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GaAs Tetrahedral Quantum Dots: Towards a Zero-Dimensional Electron-Hole System

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New GaAs quantum dot structures, called tetrahedral quantum dots (TQDs) are proposed as a way to make a zero-dimensional electron-hole system. The TQDs are surrounded by crystallographic facets fabricated using selective area MOCVD growth on (111)B GaAs substrates. The calculated energy sublevel structures of 0-dimensional electrons in a GaAs TQD show large quantum size effects, because electrons are confined three-dimensionally, and the effective size of the TQD is close to the diameter of the inscribed sphere. GaAs and AlGaAs tetrahedral facet structures on (111)B GaAs substrates partially etched to a triangular shape were grown using MOCVD. Tetrahedral growth with {110} facets occurs in the triangular areas. The cathodoluminescence intensity map for AlGaAs selective area growth shows tetrahedral dot array.

1. Introduction

Semiconductor quantum wire structures prepared by crystal growth on patterned substrates have recently been actively studied to investigate their electrical and optical properties.[1-5] We have reported about facet quantum wires[1,2] and lateral quantum wires[3] prepared on SiO_2 masked (001) and (111)B GaAs by metalorganic chemical vapor deposition (MOCVD), and the transport properties of quantum wires with 0.3-0.6 um wide.[6] Quantum wire lasers were also fabricated on V-grooved substrates by MOCVD, and the 1-dimensional energy subband structure was observed in the emission spectrum.[4,7] The advantage of these methods is that the size and shape are controlled by the substrate pattern and/or crystal growth conditions, and damage-free and contamination-free interfaces are formed.

Semiconductor quantum well dot structures are also attractive new materials because energy band structure changes to energy sub-level structure for 0-dimensional electron-hole systems. Sharp luminescence spectrum and very low threshold current were predicted for quantum well box lasers.[8] There have been several attempts to fabricate quantum dot structures using interference photolithography and plasma etching[9], and electron beam lithography and reactive ion etching[10,11]. Zero-dimensional sub-level structures were observed in optical or transport properties. These processing technologies, however, have several disadvantages, such as fabrication damage to the etched surface and non-uniform shapes. Another fabrication method is to modify AlGaAs/GaAs quantum well physical properties using focused ion beam implantation.[10] This method uses the Al/Ga interdiffusion between well and barrier regions in the partial implantation region to form a 0-dimensional carrier confinement. Therefore, the hetero-interfaces are not sharp.

It would be very promising if the quantum dot structures could be obtained by selective area growth in which GaAs dots are three-dimensionally surrounded by AlGaAs without processing damage. In this paper, we propose a new fabrication method for GaAs quantum dots using selective area MOCVD. The electron structure and fundamental fabrication experiment of quantum dot structures named tetrahedral quantum dots (TQDs) are also described.

2. Crystal and electron structures of TQDs

First, we explain a fundamental proposal to obtain TQDs by MOCVD. (111)B and (110) are quite contrasting surfaces in MOCVD, because crystal growth occurs only at high growth temperatures on (111)B surfaces, and only at low growth temperatures on (110) surfaces. There are twelve equivalent {110} surfaces in zincblende crystals, half of which are perpendicular to the (111)B surface. Three of them form the facets of a non-regular tetrahedral pyramid, and the other three {110} are the opposite sides of the three facets of the tetrahedron. Therefore, we can obtain a tetrahedral structure with three {110} facets by selective area growth on a (111)B substrate at high growth temperatures, because under these growth conditions layer growth occurs on the (111)B surface, but not on the {110} sidewalls. To obtain selective area growth, the GaAs (111)B substrate is masked with SiO_2, which is partially removed to form a triangular shape. The sides of the triangle orient to [110], [011], and [101] on the (111)B surface. The angles between the (111)B surface and the {110} facets are 35.26°, which corresponds to $\cos^{-1}(\sqrt{2/3})$.

Figure 1 shows the proposed fabrication procedure for obtaining (non-regular) tetrahedral quantum dots(TQDs) of less than 100 nm. First, thick AlGaAs buffer layers are grown on the masked substrates. Then GaAs dots are grown at a high growth temperature only near the top of the tetrahedral structures. Finally, AlGaAs is over-grown on the whole tetrahedral structure at a low growth temperature, at which crystal growth occurs on {110} facets.

The energy sublevel structures of 0-dimensional electrons in a GaAs TQD with {110} facets were also calculated. Figure 2 shows energy sub-level structures as a function of TQD size calculated using effective mass approximation with infinite confinement potential. Large quantum size effects were obtained compared with a single

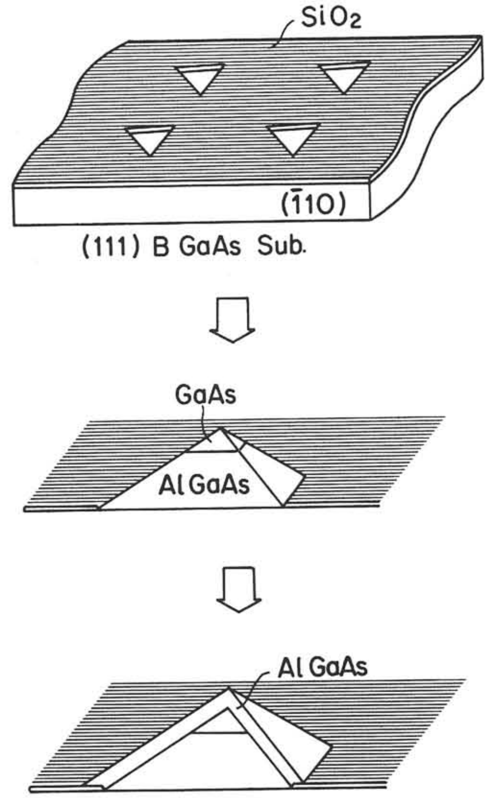

Fig. 1. The proposed fabrication procedure to obtain TQDs.

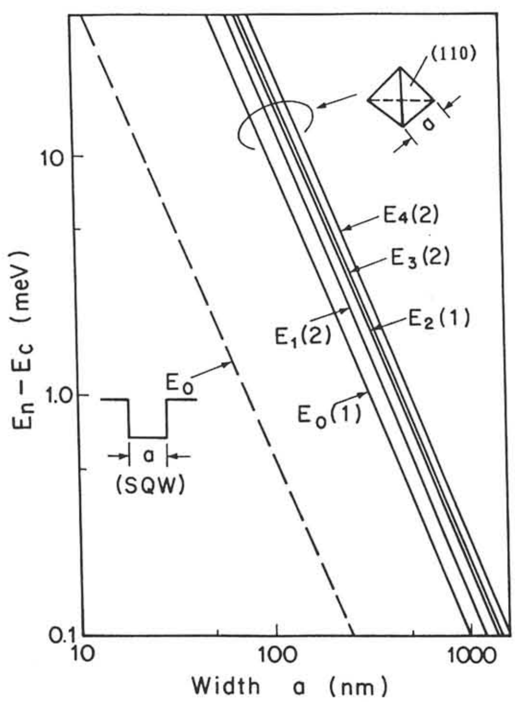

Fig. 2. The energy sub-level structures as a function of TQD size. The degeneracies for each sub-level are also shown.

quantum well, because electrons are confined three-dimensionally. Furthermore, for electrons, the effective size of the TQD is close to the diameter of the inscribed sphere, rather than the length of the side of the bottom triangle(the diameter is 20% of the side of triangle). The ground sub-level E_0 is 10meV above the bottom of the conduction band E_c for 100-nm TQD. The sub-level degeneracies are also shown in Fig.2. For grand sublevel, E_0, the electron distributes semi-spherically, and for both first sublevels, E_1, electron distributions have nodes in the center of the tetrahedron and spread to the bottom.

3. Experimental

The preliminary fabrications of TQDs were studied using low-pressure MOCVD. The MOCVD system was a horizontal low-pressure (19 Torr) reactor system, and the sources were trimethylgallium, trimethylaluminum and AsH_3. The substrates were semi-insulating GaAs (111)B wafers. After a 40-nm thick SiO_2 layer was deposited on the substrate by chemical vapor deposition, the SiO_2 partially removed to form 2 um triangles by photolithography and reactive ion etching. The sides of triangle were in the {110} directions on the (111)B GaAs surface. The growth temperature was 800°C.

Figure 3 shows a scanning electron microscope (SEM) photograph and a schematic view of the GaAs tetrahedral structures. The cleaved cross-section is a (110) surface. The angle between the (110) facets and (111)B substrate is 35.26°. An SEM top-view image of the GaAs tetrahedral array is shown in Fig. 4. No deposition occurs on the SiO_2 masked area.

Cathodoluminescence (CL) was measured for the array of AlGaAs tetrahedral dots on a GaAs (111)B substrate at 11K. The CL image of $Al_{0.22}Ga_{0.78}As$ tetrahedral dot array is shown in Fig. 5. The tuned wavelength for the CL image was 701 nm, which corresponds to $Al_{0.22}Ga_{0.78}As$ band edge emission.

Tetrahedral structures on (111)A substrates were also grown by similar methods. (111)B facet sidewalls were obtained at a low growth temperature (700°C). Another facet structure, square-based

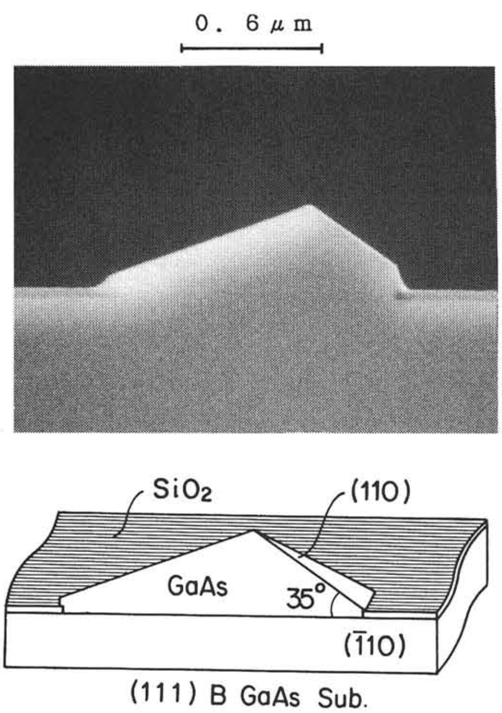

Fig.3. The schematic view and SEM image of cross-section of GaAs tetrahedral structure.

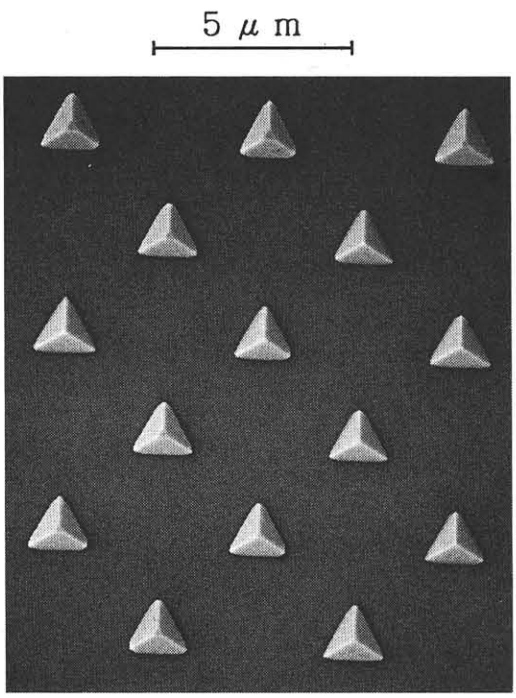

Fig.4. An SEM image of top view of GaAs tetrahedral structures with 2um length.

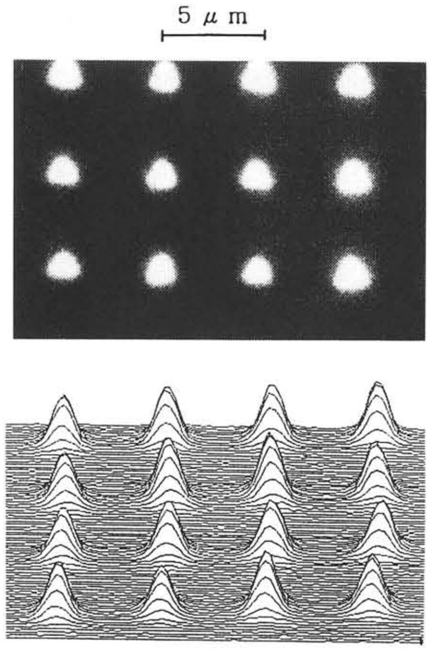

Fig. 5. Cathodoluminescence image of $Al_{0.22}Ga_{0.78}As$ tetrahedral structures with 2um length on GaAs (111)B substrate measured at 11K. Tuned wavelength is 701 nm.

pyramids with both (111)A and (111)B side walls, can also be formed on (001) substrates.

4. Summary

New GaAs quantum dots, called TQDs were proposed. Fabrication procedures using selective area MOCVD were shown. The calculated sub-level structure showed large quantum size effect, which suggests that quantum size effects can be observed even with sub-micron width TQDs. GaAs and AlGaAs tetrahedral structures with uniform shape were grown on (111)B substrates by selective area MOCVD. The CL measurements for AlGaAs tetrahedral structures also showed the strong luminescence in the tetrahedral regions.

It is interesting to note another application of this semiconductor tetrahedral structure. First, heavily doped AlGaAs TQD surrounded by non-doped GaAs can be used as the "superatom" proposed by H. Watanabe, in which electrons go around a AlGaAs "nucleus".[13] Furthermore, it is promising to use TQDs as the cold cathode in micro-fabricated vacuum tubes, or cathode ray tube(CRT).[14]

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