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Fabrication of a GaAs quantum-well-wire structure by Ga focused-ion-beam implantation and its optical properties

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A quantum-well wire was fabricated with use of local intermixing of a GaAs-Al_x-$Ga_{1-x}As$ single-quantum-well epitaxial layer induced by Ga focused-ion-beam implantation. Fine structures were observed in low-temperature photoluminescence and photoluminescence excitation spectra. These fine structures are explained by the density of states specific to the two-dimensionally confined carrier system.

A semiconductor quantum-well wire (QWW) is a two-dimensional carrier-confinement structure in which carriers can move freely only in one-dimensional direction [one-dimensional (1D) electrons or holes]. Since a two-dimensional quantum-size effect (2D QSE) is expected, the QWW has been receiving much attention from the view points of physics as well as applied physics.

Electron conduction in QWW has been reported by several groups.[1-4] Some of them fabricated QWW by reactive ion etching[1] of Si MOS (metal-oxide-semiconductor) material and other workers demonstrated 1DE in narrow channels realized by confinement due to electric potential applied to two-dimensional electron systems[2-4]. However, these reports did not describe anything about optical properties. This is mainly because 2D QSE in the optical property manifests itself only in a structure where confinement is provided for holes as well as for electrons. There have been few reports concerned with the optical properties of QWW.[5,6] In these papers QWW structures were fabricated by mesa etching of GaAs-$Al_xGa_{1-x}As$ single-quantum-well (SQW) or multiple-quantum-well (MQW) epitaxial wafer. Petroff, Gossard, Logan, and Wiegman[5] found the localization of the cathodoluminescence intensity along the QWW, and Reed *et al.*[6] found the increase of the relaxation time in the multidimensional carrier confinement system. However, the change of density of states specific to the multi-dimensional quantum-sized effects[7] has not yet been reported.

In this paper, we report on fabrication of QWW's using local intermixing of a GaAs-$Al_xGa_{1-x}As$ SQW structure induced by Ga focused-ion-beam (FIB) implantation and subsequent annealing.[8] Photoluminescence (PL) and photoluminescence excitation (PLE) spectra measured at 4 K on the QWW's are presented. They show fine peak structures,[9] which is considered to be related with the density of states specific to 2D QSE.

A GaAs (5.5 nm)-$Al_{0.5}Ga_{0.5}As$ SQW epiwafer was used in the present case, in place of the MQW one in the previous case,[8] in order to minimize the inhomogeneity in the depth direction inevitably encountered in the ion implantation process. The epilayer was undoped and grown by molecular-beam epitaxy (MBE) at a growth temperature of 650 °C. In order to fabricate QWW structures, a Ga FIB was scanned in a line (100 nm)-and-space (200 nm) pattern over the epilayer surface. Beam current, energy, and ion dose were 20 pA, 100 keV, and 1.6×10^{14} cm^{-2}, respectively. Then, the sample was annealed at 800 °C for 60 min in an H_2 ambient with the sample surface covered by the another GaAs wafer. A cross-sectional transmission electron microscope (TEM) observation shows the QWW structure laterally confined by the intermixed region in the similar fashion as reported in Ref. 8. Further, a TEM lattice image observation indicated that there were few crystalline defects in the disordered region.[10]

The optical properties of the QWW fabricated here were studied by PL and PLE spectra at ~4 K. The PL spectrum was measured under Ar laser (514.5 nm) excitation. The excitation laser power and beam diameter were 500 μW and 5-7 μm, respectively. The spectral resolution was 0.5 meV. In Fig. 1, the solid line indicates the PL spectrum measured for the QWW structure and the broken line indicates the reference spectrum measured for the SQW epilayer annealed without implantation. The reference spectrum is the same as that observed for the as-grown SQW. The PL peak of the QWW is shifted to the higher-energy side compared with that of the reference sample. This energy shift is mostly due to the small amount of intermixing that occurred even in the space region resulting from the tail of the Gaussian-shaped Ga FIB as discussed later. Most important is the well-defined multiple peak structures seen in the solid line spectrum. The peaks denoted by arrows are distinct from the noise level of the measuring system. The energy interval between the adjacent peaks was 3.8-6.2 meV for this QWW. Although a multiple peak spectrum has sometimes been observed for as-grown quantum wells, it is explained in terms of the well layer thickness fluctuation by an amount of an atomic layer.[11,12] However, this possibility can be ruled out in the present case since the as-grown SQW showed no such multiple peak structures, as shown by the broken line. Therefore, the multiple peak structures observed only in the line-and-space ion-implanted sample probably relate to the lateral confinement of the excited carriers.

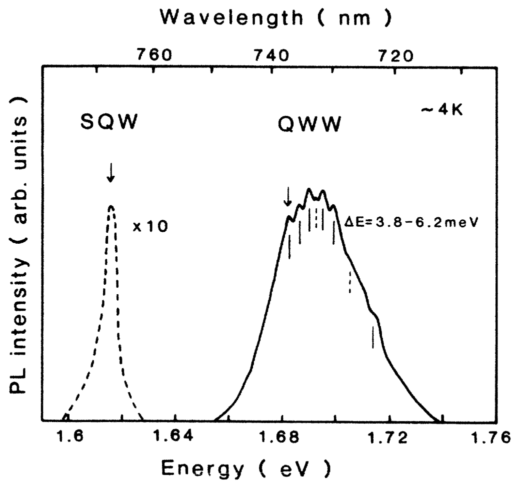

FIG. 1. Photoluminescence spectra measured at ~4 K for QWW structure (solid line) and reference SQW only annealed without implantation (broken line). Solid bars indicate the position of clear peak structures and broken bars indicate indistinct ones. Downward arrows indicate the wavelength, where excitation spectra shown in Fig. 2 were measured.

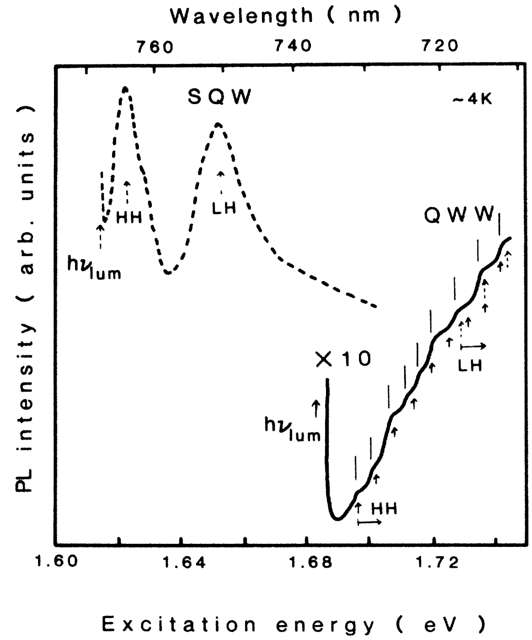

FIG. 2. Photoluminescence excitation spectra measured at ~4 K for QWW structure (solid line) and reference SQW (broken line). The detection wavelength is denoted by upward arrow $h\nu_{lum}$. Solid bars above the spectrum of QWW indicate energy positions of the observed fine structures. Solid arrows and broken arrows under the spectrum QWW indicate calculated heavy-hole related and light-hole related transitions, respectively.

Figure 2 shows the PLE spectra for the QWW and for the reference SQW. The excitation power was between 400 μW and 2 mW, and beam diameter was again about 7 μm. The detection wavelength ($h\nu_{lum}$) was set to 737 nm (1.683 eV) and 768 nm (1.615 eV) for the QWW and for the reference SQW, respectively, which were near the peaks of the respective PL spectra. The resolution of the luminescence detection was 0.5 meV. In the PLE spectrum for the reference SQW, the peaks at 1.623 eV and at 1.654 eV are the $n=1$ heavy-hole exciton and light-hole exciton, respectively. In the PLE spectra of the fabricated QWW, exciton peaks are not clear; however, the fine structures are clearly observed again. These structures are also distinct from the noise level of the measuring system. In Fig. 2, energy positions of fine structures are indicated by solid bars above the spectrum. The energy intervals of the adjacent solid bars were in the range between 5.2 and 7.4 meV, and approximately agreed with the energy interval of multiple peaks observed in PL spectrum.

Theoretically, the density of states as a function of energy $D(E)$ for electrons and holes changes from a staircase function in a quantum well (one-dimensional QW) to a saw-tooth function in a QWW (two-dimensional QW) The energy positions of the sawtooth peaks correspond to the quantum states in the QWW. Energy levels of quantum states depend both on the thickness L_z, and on the lateral width of the wire L_y. In the present QWW, $L_z \ll L_y$, so that the expected $D(E)$ near the absorption edge region is basically a series of sawtooth-like functions reflecting the energy levels quantized in the lateral direction.

For energy levels in the present two-dimensionally confined structure, we calculate lateral profile of Al content taking into consideration the Gaussian distributed Ga ion beam profile, lateral straggling of implanted Ga at 100 keV, and diffusion of implanted species. Furthermore, we

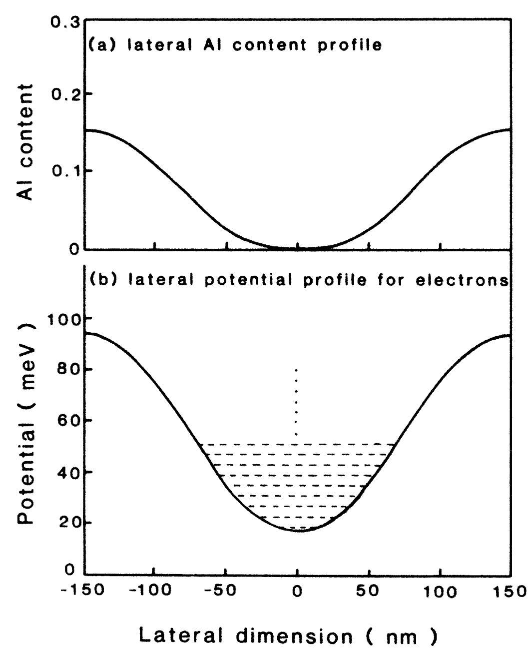

FIG. 3. Calculated lateral profile of (a) Al content along the center plane of SQW and (b) potential for electrons. Laterally quantized energy levels were calculated using Schrödinger equation and shown in (b) as broken lines.

take into account the fact that the interdiffusion constant of Al and Ga at the heterointerface is proportional to the implanted Ga density.[13] Diffusion constant of implanted Ga of 8×10^{-15} cm^2/s (Ref. 14) was also used here. The calculated lateral Al content profile along the center plane of SQW is shown in Fig. 3. The potential profile for electrons is determined from this Al content profile and also shown in Fig. 3. Energy levels of quantum states were calculated from this potential profiles using Schrödinger equation. As shown in Fig. 3, the energy-level separation is approximately constant in this case, because the potential profile is approximately parabolic in the bottom of the well. The lateral width of QWW (W) determined from half maximum of Al profile was about 160 nm. However, the effective lateral widths for the first and the second quantum levels are less than 50 nm. The same calculation was also carried out for heavy holes and light holes.

The calculated energy-level positions of optical transition are also shown in Fig. 2. Solid arrows and broken arrows under the spectrum indicate the heavy-hole related peaks and light-hole related peaks, respectively. Here, we consider only diagonal transitions. ($\Delta n=\Delta m=0$, where n and m are the quantum numbers in the z and y directions, respectively.) For the convenience of comparison between the calculation and the observation, the lowest calculated transition energy was fitted to the lowest-energy fine structure observed in PLE spectra, and the differences of the transition energies from this ground state are indicated. The energy positions of observed fine structures agreed reasonably well with the calculated heavy-hole related levels and light-hole related levels. This agreements suggests that the observed fine structures are originated from the lateral carrier confinement in the fabricated QWW.

A discussion is given on the influence of the inhomogeneity of lateral width along a QWW upon the optical-absorption spectral shape. The optical-absorption coefficient α_{QWW} at a photon energy $h\nu$ was already given as follows by taking energy broadening ΔE of the sawtooth function[7,15] into consideration.

$$\alpha_{QWW} \propto \sum_{n,m,i} \sqrt{\mu_i} \left\{ \frac{h\nu - E_{n,m,i} + [(h\nu - E_{n,m,i})^2 + (\Delta E)^2]^{1/2}}{2[(h\nu - E_{n,m,i})^2 + (\Delta E)^2]} \right\}^{1/2} . \tag{1}$$

Here, μ_i and $E_{n,m,i}$ indicate reduced effective mass of heavy hole ($i=h$) and light hole ($i=l$), and transition energy between quantized electron levels and quantized hole levels, respectively, where n and m indicate the quantum number in the z and y direction, respectively. In the present case, L_z($=5.5$ nm) is very small compared with the lateral width, therefore we consider only the lowest energy level ($n=1$) for the z-direction quantization. Exciton effects are neglected in this calculation.

As an origin of ΔE, we consider two factors. One is the thermal broadening (kT) and the other is broadening due to the inhomogeneity of the lateral wire width $[(\partial E_{n,m,i}/\partial W)\Delta]$. Here, W indicates the lateral width of QWW determined from the half maximum of Al content and Δ indicates the fluctuation of W.

$$\Delta E = \mathrm{kT} + \frac{\partial E_{n,m,i}}{\partial W}\Delta . \tag{2}$$

$(\partial E_{n,m,i}/\partial w)\Delta$ includes quantum energy-level fluctuation both by the change of effective lateral width and by the change of Al content at the bottom of well. Figure 4 shows the calculated absorption spectrum of the QWW for several degrees of inhomogeneity Δ. In Fig. 2 we observed fine structures in PLE spectra, but they are not clear peaks. This reason is considered to be the inhomogeneity Δ as shown in Fig. 4. By comparing Fig. 4 with the observed PLE spectrum shown in Fig. 2, we can estimate that the present QWW has Δ of 5–7.5 nm. From the foregoing, it is anticipated that a smaller sized FIB along with precise control in the annealing process will realize a clearer and more regular spectrum in the near future.

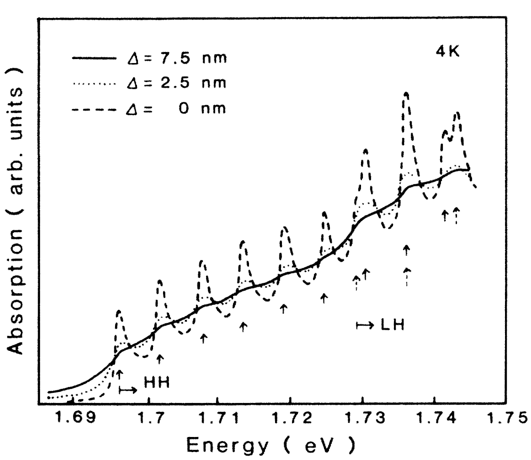

FIG. 4. Calculated absorption spectrum of QWW at 4 K under several degrees of inhomegeneity Δ in the lateral width of QWW.

In summary, a QWW structure was fabricated using local intermixing of a GaAs-$Al_xGa_{1-x}As$ single-quantum-well epitaxial wafer induced by Ga FIB implantation and subsequent annealing. The photoluminescence and its excitation spectrum measured at ~4 K showed fine structures, which are explained by the two-dimensional quantum-size effect.

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[1]W. J. Skocpol, L. D. Jackel, E. L. Hu, R. E. Howard, and L. A. Fetter, Phys. Rev. Lett **49**, 951 (1982).

[2]A. B. Fowler, A. Hartstein, and R. A. Webb, Phys. Rev. Lett. **48**, 196 (1982).

[3]C. C. Dean and M. Pepper, J. Phys. C **15**, L1287 (1982).

[4]A. C. Warren, D. A. Antoniadis, and H. I. Smith, Phys. Rev. Lett. **56**, 1858 (1986).

[5]P. M. Petroff, A. C. Gossard, R. A. Logan, and W. Wiegman, Appl. Phys. Lett. **41**, 635 (1982).

[6]M. A. Reed, R. T. Bate, K. Bradshaw, W. M. Duncan, W. R. Frenseley, J. W. Lee, and H. D. Shih, J. Vac. Sci. Technol. B **4**, 358 (1986).

[7]H. H. Hassan and H. N. Spector, J. Vac. Sci. Technol. A **3**, 22 (1985).

[8]Y. Hirayama, Y. Suzuki, S. Tarucha, and H. Okamoto, Jpn. J. Appl. Phys. **24**, L516 (1985).

[9]After submission of this paper, Cibert *et al.* independently reported multiple peak structures in low-temperature cathodoluminescence of QWW fabricated by Ga implantation induced intermixing. J. Cibert, P. M. Petroff, G. J. Dolan, S. J. Pearton, A. C. Gossard, and J. H. English, Appl. Phys. Lett. **49**, 1275 (1986).

[10]Y. Suzuki, Y. Hirayama, and H. Okamoto, Jpn. J. Appl. Phys. **45**, L912 (1986).

[11]L. Goldstein, Y. Horikoshi, S. Tarucha, and H. Okamoto, Jpn. J. Appl. Phys. **22**, 1489 (1983).

[12]T. Hayakawa, T. Suyama, K. Takahashi, M. Kondo, S. Yamamoto, S. Yano, and T. Hijikata, Appl. Phys. Lett. **47**, 952 (1985).

[13]The relation between interdiffusion and implanted Ga density is estimated from the PL peak shift in the uniformly implanted region. The linear relation between interdiffusion coefficient and Ga ion dose was realized at the dose range from 10^{12} cm^{-2} to 1.6×10^{14} cm^{-2}.

[14]Y. Hirayama, Y. Suzuki, and H. Okamoto, Surf. Sci. **174**, 98 (1986).

[15]L. M. Roth, B. Lax, and S. Zwerdling, Phys. Rev. **114**, 90 (1959).