clusters of much lower density. Similar LT-InAs dots structures were also obtained on GaAs (311) A&B substrates. The comparison of samples grown on different substrates showed that the orientation has only minor influence on the formation of the LT-InAs QDs. Figure 1(b) showed that the flat surface is randomly distributed with some micro hollows varied in size with a typical diameter of 20 nm. These hollows no longer existed after high temperature annealing, as shown in Fig. 1(c), and the surface becomes flat with extended terraces and ML-high steps. We assumed that the large InAs clusters among LT-InAs QDs have undergone an evaporating sequence during the high temperature annealing. A simple analysis gives us a clue that these hollows may be related to and probably locates on the positions of those large InAs clusters.

Figure 2 shows the AFM images of the corresponding morphologies with thin-film capping (a)&(c) and after high temperature annealing (b)&(d) for samples grown on GaAs (311) A&B. Similarly, nano hollows are observed before HT annealing, however, of larger sizes and lower densities. The hollows on the samples grown on GaAs (311) B exhibited the largest dimension and the roughest edges, and the lowest density, as shown in Fig. 2(a)&(c). After HT annealing, the GaAs (311) A surface (Fig.2 (b)) exhibits an anisotropically (along [-233]) faceted morphology, which is a typical feature for this orientation [8], whereas the GaAs (311) B surface (Fig. 2(d)) is smoother except of a few big hollows.

A similar microstructure on high temperature InAs QDs was reported by D. Granados et al [2]. They fabricated a so-called quantum ring (QR) nanostructure by MBE with As_2 source, and explained the fabrication by a list of mechanisms. Schematically, when the InAs QDs are partially covered and compressed, the QDs undergo a transition into liquid phase, changing the InAs QDs into droplets. After the capping, the imbalanced state of tensions around the InAs droplet produces ejection of material out of the center of each QD. However, it is also necessary to consider that the In(Ga)As alloying process presented in such a procedure, which may reduce the mobility and trends to avoid the formation of a crater at high substrate temperature (540°C). QR formation temperature at 500°C, is close to the MT we used to fabricate the hollow structure. However, in our case, there is no necessary to adopt As_2 for successful formation of micro hollows, and the LT InAs QDs are of a little thinner dimension (around 5nm) than the necessary height (≥7nm) to obtain efficiently a depleted central region for the growth of QRs.

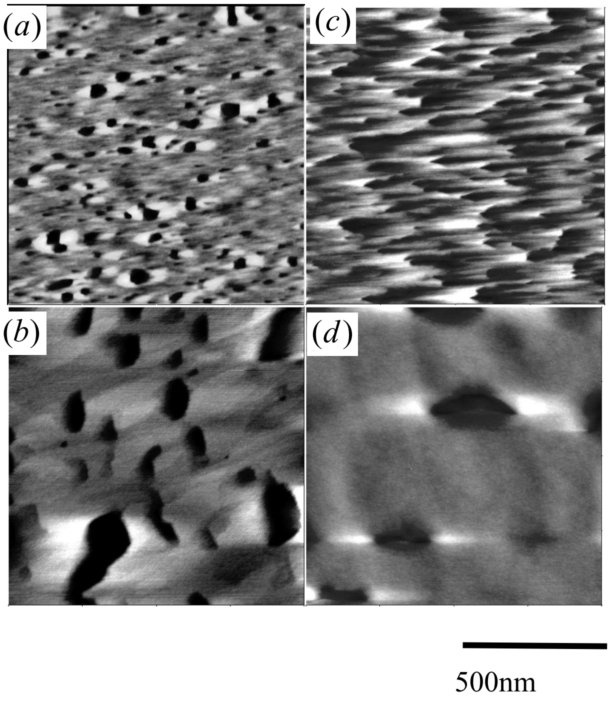

Figure 2 AFM images of the LT InAs QDs overgrown by 3 nm GaAs at MT before HT annealing on (a) GaAs (311)A, height contrast 5 nm; and (c) GaAs (311)B, height contrast 5nm; and after HT annealing on (b) GaAs (311)A, height contrast 5nm; and (d) GaAs (311)B, height contrast 5nm.

Thus, the formation mechanism of micro hollows is to be investigated, which can probably be attributed to several factors, including those considered by D. Granados et al. Typically in our case, low temperature epitaxial growth of GaAs buffer, and LT InAs quantum dots might have greatly affected the formation of micro hollows. As mentioned above, the annealing procedure after capping, and the adoption of As_2 sources are not necessary for the epitaxial growth of micro hollows. Anyway, the surface exhibits microstructures of different patterns (hollows vs rings). The influence of hollows on the quality of low temperature InAs quantum dots, and the complete effect of the high temperature annealing, certainly require much further investigation as well.

4. CONCLUSION

GaAs hollow nanostructures on different GaAs substrates are constructed above low-temperature (250 °C) InAs quantum dots after a thin GaAs layer capping at MT (480 °C). The hollows patterns differ little among samples on different orientation, and mostly absented after the high temperature annealing at HT (580°C). Their formation mechanism is simply discussed and partially attributed to the strain effects and the low temperature grown material. This method of forming GaAs hollows adopting LT growth is possibly a technique to manufacture the quantum scale micro hollow structure in a more general concept.

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