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MOCVD Methods for Fabricating Quantum Wires and Quantum Boxes

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Methods of fabricating quantum well wires by metalorganic chemical vapor deposition (MOCVD) are reviewed. There are two methods of fabricating very narrow as- grown quantum wires by crystal growth. One produces facet quantum wires and quantum boxes using crystallographic facets grown by selective area MOCVD. The other grows quantum wires using fractional-layer superlattices on GaAs vicinal surfaces. The advantage of these quantum well wire and box fabrication methods is that wire and box widths as narrow as 10 nanometers can be obtained without any processing damage.

1. Introduction

Semiconductor quantum wires and boxes have recently been actively studied to investigate their theoretical properties, and to apply them to high-speed devices, quantum interference devices, and opto-electronics devices[1-3]. There have been several attempts to fabricate quantum structures by simply restricting the lateral dimensions of quantum well or modulation doped wafers using physical or chemical processing. Processing technologies, such as reactive ion etching combined with electron beam lithograpy, have produced quantum wires and ring structures on the 30-100nm scale[4,5].

Recently, we have reported new quantum wire fabrication methods based on crystal growth, in which electron channel regions or active regions are surrounded two- or three-dimensionally by cladding materials. These methods have the advantage of forming damage-free interfaces compared to other processing techniques.

This paper reviews MOCVD methods for fabricating quantum wires and boxes based on our recent study. Facet quantum wires and boxes can be fabricated, using crystallographic facets grown by selective area growth[6-9], and quantum wires can also be fabricated using fractional-layer superlattices on vicinal surfaces[10,11].

2. Quantum wires and boxes by facet growth

In MOCVD, crystallographic facets appear during selective area growth. The facet orientations are usually low index crystal planes, such as (111)A, (111)B and (110). On these crystal planes, crystal growth rates are slow and they depend strongly on the growth conditions. Using these facet properties, we fabricated three kinds of quantum confinement structures: facet quantum well wires[6,7], lateral quantum well wires[8], and tetrahedral quantum dots[9].

2.1 Facet quantum well wire

GaAs quantum well wires were fabricated on (111)B crystallographic facets by selective area growth. Figure 1a shows a schematic diagram and an scanning electron microscope (SEM) photograph of the cross-section of an $Al_{0.3}Ga_{0.7}As$/GaAs double-hetero (DH) structure facet quantum wire. The substrates were GaAs (001) wafers with SiO_2 stripe masks(2µm-wide lines and spaces). The stripes were oriented to the [110] direction. First, undoped $Al_{0.3}Ga_{0.7}As$/GaAs DH structures were selectively grown on SiO_2 stripe masks with high AsH_3 partial pressure and a low growth temperature (650°C). The selectively grown DH layers were trapezoidal with {111}B facets as the sidewalls. The results suggest that no crystal growth occurs on the SiO_2 mask region, or even on the {111}B sidewalls. The group III source materials diffuse through the {111}B sidewalls to the (001) top surface.

Next, undoped and Si-doped $Al_{0.3}Ga_{0.7}As$ were grown over the {111}B and (001) facets at 800°C. At higher growth temperatures, crystal growth occurs both on {111}B and (001) surfaces. Modulation doped electrons

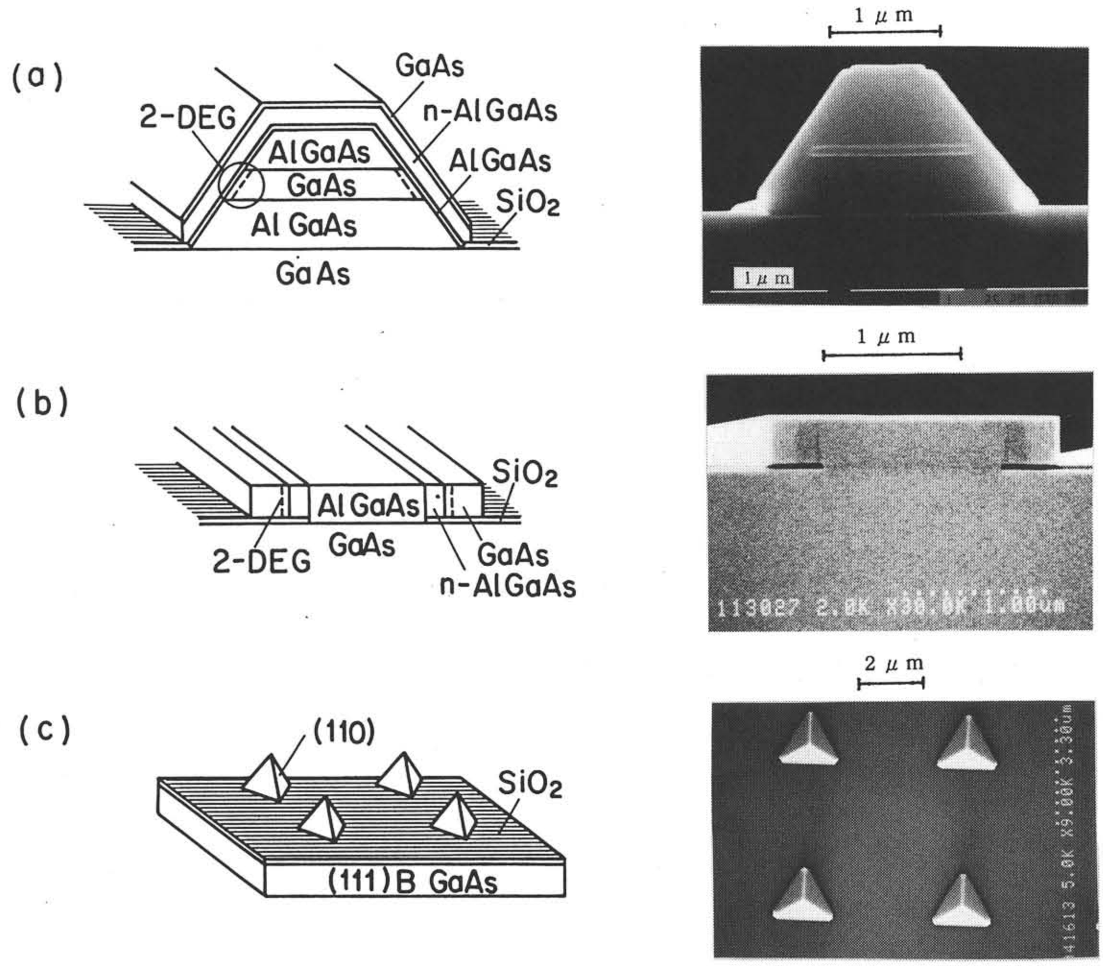

Fig.1 Schematic diagrams and SEM photographs of (a) facet quantum wire, (b) lateral quantum well wire, and (c) tetrahedral quantum box.

accumulate in the GaAs at the (111)B sidewall interface, and the GaAs channel width can be controlled by the growth thickness of GaAs. The GaAs channel width in Fig. 1a is 0.1μm. The existence of a 2DEG on {111}B facets was confirmed by the dependence of Shubnikov-de Haas (SdH) oscillations on magnetic field direction.

A similar facet quantum wire with a wider channel width (0.3-1.0um) was used to investigate quantum interference properties, such as universal conductance fluctuations and negative magnetic resistance. We also observed the temperature dependence of the inelastic scattering lengths in both 1 dimensional and 2 dimensional electron cases[12].

Compared with other techniques for fabricating quantum well wires, the advantage of this technique is that there is no size fluctuation in the quantum wire width along the wire direction, because the wire width is fundamentally determined by the growth thickness of the trapezoidal GaAs layer.

2.2 Lateral quantum well wires

In selective area growth, it is very convenient if we can obtain arbitrarily-shaped quantum structures by independently controlling the vertical growth and lateral growth by changing the growth conditions. In MOCVD, (111)B and (110) are extremely contrasting surfaces, because crystal growth only occurs at a high growth temperature on (111)B surfaces, but at a low growth temperature on (110) surfaces. Therefore, if we use (111)B substrates and {110} sidewalls perpendicular to the surfaces in selective area MOCVD growth, we can control the growth on (111)B top surface and {110} sidewalls independently by changing the growth conditions. Furthermore, we can obtain various lateral structures, such as lateral quantum wires and lateral superlattices.

Figure 1b shows typical GaAs lateral quantum wires (LQWs) on {110} sidewalls perpendicular to the SiO_2 stripe masked (111)B substrates grown by using two-step growth. First, rectangular AlGaAs layers whose sidewalls had {110} facets, were grown on (111)B GaAs at a high growth temperature. Next, Si-doped AlGaAs and non-doped GaAs layers were sequentially grown on {110} sidewalls at low growth temperatures.

The existence of a quasi-one dimensional (Q1D) electron gas on the {110} sidewalls was confirmed by the orientation dependent SdH oscillations. For the sample shown in Fig. 1b, the lateral GaAs width measured by SEM is 0.35μm. The actual channel widths of the Q1Ds on {110} sidewalls were determined by fitting the magnetoconductance in a weak magnetic field using a one-dimensional weak localization theory. The width of the electron channel is about 160nm, which is smaller than the geometrical width. This indicates that there is a vertical depletion length of about 100nm at each channel edge.

There are many applications of this alternate vertical and lateral growth. If DH semiconductor laser structures are grown on SiO_2 stripe-masked GaAs (111)B substrates with facets several hundred nanometers wide, {110} laser cavities are automatically formed. Furthermore, AlGaAs/GaAs lateral superlattices can be formed on {110} sidewalls.

2.3 Tetrahedral quantum dots

New GaAs quantum dot structures, called tetrahedral quantum dots (TQDs) are one way to make a zero-dimensional electron-hole system. They can be fabricated using similar procedures as for lateral quantum well wires. The substrates were SiO_2 masked (111)B GaAs partially etched to remove a triangle of SiO_2.

Figure 1c shows the tetrahedral facet structures on GaAs (111)B substrate. Growth temperature was 800°C, and sidewalls showed (110) facets. Although the side of the tetrahedron was 2μm in this trial, it is easy to obtain sub-micron sized tetrahedrons, by the same procedure: First, thick AlGaAs buffer layers were grown on the substrate. Next only near the top of the tetrahedral structure, GaAs dots were grown. Finally AlGaAs was over-grown on the whole tetrahedral structure at a low growth temperature. Under these growth conditions, crystal growth occurs on (110) facets.

The energy sublevel structures of 0-dimensional electrons in a GaAs TQD were also calculated. Large quantum size effects were obtained compared with a single quantum well, because electrons are confined three-dimensionally. Furthermore, for electrons, the effective size of the TQD is small: close

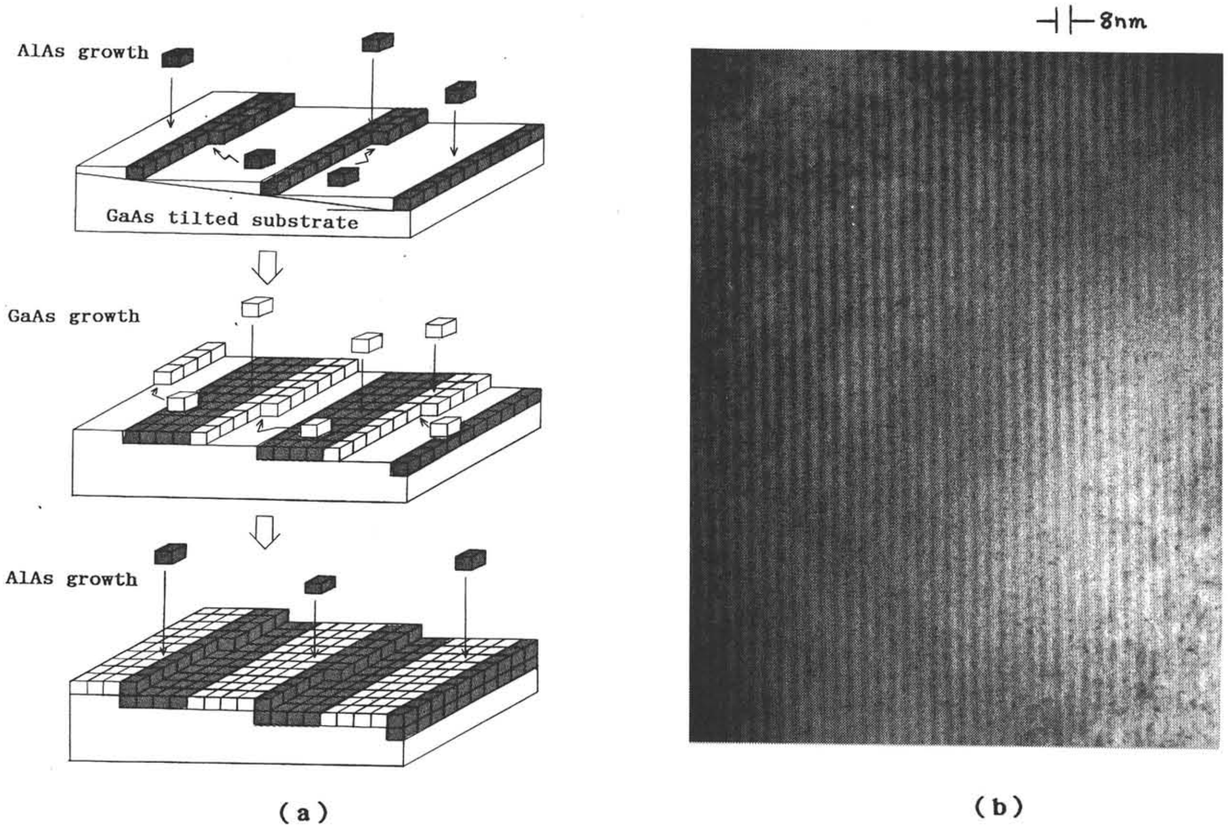

Fig.2 (a) Fabrication procedure and (b) TEM photograph of surface view of FLS.

to the diameter of the inscribed sphere, rather than the length of the side of the tetrahedron. The ground sublevel E_0 is 10 meV above the bottom of the conduction band E_c for 100-nm TQDs.

TQDs are interesting structures for investigating 0-dimensional excitons and nonlinear optical properties, and for applying to quantum dot lasers.

3.Quantum wire array on GaAs vicinal surface

A GaAs quantum well wire array less than 10nm wide was fabricated by MOCVD. The fabrication method is based on $(AlAs)_{1/2}(GaAs)_{1/2}$ fractional-layer superlattice (FLS) growth on (001) GaAs substrates slightly misoriented toward [$\bar{1}10$]. Figure 2a shows the crystal growth procedure for an FLS grown on a (001) vicinal surface, which was first proposed by P.M.Petroff[13]. Growth must be controlled to exactly half a monolayer, two-dimensional growth on the terrace must be prevented, and terrace widths must be equal.

Very thin epitaxial layer growth, such as alternate half-monolayer growth, was achieved at a low growth rate and rapid change in the gas composition inside the reactor. The growth temperature was 600°C. The substrate misorientation angles were 1.0 -3.5 , corresponding to superlattice periods of 16nm-5nm. Figure 2b shows transmission electron microscope (TEM) photographs of the top of an FLS. The clear contrasts between the AlAs (bright region) and GaAs (dark region) have a 8-nm period, which is equal to the mean terrace width on a 2-degree-tilted substrate. Furthermore, these TEM images prove that each superlattice period has a uniform width.

Polarization-dependent optical absorption in FLS shows the absorption anisotropy at the band edge caused by the carrier confinement effects in the parallel direction of superlattices[14]. The observed separation in the band edge wavelengths corresponds to the energy difference between the heavy- and light-hole related transitions.

Quantum well wire (QWW) arrays having both FLS and GaAs layers as a well region were also fabricated. Shorter wavelength photoluminescence was observed for QWWs on substrates tilted at large angles, which shows the quantum size effects in QWWs. From a comparison of measured and calculated photoluminescence energies, the thickness of the lateral interface mixing layer was estimated to be several monolayers[15].

We also fabricated quantum wire transistors and electron wave interference transistors, in which we observed the mobility modulation effect and electron wave interference effect[16,17]. The FLS structure is very promising for new types of low-dimensional electron and optical devices

4. Summary

Quantum well wires and boxes were fabricated by MOCVD. Facet quantum wires, lateral quantum wires and tetrahedral quantum boxes were grown using selective area growth. Their fundamental characteristics of low-dimensional electron gas were discussed. We also fabricated quantum well wire arrays on GaAs (001) vicinal surface using fractional-layer superlattices.

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