Photoluminescence Spectra and Anisotropic Energy Shift of GaAs Quantum Wires in High Magnetic Fields

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Magnetophotoluminescence spectra of GaAs quantum wires with lateral and vertical dimensions of 20 and 10 nm, respectively, were measured up to 40 T with three orthogonal magnetic field configurations. The observed photoluminescence peak shift with increase of applied magnetic field was strongly dependent on the direction of magnetic field, which directly demonstrates the existence of two-dimensional confinement in the quantum wires. It was found that the excitons were anisotropically shrunk in the quantum wires, and that the observed magnetic energy shift was consistent with the size of the quantum wire structure.

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Two-dimensional (2D) confinement of carriers in quantum wires (QWRs) is an important phenomenon in physics, as well as for applications to semiconductor lasers and other functional devices [1,2]. Many workers have intensively investigated the realization of QWR structures with various fabrication techniques [3-7]. *In situ* fabrication techniques embedding QWRs in barriers are promising for reducing damage or impurities and the resulting nonradiative recombination at the surfaces or the interfaces. Recently, by the growth technique of metal-organic chemical vapor deposition (MOCVD) on V grooves, GaAs QWRs embedded in AlGaAs have been produced [4,8,9]. The QWRs exhibited clear cathodoluminescence (CL) [9] or photoluminescence (PL) spectra [10], and an anisotropic polarization dependence of the PL excitation (PLE) spectra.

In order to obtain evidence of 2D confinement in QWRs, the blueshift or polarization anisotropy of PL or PLE spectra has been studied [9-12]. However, it is pointed out that the blueshift or the polarization anisotropy itself is not a proof of 2D confinement [13]. Magneto-optical measurements were also carried out for QWRs prepared by the etching of quantum wells (QWLs), and the confinement energy or the exciton binding energy was estimated [14,15]. However, because the values were estimated from data in low magnetic fields and for one magnetic field direction, they were largely dependent on the theory with simplified approximations and fitting parameters. In order to clarify 2D confinement experimentally and more clearly, measurements with a three-dimensional variation of the direction of strong external fields on well-defined QWRs, and consistency among the data, are required.

In this paper, we report high field magneto-PL (MPL) spectra of *in situ* fabricated GaAs QWRs, where the orientation of applied magnetic fields was varied in three independent directions relative to the QWRs. We observed a clear dependence of the PL spectra on both the magnitude and the direction of the magnetic fields. It was found that the excitons were anisotropically shrunk in the QWRs, and that the size of the QWRs estimated from the energy changes was consistent with that determined by the high-resolution secondary electron image (SEI) of the QWR structure.

A schematic cross section and the SEI of the sample in this work are shown in Figs. 1(a) and 1(b), respectively. The QWRs were *in situ* fabricated by a MOCVD selective growth technique. This fabrication technique is basically based on the growth technique reported in Ref. [4], but here, in order to obtain high-density QWRs with a smaller period on sharper V grooves, a selective-growth

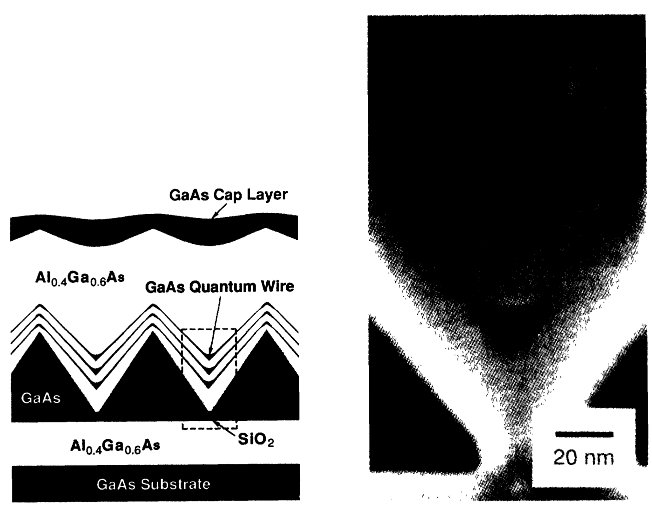

FIG. 1. (a) Schematic illustration of the cross section of the vertically stacked multiple quantum wires, and (b) high-resolution secondary electron image of the region near the quantum wires of which the area is corresponding to that surrounded by broken lines in (a).

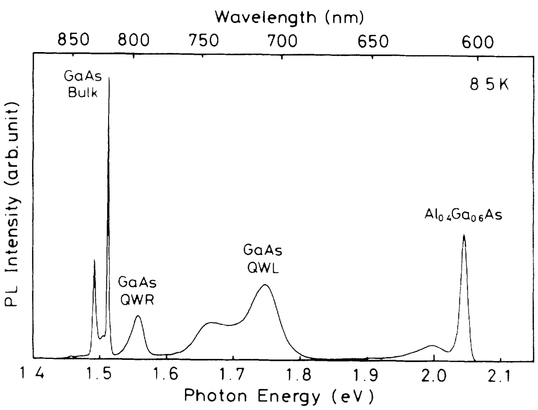

FIG. 2. Photoluminescence spectra of the sample shown in Fig. 1.

technique using SiO_2-masked substrates was employed [10]. As shown in Fig. 1, three vertically stacked triangular-shaped GaAs QWRs, of which the average base length and height were about 20 and 10 nm, respectively, were embedded in $Al_{0.4}Ga_{0.6}As$ layers. Here, the QWRs were aligned parallel to a $\langle 01\bar{1}\rangle$ direction in an area of 3×3 mm^2, and the horizontal period was 200 nm.

The magnetic fields were generated with a pulsed magnet and PL spectra at 4.2 K were detected using an optical multichannel analyzer system [16], where the PL spectra were obtained by use of Ar^+ laser light with a wavelength of 514.5 nm. The pulse duration of the magnetic field was 10 msec and the variation during the measurement was within $\pm 3\%$ at the top of the pulsed magnetic field. For the present MPL measurement, three kinds of configurations $\mathbf{W}\perp\mathbf{B}\parallel\mathbf{k}$, $\mathbf{W}\perp\mathbf{B}\perp\mathbf{k}$, and $\mathbf{W}\parallel\mathbf{B}\perp\mathbf{k}$ were taken, where **W**, **B**, and **k** are, respectively, the direction along the QWRs, the applied magnetic field vector, and the wave-number vector of the PL spectra which is equal to the direction perpendicular to the substrate. Note that $\mathbf{W}\perp\mathbf{B}\parallel\mathbf{k}$ and $\mathbf{W}\perp\mathbf{B}\perp\mathbf{k}$ are different configurations in this case because of the triangular-shaped QWRs.

PL spectra of the sample shown in Fig. 1 are plotted in Fig. 2. Here, the PL peak at 1.560 eV corresponds to the first subband state of the GaAs QWRs, the PL peak at 1.514 corresponds to a GaAs bulk transition, probably (D_0,X) [17,18], and that at 1.493 eV may correspond to the transition at carbon impurities. A broad peak at 1.75 eV and its shoulder at 1.66 eV correspond to GaAs QWLs grown on $(111)A$ sidewalls and their top regions, respectively. These assignments are qualitatively consistent with the CL investigation [9]. On the other hand, a PL peak at 2.046 eV originates from $Al_{0.4}Ga_{0.6}As$, and the broad one around 2.00 eV may be from AlGaAs grown near the bottom of the V grooves with a little smaller Al composition. The energy difference between the PL peak of the QWRs and that of the bulk was 46 meV, which is in good agreement with the calculated quantized energy for the present QWR structure [19].

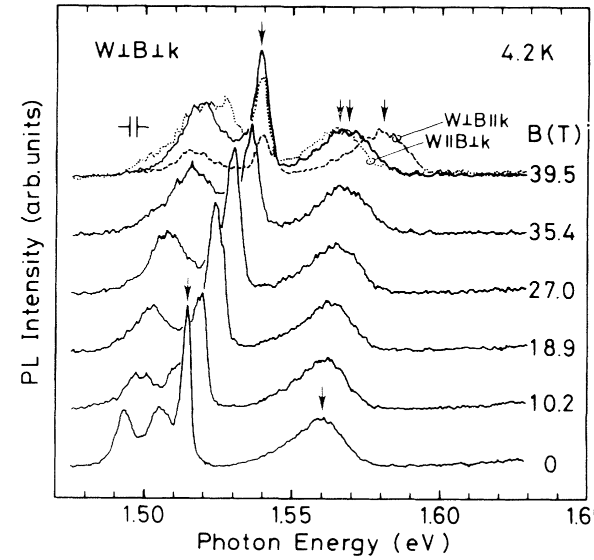

FIG. 3. Magnetophotoluminescence spectra of the GaAs quantum wires and the GaAs bulk for $\mathbf{W}\perp\mathbf{B}\perp\mathbf{k}$. Each spectrum was measured at the magnetic field indicated on the right-hand side of the spectra. Spectra for $\mathbf{W}\parallel\mathbf{B}\perp\mathbf{k}$ and $\mathbf{W}\perp\mathbf{B}\parallel\mathbf{k}$ are also shown for the highest magnetic field by dotted and dashed lines, respectively.

The large PL intensity of the QWRs is realized by their high density structure.

Typical experimental recordings of MPL spectra are shown in Fig. 3, where each spectrum was measured at the magnetic field indicated on the right-hand side of the spectra with the configuration $\mathbf{W}\perp\mathbf{B}\perp\mathbf{k}$. Spectra for $\mathbf{W}\parallel\mathbf{B}\perp\mathbf{k}$ and $\mathbf{W}\perp\mathbf{B}\parallel\mathbf{k}$ are also shown for the highest magnetic field for comparison. The PL peak positions for the three configurations are plotted as a function of magnetic field in Fig. 4, to show clearly the energy shifts. As shown in this figure, the bulk PL peak shifts are almost equally independent of the configuration in all the magnetic field regions. However, the PL peak shifts of the QWRs clearly depend on the configuration.

In the low magnetic field region the PL peak positions were diamagnetically changed, and from the data under 10 T the diamagnetic coefficients were determined as 16.3, 7.0, and 4.5 $\mu eV/T^2$ for $\mathbf{W}\perp\mathbf{B}\parallel\mathbf{k}$, $\mathbf{W}\perp\mathbf{B}\perp\mathbf{k}$, and $\mathbf{W}\parallel\mathbf{B}\perp\mathbf{k}$, respectively. These values are not only much smaller than that in the bulk, 103.9 $\mu eV/T^2$, but also comparable to or smaller than that in QWL with a thickness of about 6 nm [20,21]. In the high magnetic field region the energy shifts of the QWRs changed almost linearly against the magnetic field, in the same way as the bulk regarding the Landau level shift. In particular, energy change of the QWRs for $\mathbf{W}\perp\mathbf{B}\parallel\mathbf{k}$ became almost parallel to that of the bulk. This behavior cannot be explained in terms of the change of the band structure related to the GaAs bulk state [13]. It is considered that the exciton or the cyclotron radius becomes much smaller than the width of the confinement potential in the high

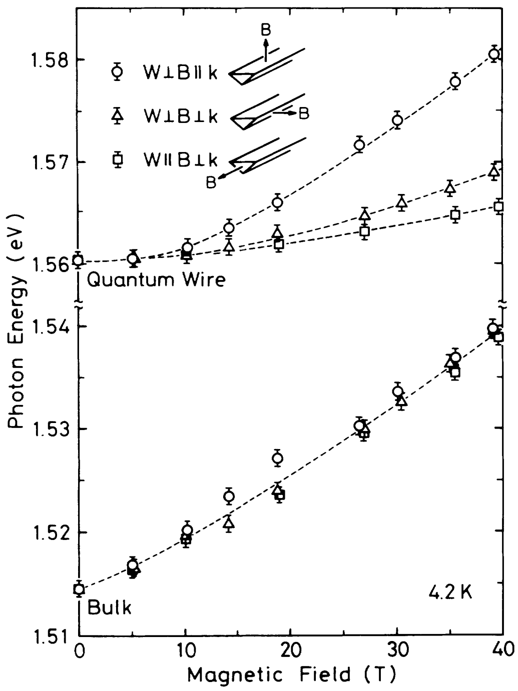

FIG. 4. Photoluminescence peak positions from the quantum wires and the bulk as a function of applied magnetic field for various configurations, where circles, triangles, and squares with error bars represent the data for **W⊥B∥k**, **W⊥B⊥k**, and **W∥B⊥k**, respectively, and the dashed curves are guides to the eye.

magnetic field region.

Magnetic field effects can be treated as a small perturbation in the low magnetic field region. Then, the diamagnetic energy shift is written as follows in first-order perturbation theory assuming anisotropic hydrogenlike excitons [22]:

$$E_{B_i^2}=\frac{4\pi^2\hbar^4\varepsilon^2}{e^2\mu\mu_j\mu_k}B_i^2,\quad i,j,k=x,y,z\,, \tag{1}$$

where $\hbar$, ε, and e are the Planck constant, dielectric constant, and charge of the electron, respectively, and μ is defined as

$$\frac{1}{\mu}=\frac{1}{3}\left(\frac{1}{\mu_x}+\frac{1}{\mu_y}+\frac{1}{\mu_z}\right), \tag{2}$$

with μ_x, μ_y, and μ_z anisotropic reduced exciton masses. Here, these masses are phenomenologically introduced to include the effect of anisotropic confinement and resulting band mixing. This approximation is appropriate under the condition that the exciton confinement is not extremely large and that $\gamma_i=\hbar\omega_{ci}/R^*$ is small, where $\omega_{ci}=eB_i/(\mu_j\mu_k)^{1/2}$ $(i,j,k=x,y,z)$ and R^* are the cyclotron frequency and the exciton Rydberg constant, respectively. By using experimentally determined diamagnetic shifts and Eqs. (1) and (2), the reduced exciton masses μ_x, μ_y, and μ_z were estimated as $0.293m_0$, $0.126m_0$, and $0.081m_0$, respectively, while that in the bulk was $0.059m_0$, where m_0 is the free electron mass, and x and z are defined to be parallel to **k** and **W**, respectively. Here, for the dielectric constant ε, the static dielectric constant of GaAs, $13.1\varepsilon_0$, is employed because the binding energy of the exciton is much smaller than the LO-phonon energy 36.8 meV [23], where ε_0 is the dielectric constant in vacuum. From these values, R^* or the ground-state binding energy $E_b=e^4\mu/32\pi^2\hbar^2\varepsilon^2$ was estimated as 10.1 meV, and the Bohr radius $a_{0i}=4\pi\hbar^2\varepsilon/e^2\mu_i$ $(i=x,y,z)$ as 2.4, 5.5, and 8.6 nm, respectively, while for the bulk $E_b=4.7$ meV and $a_0=11.8$ nm. Here, note that the Bohr radius of excitons in the directions of confinement in the QWRs is much smaller than that in the bulk corresponding to the width of the QWR structure; however, that in the free direction of the QWRs is slightly smaller but almost equal to that in the bulk. Thus, the excitons are anisotropically shrunk in the QWRs by the 2D confinement effect.

On the other hand, in order to interpret the experimental results in the high magnetic field region, where the Coulomb interaction can be approximately neglected, the following parabolic potential is employed as the 2D confinement potential:

$$V=\tfrac{1}{2}m^*\omega_{0x}^2x^2+\tfrac{1}{2}m^*\omega_{0y}^2y^2\,, \tag{3}$$

where m^* $(=0.067m_0$ [24]) is an effective mass of an electron, and ω_{0x} and ω_{0y} are resonant frequencies. Here, the contribution by holes is assumed to be small and neglected because their effective mass $(0.48m_0)$ is much larger than that of electrons in GaAs [24]. When the magnetic field is applied perpendicularly to the QWRs and parallel to the x or y direction, the energy shift is analytically solved as follows [25]:

$$E=\begin{cases}(N+\tfrac{1}{2})\hbar\omega_{0x}+(M+\tfrac{1}{2})\hbar(\omega_{cx}^2+\omega_{0y}^2)^{1/2}, & \mathbf{B}\parallel\mathbf{x}, \quad (4)\\ (N+\tfrac{1}{2})\hbar(\omega_{cy}^2+\omega_{0x}^2)^{1/2}+(M+\tfrac{1}{2})\hbar\omega_{0y}, & \mathbf{B}\parallel\mathbf{y}, \quad (5)\end{cases}$$

where N and M are zero or positive integers, and $\omega_{ci}=eB_i/m^*$ $(i=x,y)$ is a cyclotron frequency. The kinetic energy in the z direction is omitted for optical transitions. Concerning the energy shift by the magnetic field, by fitting Eqs. (4) and (5) to the experimental data at more than 30 T ($\gamma_x=3.4$, $\gamma_y=2.2$) for **W⊥B∥k** and **W⊥B⊥k**, the confinement energies for the lowest subband, $\hbar\omega_{0y}/2$ and $\hbar\omega_{0x}/2$, were estimated as 18 and 62 meV, respectively. These energies correspond to the well widths of $L_y=17.7$ nm and $L_x=9.5$ nm for the square potential with infinite height. These values are a little small but qualitatively in good agreement with the base length (20 nm) and the height (10 nm) of the triangular-shaped QWR structure, respectively.

When the magnetic field is applied parallel to the QWRs, the energy shift is represented as follows [26]:

$$E=(N+M+1)\tfrac{1}{2}\hbar(\omega_{cz}^2+4\omega_0^2)^{1/2}+(N-M)\tfrac{1}{2}\hbar\omega_{cz}\,,\quad \mathbf{B}\parallel\mathbf{z}\,, \tag{6}$$

where this equation is for the cylindrical-symmetry case ($\omega_{0x}=\omega_{0y}=\omega_0$). By fitting Eq. (6) to the experimental data at more than 30 T ($\gamma_z=1.8$) for $\mathbf{W}\parallel\mathbf{B}\perp\mathbf{k}$, the confinement energy for the lowest subband $\hbar\omega_0$ was estimated as 104 meV. This value is a little larger than the total confinement energy, $\hbar\omega_{0x}/2+\hbar\omega_{0y}/2=80$ meV, because the data in this configuration include a comparatively large diamagnetic contribution, but they are reasonably close, which supports the present model for interpreting the experimental results. The obtained confinement energy minus the QWR exciton binding energy plus the bulk exciton one at $B=0$ (73.8 meV) is larger than the energy between the PL peak position of the QWRs and that in the bulk (46 meV). This discrepancy may be due to the neglect of the contribution of holes, the application of parabolic potentials, and the difference between the cross section shape of the actual QWR structure and that in the calculation in the second model. However, this discrepancy will be eliminated by more rigorous calculations [27] or experiments using higher magnetic fields in which the condition $\gamma\gg1$ is fully satisfied.

In conclusion, the observed anisotropic magnetic field dependence of the PL peak shift of the QWRs demonstrates a direct evidence for the existence of 2D confinement in the QWRs. The measurement of anisotropic magnetic field dependence is a useful method for confirming 2D and further 3D confinement.

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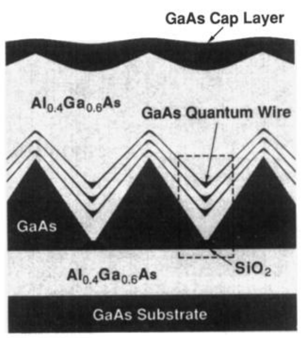
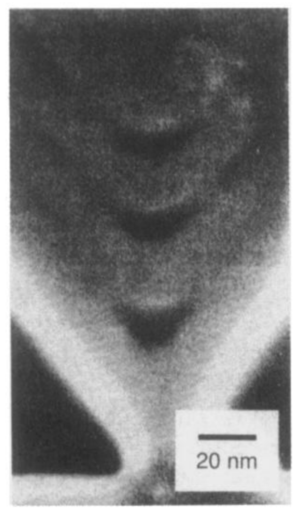


(a)



(b)

FIG. 1. (a) Schematic illustration of the cross section of the vertically stacked multiple quantum wires, and (b) high-resolution secondary electron image of the region near the quantum wires of which the area is corresponding to that surrounded by broken lines in (a).