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Fabrication and Optical Properties of Quantum Wires and Dots

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Fabrication and optical properties of GaAs quantum wires and quantum dots using an *in-situ* MOCVD selective growth technique on SiO2 patterned substrates. GaAs quantum wires with a lateral width less than 10 nm were obtained. The photoluminescence (PL) and magneto-PL measurements clearly demonstrate the existence of the quantum wire effects in the structures. In addition, the exciton radiative lifetime is also measured, showing dependence of the lifetime on the lateral width. Using a similar but slightly different selective growth technique, GaAs dots with a dimension of 25nmx25nmx12nm surrounded by AlGaAs regions were also prepared.

1. Introduction

A reduction of dimensionality of the electron motions in quantum nano-structures such as quantum wires and quantum dots brings new phenomena in semiconductor physics. Moreover, it allows new device concept to be considered and permits improvements in performance of the transistors and lasers[1, 2]. Particularly, in the optical devices, the electronic states can be fully quantized, in contrast to the situation in transport devices, where the electrons need propagate along the channels.

Recently full confinement of photons (or optical wave) has been also discussed for the future zero-threshold lasers in which the electron-hole pairs are coupled with only a single spontaneous emission mode. Consequently, as for the semiconductor lasers, the full-quantization of both electrons and photons is the ultimate direction forward[3]. The goal is, however, far away because the fabrication technology for such low-dimensional structures is still under development. In order to explore the frontier of the new physics experimentally and develop new optical and electronic devices, sufficiently small and uniform nano-structures need to be obtained so that all carriers are populated at the lowest subband for both the conduction band and the valence band. In addition, a three-dimensional optical cavity with extremely high reflectivity must be also prepared.

In this paper, we discuss fabrication and optical properties of the quantum wires using a *in-situ* MOCVD growth technique[4-6]. Using this technique, triangular-shaped GaAs quantum wires with the lateral width less than 10 nm are fabricated. The optical properties of the quantum wires including photoluminescence (PL), magneto-PL, and the exciton radiative lifetime are studied in order to confirm the existence of the two-dimensional quantum confinement in our structures. Using a similar but slightly different selective growth technique, GaAs quantum dot structures of 25nm x 25nm x 12nm are successfully prepared[7,8].

2. Fabrication of GaAs Quantum Wires

In order to fabricate the quantum nano-structures, wet chemical etching, reactive ion etching, ion beam implantation and ion beam milling have been investigated. These methods, however, suffer from free surface effects, creation of a damage field during implantation, or a loss of interface control due to the random nature of the disordering mechanism. To avoid these problems, growth techniques on masked substrates and non-planer substrates[9-12] have been also investigated. Here, we show GaAs quantum wires and dots fabricated by an in-situ MOCVD selective area growth technique on a SiO2 patterned substrate on which the V-groove structures are formed by the growth.

Details of the fabrication procedure for the quantum wires are described in Ref.[4]. Figure 1 shows a high-resolution a cross sectional SEM image of the quantum wire array with 20nm period and its illustration. As shown in this photograph, even though there is ~30% lateral size fluctuation in SiO_2 mask, the quantum wires are uniformly formed, which is due to the relaxation of the size deviation by the appearance of the facet due to the lateral selective growth of the triangular prisms.

By changing the growth time of GaAs material for the quantum wires, we obtained the quantum wires with various lateral widths. Figure 2 shows high-resolution SEMs of the quantum wires region with lateral widths of ~10, ~15, ~25, ~35nm, respectively. Each quantum wire smoothly connects to quantum well layers with ~2, ~3, ~5, ~7nm thickness. As shown in this photograph, the quantum wire with Lx~10nm was obtained by systematic change of the growth time.

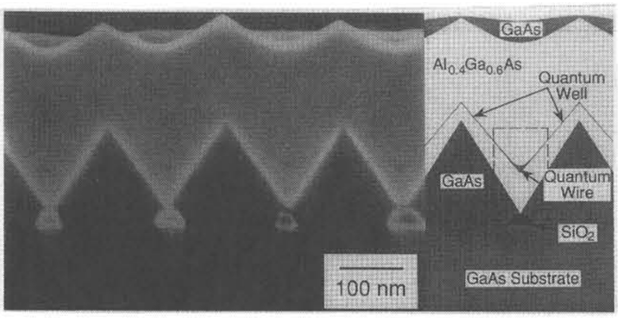

Fig.1: A high-resolution scanning electron micrograph of GaAs triangular-shaped quantum wire array structures with the lateral width of ~15nm and its illustration.

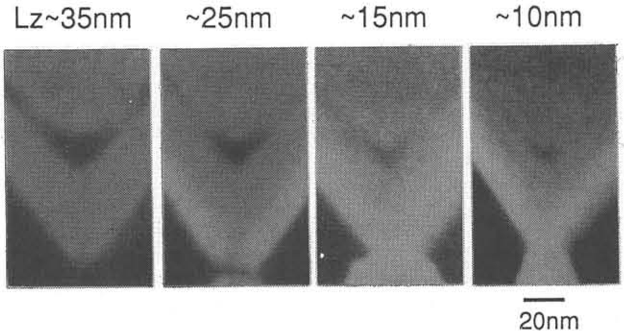

Fig.2: High-resolution scanning electron micrographs of the part of the quantum wires with lateral widths of ~10, ~15, ~25, ~35 nm, respectively.

Photoluminescence Spectra (PL) spectra from the quantum wire structures are measured at 20K as a function of the lateral widths of 0, ~7, ~10, ~15, ~25, ~30, ~35nm as shown in Fig. 3(a). In this figure, the hatched PL peaks are corresponding to the quantum wires. Figure 3(b) shows the energy shift ΔE of the PL peak of the quantum wires versus the lateral width Lx. The ΔE is defined as the energy difference between the PL peaks of the GaAs bulk and the quantum wires As shown in these figures, systematic blue shifts are observed with decreasing Lx, which is due to enhancement of the two-dimensional quantum confinement effect. The solid calculation curve in the figure is based on a simple one band model. These results indicate that a strong lateral confinement is achieved in the present structures.

3. Magneto-Photoluminescence and Exciton Radiative Lifetime

If electrons are really confined two-dimensionally in the quantum wires, the behavior of the Landau shift should depend on the direction of the applied magnetic fields. Therefore measurements of magneto-PL spectra were performed for the quantum wires with the lateral width of 20nm using pulsed magnetic fields at 4.2 K. The pulse duration of the magnetic field was 10 msec and the maximum field was about 40 T. PL spectra were detected with an optical multi-channel analyzer system installed at the exit of the monochromator through the optical fiber.

The PL peak position from the quantum wires and the bulk at the three configurations (i.e., ***B//x,B//y,B//z***) are plotted as a function of applied magnetic fields in Fig.4. As shown in this figure, the behavior of the PL peak shift ΔE is different between the bulk and the quantum wires. The bulk PL peak shifts at various magnetic fields are almost equally independent on the configurations throughout the magnetic field region. In contrast, PL peak shift of the quantum wires is clearly depending on the configuration. When the magnetic field is applied in parallel with the quantum wires (***B//x***), the energy shift with the increase of the magnetic field is the smallest. This can be explained by a classical picture in which the cyclotron motion on the plane perpendicular to the magnetic field is restricted by the two dimensional lateral potentials of the quantum wires. On the other hand, there is also anistropic effect when the magnetic field is applied in the two directions perpendicular to the quantum wires. The results indicate that the cross sectional shape of the quantum wires are not isotropic.

Next, we performed time resolved measurements of PL in these quantum wires. Figure 5 shows the lateral width dependence of the exciton radiative lifetime in the quantum wires. For all the measurements, monoexponential decay of the photoluminescence up to 2 ns was observed. The results indicate that the lifetime increases from 260 ps to 422 p. The increase of the radiative exciton lifetime in the quantum wires can be explained by the decrease of the coherent volume Vc, within which excitons oscillate coherently, due to the

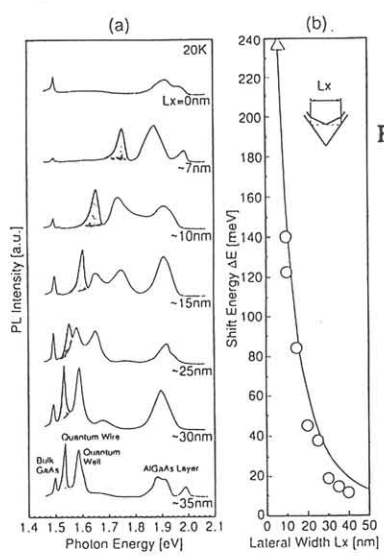

Fig.3:(a) Photoluminescence (PL) spectra from the quantum wire structures measured as a function of the lateral wire widths at 20K. (b) The energy shift ΔE of the PL peak of the quantum wires versus the lateral width Lx.

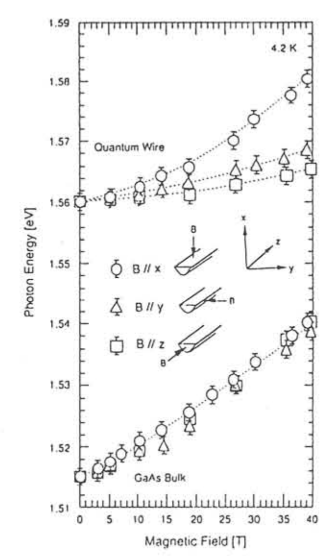

Fig.4: PL peak positions from the quantum wires and the bulk as a function of applied magnetic field for various configurations. Circles, triangles and squares represent the data for ***B//x,B//y,*** and ***B//z*** , respectively.

decrease of the lateral width. The solid curve is the calculated result taking account of the fact that the transition probability $W(\mathbf{k},\omega)$ which is inversely proportional to the carrier lifetime τ is given by

$$W(k,\omega) = A / \varphi(0) /^2 Vc$$

where φ is the wavefunction which describes relative motion of an exciton and a hole. A is a constant. $|\varphi(0)|^2$ is obtained by solving the Schrodinger eqation and Vc is square of the laterral width of the quantum wires multiplied by the coherent length in the direcion parallel with the wires.

4. Fabrication of Quantum Dots

Fabrication trials of quantum dot structures using masked substrate have been intensively investigated by several groups. Here the GaAs quantum dots were fabricated by the MOCVD selective growth technique on SiO2 patterned (100) GaAs substrates[7]. The masks are consisted of 100nmx100nm mm^2 windows with a period of 140nm. First, $Al_{0.4}$ $Ga_{0.6}$ As plinths are formed on the SiO2 masks. Then, the GaAs is grown on the top of the AlGaAs plinths, followed by the growth of $Al_{0.4}$ $Ga_{0.6}$ As so that the GaAs quantum dots are embedded by $Al_{0.4}$ $Ga_{0.6}$ As.

Figure 6 is the cross sectional view of the GaAs surrounded by AlGaAs and its illustration. The photograph indicates that the lateral with of the quantum dots is 25nmx25nm. We believe that this lateral width is the smallest so far as for the GaAs quantum dots embedded by AlGaAs materials.

Even from this small structures, PL can be observed. Figure 7 shows PL spectra of the quantum dot structures excited by an CW argon lasers. In this case electron-hole pairs are excited in the barrier region and then relaxed into the quantum dot region. The energy shift of the PL peak from the quantum dot region is about 18meV. We believe that this energy shift is resulting from the lateral confinement of electrons. The full width of half maximum (FWHM) of the PL peak is broad compared to those of the quantum wires. However, the tail of the luminescence at the low energy side disappears at the photon energy of the bulk GaAs. This indicates that the broadening is not due to strain and defect effects but due to size variation of the quantum dots. In the measurement, more than 100,000 quantum dots are simultaneously excited. Excitation of smaller number of quantum dots are discussed elsewhere.

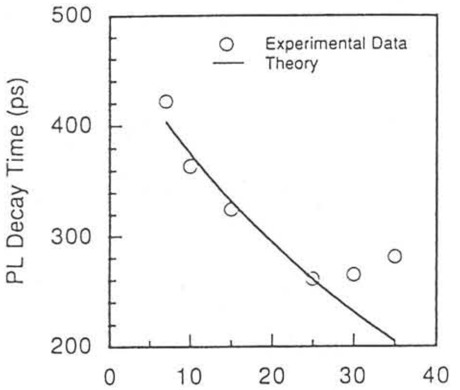

Fig.5: Dependence of exciton radiative lifetime on the lateral width of the quantum wires. The solid curye is calculation.

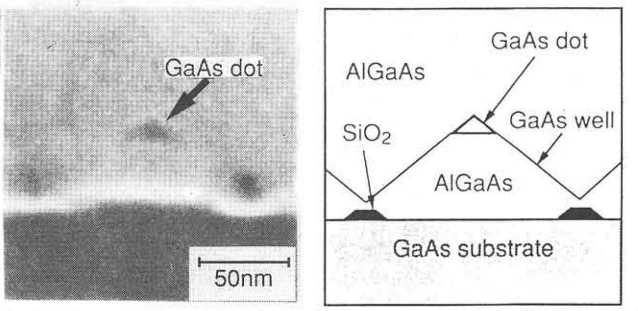

Fig.6: The cross section of the GaAs quantum dot with a lateral width of 25nm and its illustration.

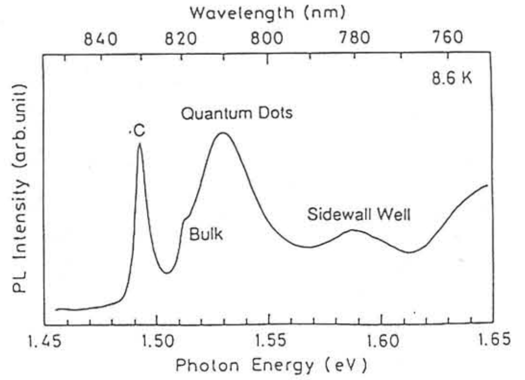

Fig.7: Phtoluminescence spectra of the GaAs quantum dot structures

5. Conclusion

We discussed fabrication and optical properties of GaAs quantum dots and quantum wires using an *in-situ* MOCVD selective growth. GaAs quantum wires with a lateral width less than 10 nm were obtained. The PL and magneto-PL clearly demonstrate the existence of the quantum wire effects. The measurements of the radiative exciton lifetime shows its dependence on the lateral width of the quantum wires. Using a similar technique, GaAs quantum dots with a lateral dimension of 25nm were successfully obtained.

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