Extended Abstracts of the 1997 International Conference on Solid State Devices and Materials, Hamamatsu, 1997, pp. 562-563

Perfect Spatial Ordering of Self-Organized InGaAs/AlGaAs Box-Like Structure on GaAs (311)B Substrate with Buried Silicon-Nitride Dot Array

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1. Introduction

Self-organization of quantum box-like structure during the crystal growth is the most promising technology for fabricating semiconductor quantum box devices. However, the lack of positional controllability and the considerable size fluctuation have hindered practical device application of the self-formed quantum box structure. In this paper, we report, for the first time, the perfect spatial ordering of self-formed box-like structure arrays grown on GaAs (311)B substrate. We used a novel selective-area-growth technique with lithographically defined ultra-fine silicon-nitride (SiN) dot array [1].

2. Formation of surface AlGaAs hollows induced by buried SiN dots

Dot array patterns were defined in a 20nm thick SiN film deposited by plasma chemical vapor deposition on GaAs (311)B and (100) substrates by using electron-beam lithography and dry-etching. SiN dots were square with base-length of 40-80 nm. Epilayers were grown by metalorganic vapor phase epitaxy (MOVPE) at 750°C. After the growth of a thin GaAs (10 nm) buffer layer, 60nm thick $Al_{0.5}Ga_{0.5}As$ and 35 nm thick $Al_{0.4}Ga_{0.6}As$ layers were grown on the dot-masked substrate. Such ultra-fine SiN dots were completely buried by AlGaAs lateral overgrowth. The surface of the AlGaAs layer on the (100) substrate was flat. On the contrary, we found that an SiN dot generates a pentagonally shaped hollow on the surface of the AlGaAs layer on (311)B substrate as a result of racing between the facet growth and lateral overgrowth. The schematic of the grown structure is illustrated in Fig. 1. The position of the pentagonal hollow is shifted from the SiN position towards the [-2 3 3] direction by the relationship:

~(thickness of whole AlGaAs epilayers) / (*tan*29.5°).

An atomic force microscope (AFM) image of an array of surface pentagonal hollows is shown in Fig. 2. The details on the AlGaAs hollow formation will be presented elsewhere.

3. Self-organization on the hollow array surface

To study the ordering nature of self-organization of a strained InGaAs film on GaAs(311)B substrate[2], InGaAs/AlGaAs epilayers were overgrown successively on the AlGaAs epilayers with the arrays of pentagonal hollows by MOVPE. We prepared three structures: an SQB sample with one 3.5nm thick strained $In_{0.3}Ga_{0.7}As$ capping layer on the pentagonal cell arrays; a DQB sample with two layers of 3.5nm thick $In_{0.3}Ga_{0.7}As$ separated with 65nm thick AlGaAs; and a TQB sample with three layers of 3.5nm thick $In_{0.3}Ga_{0.7}As$ separated with 35nm thick AlGaAs barriers. After the growth of InGaAs layers, the growth was interrupted for 2 minutes to induce the self-organization.

Figure 3(a) shows the cross-sectional SEM picture of an SQB sample after stain etching. The box-like structure is formed selectively inside the hollows. The inside of the pentagonal hollows are composed of a (-1-1-1) surface and other intermediate surfaces, which are preferable for the InGaAs growth; whereas the AlGaAs (311)B surface outside the hollows is not suited for the InGaAs growth. Consequently, almost all InGaAs deposits inside the hollows and reorganizes into a box-like structure during the growth interruption.

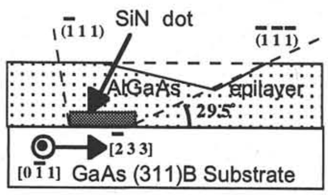

Fig. 1 Formation of surface hollow of AlGaAs epilayer by buried SiN dot.

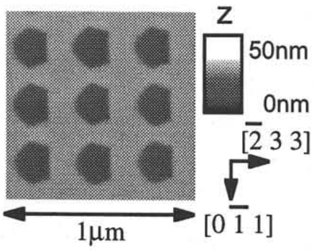

Fig. 2 AFM image of a 300-nm-pitch hollow array formed on AlGaAs epilayer.

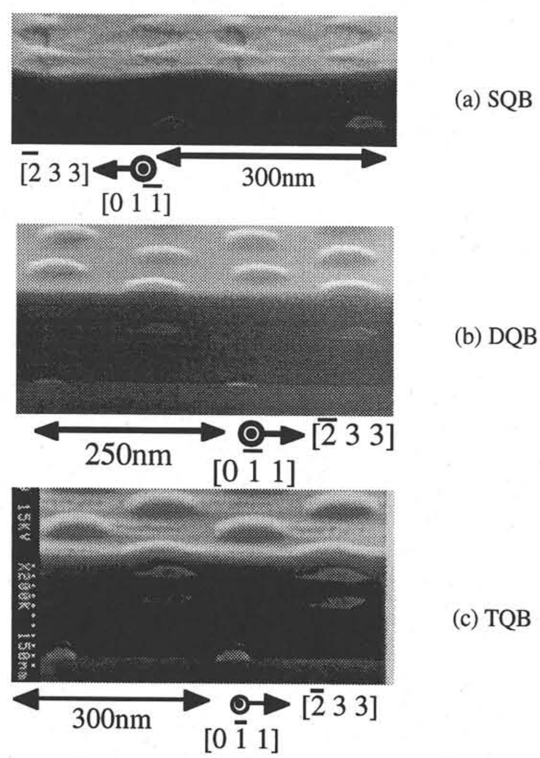

Fig. 3 Cross-sectional SEM images of the self-organized InGaAs/AlGaAs box-like structure array.

Vertical alignment of the box-like structure array was achieved in both DQB and TQB samples as shown in Figs. 3(b) and 3(c), respectively. The upper box is sitting precisely on the bottom box. This could be caused not by the AlGaAs facet growth but by the strain field driven growth. It is noted that the pairing probability of the bottom and upper boxes is highly dependent on the pitch of SiN dot arrays. Figure 4 compares AFM images of the top surface of DQB sample with various SiN dot pitches. On the non-patterned areas the box structures are nearly randomly formed as shown in Fig. 4(a). However, the pairing probability is gradually increased when the pitch is larger than 200 nm as shown in Fig. 4(b)-(d). Finally, the perfect spatial ordering of box-like structure arrays is achieved on 250nm pitch SiN dots without any deficient or excess formation as shown in Fig. 5. Although two structures are separated by more than 50nm, the 100% pairing is obtained in the wide pitch range of 250-300 nm. Further increase in pitch causes the evolution of excess boxes. The existence of optimum pitch for the spatial ordering may be a unique nature of self-organization on (311)B substrate. The same perfect spatial ordering was obtained in the TQD sample as shown in Fig. 6. The direction of lateral alignment in ordered structure can be changed by the SiN dot array patterns.

As clearly imagined from Fig.4, the size uniformity is improved by the spatial ordering. The standard deviation in lateral size calculated from 100 boxes in Fig. 5 is about 10 nm, which is less than 1/3 on non-patterned area.

4. Summary

We have found novel phenomena forming pentagonal hollows on AlGaAs surface when fine SiN dots on GaAs(311)B substrate are buried with AlGaAs. By using these hollows as a templet, we have realized perfect spatial ordering of InGaAs/AlGaAs dot-like structures. Our approach using lithographic technology to assist the ordering in self-organization can be one of the most promising method to realize nano-structure semiconductor optical and electronic devices.

References

1) E. Kuramochi, J. Temmyo, H. Kamada, and T. Tamamura, to be published in Appl. Phys. Lett..

2) R. Nötzel, J. Temmyo and T. Tamamura, Nature, 369, 131 (1994)

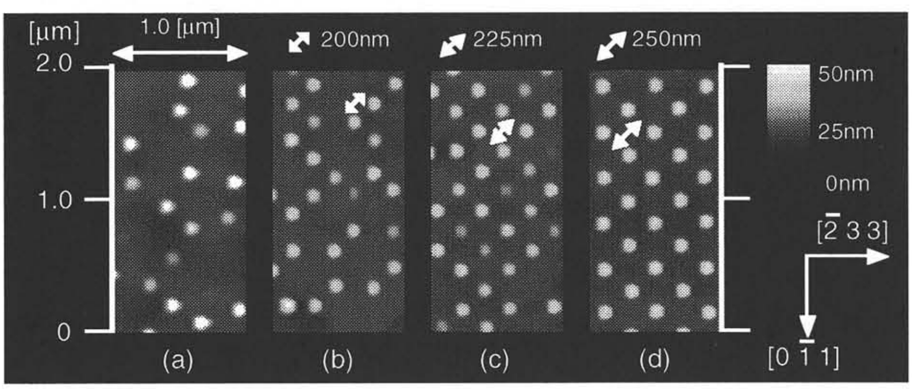

Fig. 4 AFM images of SiN dot pitch dependence in surface box-like structure of a DQB sample. (a) on non-patterned area; (b) 200-nm-pitch; (c) 225-nm-pitch; (d) 250-nm-pitch.

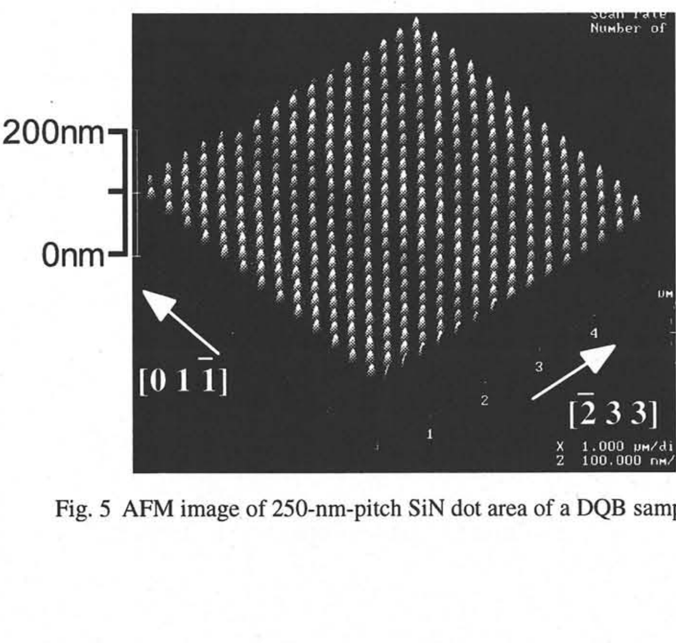

Fig. 5 AFM image of 250-nm-pitch SiN dot area of a DQB sample (5 × 5 μm).

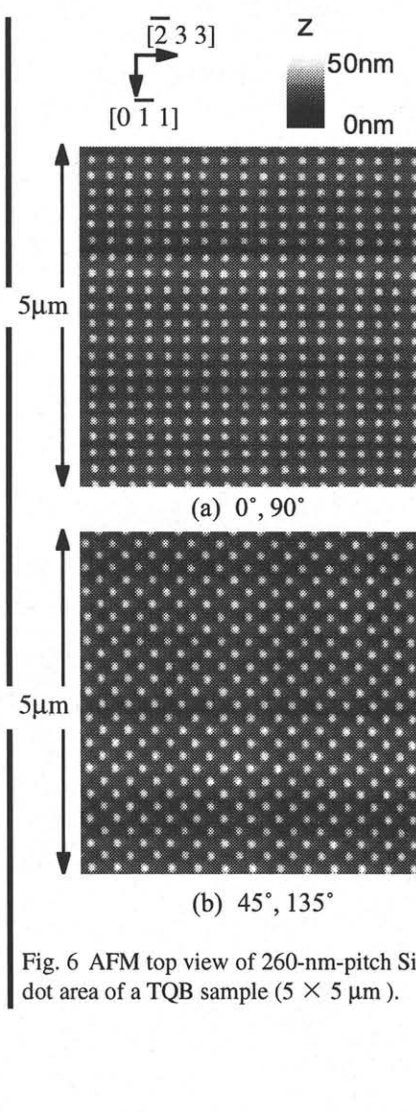

Fig. 6 AFM top view of 260-nm-pitch SiN dot area of a TQB sample (5 × 5 μm).