Observation of exciton states in GaAs coupled quantum wires on a V-grooved substrate

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The exciton states of GaAs coupled quantum wires are investigated by the measurement of photoluminescence excitation (PLE) in comparison with those of single quantum wires. In the PLE spectra of single quantum wires (wire thickness=4.5 nm), sharp exciton peaks of the first two heavy hole-like transitions are observed with large energy difference of 47 meV, while two adjacent exciton peaks with the small energy splitting of 24 meV are observed in the coupled quantum wires (wire thickness=5 nm, barrier thickness=3 nm). From the measurements of the barrier thickness dependence, these exciton states agree well with the coupled states of the quantum wires calculated by the finite element method. © 1997 American Institute of Physics. [S0003-6951(97)03349-4]

The low dimensional structures have been actively studied since superior optical and electronic characteristics are theoretically expected. The coupled lower dimensional structures, such as coupled quantum wires and dots, are more attractive candidates since they can be applied not only for new functional devices but also for the ultrafast optoelectronic devices with quantum oscillation.

We have reported the fabrication of coupled quantum wires by using flow rate modulation epitaxy and also reported the theoretical analysis of the electron states in coupled quantum wires. However, the exciton states in the crescent shaped coupled quantum wires have not been clarified yet. In this letter, we have investigated the optical properties in the crescent shaped GaAs coupled quantum wires by the photoluminescence excitation (PLE) measurement and observed the exciton states including the coupled states.

In order to fabricate high quality quantum wires, we use the selective growth on a nonplanar substrate. The quantum wire array with period of 4.8 μm was fabricated by the process described in the previous publication. Figure 1 shows the cross-sectional transmission electron microscope (TEM) picture of the coupled quantum wire samples, with different barrier thickness of (a) 1.5 nm, (b) 2.3 nm, and (c) 3.3 nm. Very small crescent shaped GaAs quantum wires with a central thickness of 5 nm separated by a thin Al0.38Ga0.62As barrier layer are clearly observed at the bottom of the V grooves. The vertical quantum film with Al contents of 0.28 can be seen along the (100) direction which is automatically formed during the growth.

The charge density probability associated with the first three confined electron states (conduction subbands) in the coupled quantum wires are calculated by the finite element method (FEM) using the same procedure in Ref. 10 with same parameter of Ref. 6 with the results shown in Fig. 1(d). The first, the second, and the third states, correspond to the symmetric state (1e), the antisymmetric state (2e), and the transverse electron-wave state (3e) due to the confinement in the transverse (x) direction. In the following, we call the exciton states for electron and heavy hole like transition as ie→jhh, and for the light hole like transition as ie→jlh, where i(=1,2,...,n) and j(=1,2,...,m) are the quantized number of the wave function for electron and heavy holes, respectively.

Figure 2 shows the PLE spectra of quantum wires measured at 20 K with the polarization of excitation laser parallel (PLE∥) and perpendicular (PLE⊥) to the quantum wires for (a) single quantum wire with the wire thickness of 4.5 nm, (b) weakly coupled quantum wires with wire thickness of 5 nm, and barrier thickness of 3 nm, and (c) strongly coupled quantum wires with wire thickness of 5 nm and barrier thickness of 2 nm.

In the single quantum wire, sharp exciton peaks of the first two heavy hole-like transitions at 1.6521 and 1.6986 eV are observed with a large energy difference of 46.5 meV. These peaks are due to the transition of fundamental (1e→1lh), and the second (2e→2lh) states because their energy difference is in good agreement with the theoretical analysis of FEM of 44 meV. In the spectra of PLE⊥, the first light hole-like transitions 1e→1lh and 1e→2lh at 1.666 and 1.6773 eV are also observed.

In the weakly coupled quantum wires with barrier thickness of 3 nm, the adjacent two peaks at 1.6325 and 1.6568 eV appear near the fundamental transition energy in PLE∥. These peaks are regarded as the symmetric states 1e→1lh, antisymmetric states 2e→2lh because the energy separation of 24.3 meV between 1e→1lh and 2e→2lh is close to 19 meV of the theoretical analysis.

In the strongly coupled quantum wires with barrier thickness of 2 nm, different structures are observed in the PLE∥. The first two peaks at 1.6409 and 1.6820 eV are regarded as symmetric states 1e→1lh, antisymmetric states 2e→2hh by comparison of the energy separation between 1e→1lh and 2e→2hh of 41.1 meV to that of the theoretical analysis of 33 meV. The separation energy between 1e→1lh and

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$2e-2hh$ becomes larger compared to the weakly coupled quantum wires and the light hole-like transition $1e-1hh$ with energy of 1.6641 eV are observed between $1e-1hh$ and $2e-2hh$ in PLE.

The Stokes shift for single quantum wires (thickness of wire: 4.5 nm) is 4.4 meV. While those for coupled quantum wire (thickness of wire: 5 nm) with barrier thicknesses of 1.5, 2, and 3 nm are 6.3, 6.5, and 4.1 meV, respectively. The Stokes shift becomes larger for the strongly coupled quantum wire. Also that for weakly coupled quantum wire with wire thickness of 3 nm is almost the same as that of single quantum wires. Large Stokes shift in the strongly coupled quantum wires might be caused by another localization factor due to the interface quality of the AlGaAs barrier layer. A decrease of the barrier thickness enhances the influences of the atomic surface roughness of the AlGaAs layer which causes not only broadening of the PL linewidth but also increases the localization energy.

The PL wave-length of the quantum wire is believed to be the growth rate difference and not due to the difference of Al composition. From the theoretical analysis, the decrease in thickness of barrier layer increases each transition energy. The decrease in the thickness of barrier layer increases the splitting energy between symmetric states $1e-1hh$ and antisymmetric state $2e-2hh$ and decreases the transition energy of symmetric states $1e-1hh$, $3e-3hh$, and increases the transition energy of antisymmetric states $2e-2hh$. Thus we can expect theoretically that the increase in the energy of $1e-1hh$ and
3e−3hh is smaller than the increase in the energy of 2e−2hh versus the increase of PL energy. In order to confirm this we have plotted the transition energy of $E(1e−1hh)$, $E(2e−2hh)$, and $E(3e−3hh)$ as a function of the PL energy $E(PL)$ of 1e−1hh and obtained the line with the slope of $\Delta E(1e−1hh)/\Delta E(PL) \sim 1.0$, $\Delta E(2e−2hh)/\Delta E(PL) = 1.55$, $\Delta E(3e−3hh)/\Delta E(PL) = 1.36$. These slopes are in good agreement with the theoretical results with the slopes of 1.00, 1.67, and 1.31 for 1e−1hh, 2e−2hh, and 3e−3hh, respectively, where we assume that both the thickness of quantum wire layer and barrier layer change with the same rate.

The splitting energy between symmetric states 1e−1hh and antisymmetric states 2e−2hh are measured from LT PL (15 K, intensity of 46 W/cm$^2$), RT PL (290 K, intensity of 2.3 W/cm$^2$), and LT PL (20 K) at the central area of the wafer for several samples with different barrier thickness and fixed thickness of bottom (r1) and top (r2) quantum wires (r1 ~ 5.1 nm and r2 ~ 4.6 nm). The results are shown in Fig. 4. Because the subpeak of antisymmetric states 2e−2hh in PL spectra were separated by using the Gaussian distribution fitting, the error of about a few meV exist in the data of PL. The solid and dotted curves show the theoretical values calculated by FEM for antisymmetric states 2e−2hh, and those of higher order coupled states 3e−3hh, respectively. The theoretical curves approach the fixed value of 6 meV when the barrier thickness exceeds 5 nm. This value corresponds to the difference of the energy between the top and the bottom quantum wires.

The barrier thickness dependence is large for the coupled states 2e−2hh, while it is small for the transverse states 3e−3hh. The energy splitting between 1e−1hh and 2e−2hh, which increases with the decreasing barrier thickness, can be explained as the coupling effect in the coupled quantum system. The deviation between LT PLE and the theoretical one may be explained by the fact that the energy difference between top and bottom quantum wire is larger by several meV for these samples, which is caused by the reading error of the TEM picture in the theoretical analysis.

The splitting energy between 1e−1hh and 2e−2hh for low temperatures (LT) PLE is almost the same as those of low temperature (LT) PL in these coupled quantum wires except in the strongly coupled quantum wire with barrier thickness of 1.5 nm. Recently, Wang et al. reported the difference of the Stokes shift between 1e−1hh (Stokes shift: 4 meV) and that of 2e−2hh (Stokes shift: 17 meV) for single quantum wire (thickness of 4.5 nm). They explained this by the strong localization in 2e−2hh states due to the spatial separation of the wave function with different confinement.12 As can be seen from Fig. 1(d), the spatial separation of the wave function of symmetric 1e−1hh and antisymmetric states 2e−2hh is small. The splitting energy difference between LT PL and LT PLE, which corresponds to the Stokes shift difference between 1e−1hh and 2e−2hh, for weakly coupled quantum wire is smaller than those of single quantum wire of 13 meV.12

In summary, we have investigated exciton states including coupled states in the coupled quantum wires by the examination of PL and PLE. In the polarization dependent PLE characteristics, coupled states of symmetric states 1e−1hh and antisymmetric states of 2e−2hh were clearly observed for the coupled quantum wires. The splitting energy, i.e., the energy difference between 1e−1hh and 2e−2hh states, increases as the barrier thickness decreases from 6 to 1.5 nm, which is in good agreement with theoretical analysis.