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Three-Dimensionally Confined Nanostructures Grown by MBE on Square-and Triangular-Hole Patterned GaAs (311)A Substrates

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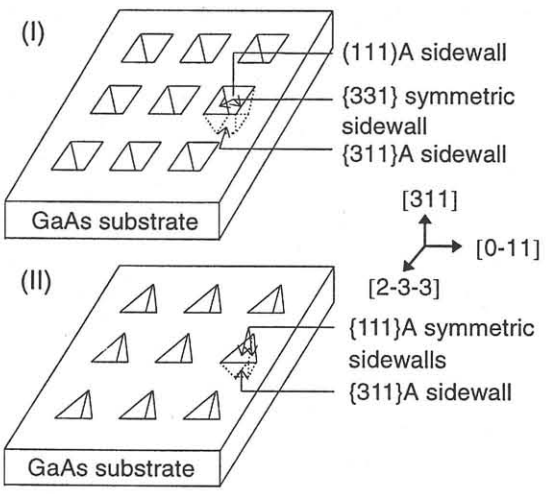
1. Introduction

Epitaxial growth on patterned high-index surfaces has revealed novel self-limiting growth mechanisms on the nanometer scale, thus becoming a unique approach to fabricate low-dimensional semiconductor structures [1,2]. We have studied the evolution of the surface morphology of square-shaped hole patterns on GaAs (311)A substrates during molecular beam epitaxy (MBE) [3,4]. The preferential migration of Ga adatoms from the symmetric sidewalls of the holes to top regions results in triangular-shaped dot-like (TD) arrays located on the original substrate surface in-between the holes. The (111)A sidewalls inside the holes, however, show pronounced roughening which deteriorates the overall surface morphology.

In this work, highly improved uniformity of TD structures with entirely smooth surface morphology has been achieved by applying triangular-hole patterns to eliminate the rough (111)A sidewalls. The lateral variation of quantum-well (QW) confinement energy around the top portion of the TD structures is evidenced by cathodoluminescence (CL) spectroscopy and imaging. Hence, the formation of TD structures provides a new route to realize dense arrays of three-dimensionally confined nanostructures in a controlled manner.

2. Sample preparation and experimental setup

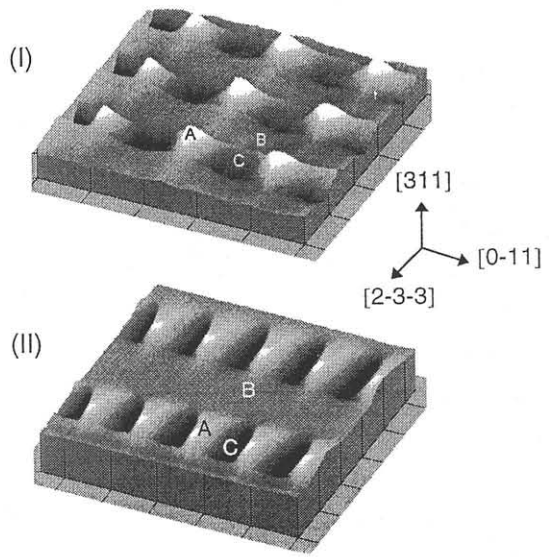


Figs. 1. Schematic illustration of the as-etched GaAs (311)A substrates patterned with (I) square-holes and (II) triangular-holes with acute angle pointing towards [-233].

The substrates I and II were patterned with square- and triangular-hole patterns, respectively. Fig. 1 (I) and (II) show schemes of the as-etched sample surfaces. The native oxide was desorbed at 400°C by atomic hydrogen irradiation which was crucial for obtaining a clean sample surface and smooth growth morphology. The MBE growth sequence comprised a 2.5 μm thick GaAs buffer layer, followed by a 20 nm/ 3 nm/ 20 nm $Al_{0.5}Ga_{0.5}As$/GaAs/$Al_{0.5}Ga_{0.5}As$ QW layer, which was covered by 500 nm $Al_{0.5}Ga_{0.5}As$ and a 20 nm GaAs cap layer. The surface morphology of the samples was investigated by atomic force microscopy (AFM). The CL measurements were performed at 5 K to characterize the lateral confinement in the TD structures.

3. Formation of TD structures

Figs. 2 (I) and (II) present the three-dimensional AFM images of the TD structures I and II grown on



Figs. 2 AFM images of structures I and II. The three portions distinguished by CL are marked A, B and C, respectively.

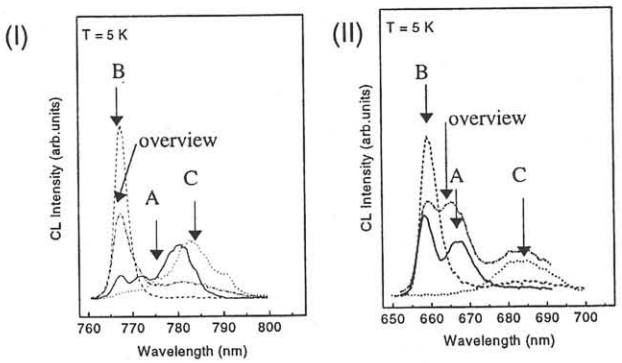
the substrates I and II, respectively. The TD structure I develops in the regions between the holes. The perpendicular (111)A sidewalls of the holes in structures I show pronounced roughening. In contrast similar TDs structures are obtained with entirely

smooth surface morphology for triangular hole patterned substrates, in which the rough (111)A sidewalls of the holes are suppressed very effectively.

The formation of the TD structures on patterned GaAs (311)A substrates is governed by the preferential migration of Ga adatoms from the sidewall of the holes along [2-3-3] to the top surface [3]. In the case of triangular-hole patterns, the tilted sidewalls of the holes promote the formation of the tips to enlarge along [2-3-3], simultaneously suppressing the formation of the opposite rough (111)A sidewalls.

4. Characterization of TD structures

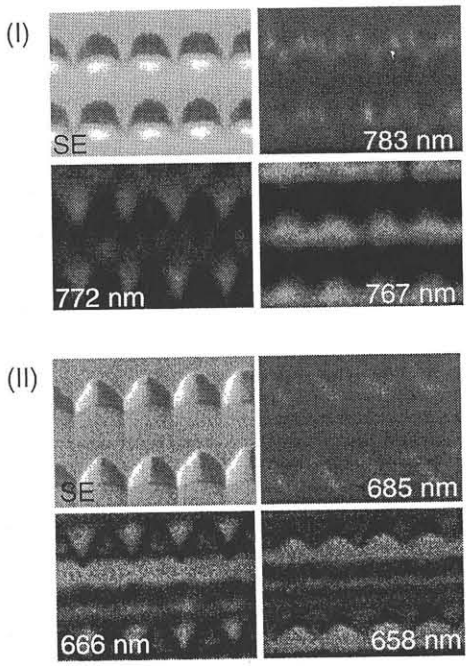
The lateral variation of the QW width in the TD structures is directly confirmed by the CL measurements. The CL spectra excited in the regions A, B, and C, as well as the average spectra, are shown in Fig. 3 (I) and (II). The average spectrum of the structure shows three features as indicated in the curves. For spot excitation, the emission at those three wavelengths becomes dominant in regions A, B, and



Figs. 3. CL spectra of the TD structure I and II taken at 5 K from a scan field of 50 μm^2 (overview excitation) and for spot excitation in the areas A, B, and C, as indicated in the Figs. 2.

C, respectively. The CL spectra reveal improved energy separation between region A and B of 22 meV for structure II compared to 11 meV for structure I, which is thus in the range of k_BT at room temperature due to well defined variation of the QW width.

Fig. 4 shows the spatial assignment of the emission in CL imaging together with the corresponding secondary electron (SE) images of the sample surfaces. The three features distinguished in the CL spectra originate from the sidewalls, top portions and stripe like regions of the TD structures. The CL intensity distribution corresponding to the top portion of TD structure II shows higher definition and uniformity of the contrast compared to that of TD structure I, indicating the improved uniformity for triangular-shaped holes.



Figs. 4. Secondary electron (SE) images and CL images of TD structures taken at 5 K for TD structures I and II, respectively.

5. Conclusion

Improved uniformity of TD structures grown by MBE on GaAs (311)A substrates is achieved by applying triangular-shaped hole patterns. The high lateral energy barrier around the top portion of TD structures is produced by the large variation of the GaAs quantum well width induced by the triangular hole patterns. We believe that the formation of the TD structure can be utilized for the direct synthesis of dense arrays of three-dimensionally quantum-confined nanostructures.

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