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Control of Self-Formed GaAs Nanoholes Combined with InAs Quantum Dots

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1. Introduction

Recent progress in nano-fabrication technologies has enabled some constructions of quantum-dot (QD) devices and some studies of fundamental physics in zero-dimensional electron system. However, it is very difficult to fabricate metal-electrode wires for contacting with high-density-QDs, embedded in the semiconductor matrix. The electrode with a nano-scale size should be prepared closely to embedded QDs for precise control of the carrier injection and high injection efficiency. Recently, we have demonstrated self-formation of GaAs nanoholes combined only with embedded InAs QDs [1]. In this technique, GaAs nanoholes are naturally formed on embedded InAs QDs without lithography and etching processes.

In this paper, we present this self-formation technique of GaAs nanoholes and will discuss about the formation mechanism and control of the nanohole size.

2. Experimental

The samples were fabricated by conventional solid-source molecular beam epitaxy (MBE). A 200-nm-thick GaAs buffer layer was deposited on the GaAs(001) substrate at 590°C, and then the substrate temperature was rapidly cooled down to 500°C for the InAs growth. As reported previously, uniform InAs QDs were grown by using Stranski-Krastanov (SK) mode under low growth rate (0.035 monolayer (ML)/s) and low arsenic pressure (3×10^{-7} Torr) conditions [2]. Following the InAs-QD growth the 10-nm-thick GaAs capping layer was grown at 450°C. After the capping growth, GaAs nanoholes were formed only by thermal annealing process in the MBE chamber. The annealing temperature was 500-550°C.

GaAs nanoholes fabricated by annealing were analyzed by using atomic force microscopy (AFM) and high angle annular dark field (HAADF)-scanning transmission electron microscopy (STEM).

3. Results and discussion

Figure 1 shows AFM images of the 10-nm-thick GaAs capping layer before (a) and after annealing at 500°C for 5 min (b). GaAs nanoholes were spontaneously formed only by annealing process. Nanohole density of 3×10^{10} cm^{-2} coincided with density of InAs QDs. Figure 2 shows the (110) cross-sectional HAADF-STEM image of the GaAs nanohole and the embedded InAs QD after the annealing. It is clearly found that GaAs nanoholes are formed just above embedded InAs QDs. The GaAs capping layer accumulates tensile strain due to the InAs QD. In particular, the GaAs layer on the InAs QD is more energetically unstable. Therefore, in case of a thin GaAs capping layer (less than about 12 nm), the thermal annealing process induces desorption of unstable GaAs molecules from the capping layer just above InAs QDs. This self-formation process is expected for convenient techniques of contact nanoholes and nano-markers of embedded QDs.

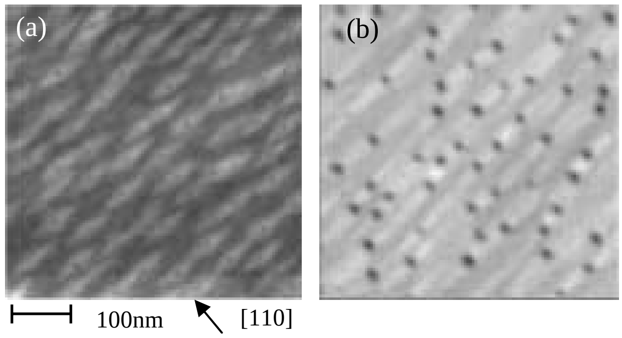

Fig.1. AFM images of the GaAs capping layer before annealing (a) and after annealing (b).

The nanohole size could be controlled by adjusting the anneal condition and thickness of the capping layer. Figure 3(a) shows the lateral size and depth of GaAs nanoholes as a function of the annealing time. As the annealing time increases, the nanohole size enlarges and then saturates. Since the formation of the nanohole provides relaxation of the strained GaAs capping layer, desorption of unstable GaAs will be suppressed: the nanohole size will saturate.

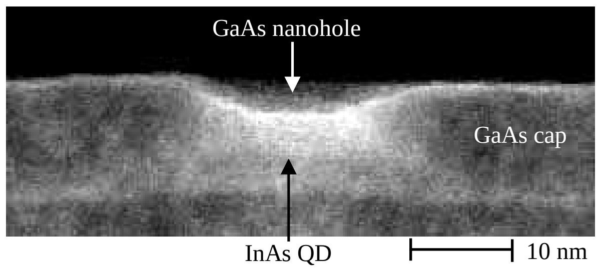

Fig.2. (110) cross-sectional HAADF-STEM image of InAs QD and GaAs nanohole after annealing.

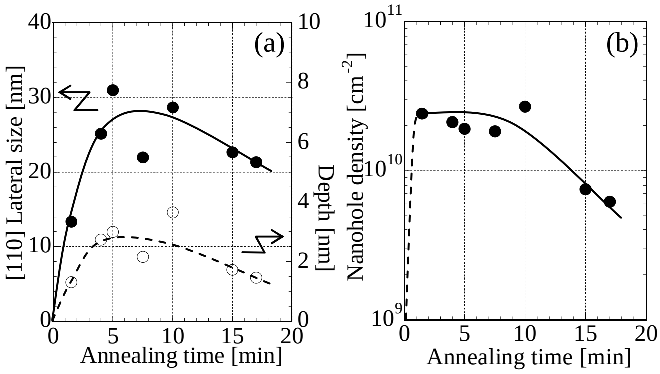

Fig.3. GaAs nanohole size (lateral size and depth, (a)) and nanohole density (b) as a function of annealing time. Annealing temperature was 500°C.

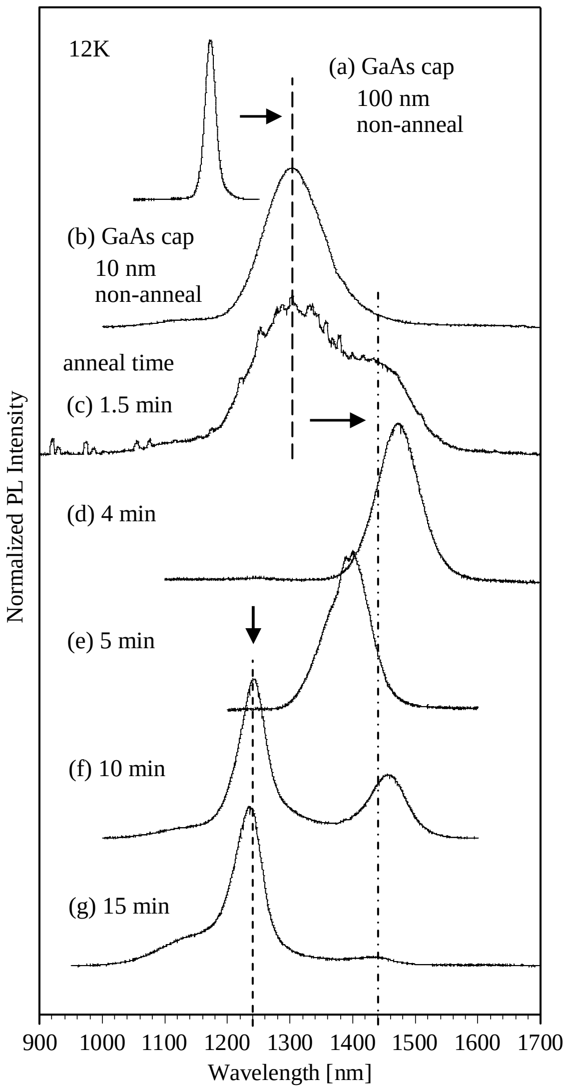

Fig.4. Low-temperature (12K) PL spectra of InAs QDs embedded in the 10-nm-thick GaAs layers as a function of annealing time. Annealing temperature was 500 °C. PL spectrum of (a) was obtained from InAs QDs embedded in the 100-nm-thick GaAs layer without annealing.

Here the bottom of the nanohole reaches the top of the InAs QD, as shown in Fig. 2. Thereby, it is possible that unstable InAs molecules are slightly desorbed from the QD. When the annealing time is longer than about 10 min, the nanohole size decreases. In addition, nanohole density also decreases for more than 10 min, as shown in Fig. 3(b). It means disappearance of the nanohole (i.e. the re-embedding growth on the nanoholes) during the long annealing.

Figure 4 shows low-temperature PL spectra of InAs QDs as a function of the annealing time. The PL spectrum of InAs QDs embedded into the 10-nm-thick GaAs layer (b) appears at the low energy side, as compared with that embedded into the 100-nm-thick GaAs layer (a). It is due to the weak compressive strain for the thin GaAs capping layer. After the nanohole fabrication, the PL peak more shifts toward the low energy side (c, d, e) because of the strain relaxation. However, when the annealing time is longer than about 10 min, the PL peak intensity of about 1440 nm decreases, and a new PL peak instead appears at about 1240 nm (f, g). As mentioned at Fig. 3(b), nanohole density decreased for more than about 10 min in the annealing time. Therefore, it is considered that the new PL spectrum is attributed to the re-embedding growth of the InGaAs on the nanoholes. It is possible that the In composition of the re-embedded InGaAs layer is introduced by the In surface segregation on the InAs QD and by re-incorporation of desorbed In atoms during the annealing.

4. Conclusions

GaAs nanoholes were spontaneously formed on the embedded InAs QDs by the thermal annealing. The nanohole size could be controlled by adjusting the anneal time, temperature and thickness of the capping layer. As the anneal time increased, the nanohole size enlarged and then saturated. Furthermore, the reduction of nanohole density was observed for the long anneal time because of the re-embedding growth on the nanoholes. The nanohole structure was strongly related to the strain of the capping layer and affected PL properties of InAs QDs.

References

[1] T.Satoh and K.Yamaguchi, Int. Symposium on Quantum Dots and Photonic Crystals 2003, P-3 (2003) p.23.

[2] K.Yamaguchi, K.Yujobo and T.Kaizu, Jpn. J. Appl. Phys. **39**, L1245 (2000).