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Electron States in Crescent GaAs Coupled Quantum-Wires

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The electron states in crescent GaAs coupled quantum-wires fabricated on V-grooved substrate have been investigated by using both the theoretical analysis of finite element method (FEM) and the experiment on photoluminescence (PL) characteristics. The symmetric and the anti-symmetric electron states of the crescent GaAs coupled quantum-wires are clarified by the FEM analysis. In the PL measurement, the clear energy splitting between the symmetric and the anti-symmetric states are observed. These experimental results are in good agreement with the theoretical analysis.

1. Introduction

The coupled lower dimensional structures, such as coupled quantum-wires and -dots[1][2], can be applied not only for new functional devices but also for the ultrafast optoelectronic devices with quantum oscillation[3][4]. We have reported the fabrication of coupled quantum-wires by using flow rate modulation epitaxy and reported the preliminary characteristics.[5] However, the electron states in the crescent coupled quantum-wires have not been investigated yet.

In this paper, we report the electron states in the crescent GaAs coupled quantum-wires by both the theoretical analysis using the finite element method (FEM) and the temperature characteristics of photoluminescence (PL). As a result, the experimental data agree with the theoretical analysis and this explains the coupling effect in the coupled quantum-wires.

2. Structure of coupled quantum-wires

The GaAs coupled-quantum wires were fabricated by the growth of a GaAs, an AlGaAs buffer layers, a GaAs quantum-wire, an AlGaAs barrier layer, a GaAs quantum-wire and a AlGaAs protection layer on the (100) oriented V-grooved GaAs substrate using the metalorganic chemical vapor deposition (MOCVD) growth method[5]. In order to obtain very small size and high quality quantum wires, we used the flow rate modulation epitaxy (FME) method during the growth of GaAs quantum wires[6]. After the masks were formed on the quantum-wires, the (100) quantum-films on the mesa top and the (111) quantum-films around the mesa top were removed using chemical etching.

(a)

(b)

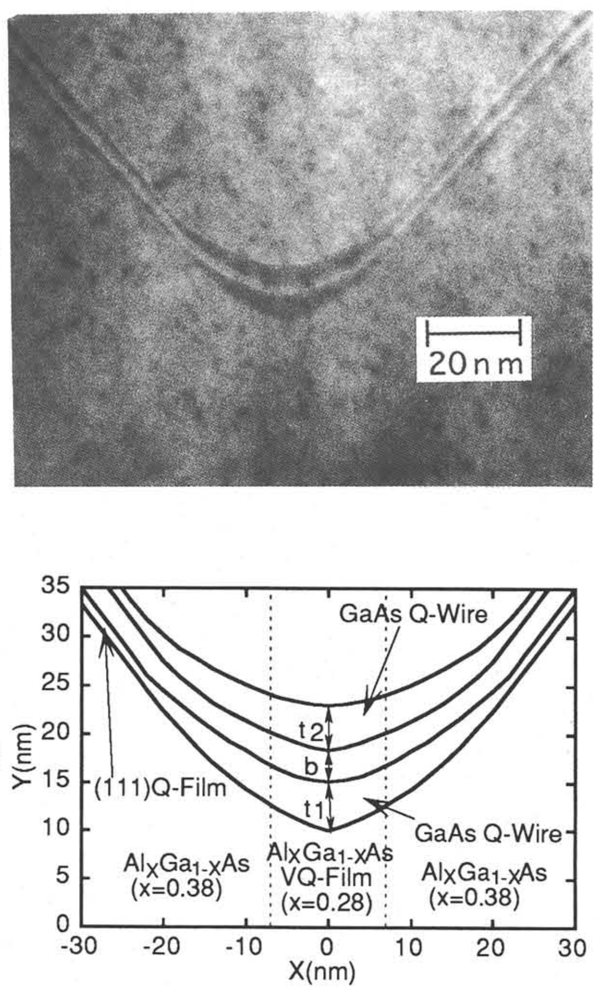

Fig.1(a) TEM picture of coupled quantum-wires
(b) Analysis model (b=3nm)

The cross-sectional TEM picture of the coupled quantum-wire are shown in fig.1(a). Very small crescent shaped quantum-wires with a central thickness of 5nm and a lateral width of 30nm (effective width of 15nm) separated by a 2nm thick AlGaAs barrier layer are clearly observed at the bottom of the V-groove. The top and the bottom quantum-wires have almost the same crescent shape, while the central thickness and the width of the top quantum-wire is slightly thinner and slightly wider than those of the bottom quantum wire, respectively.

3. FEM analysis

The analytical model of the coupled quantum-wires is traced from the TEM picture and is shown in Fig.1(b). This consist of two crescent GaAs quantum-wires, $Al_{0.38}Ga_{0.62}As$ barrier layers, and an $Al_{0.28}Ga_{0.72}As$ vertical quantum film.

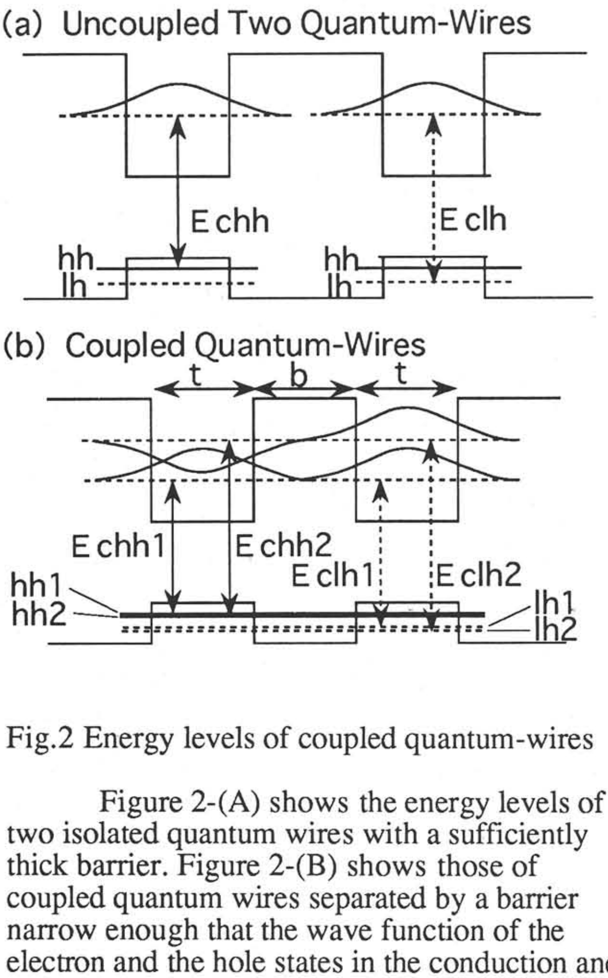

Fig.2 Energy levels of coupled quantum-wires

Figure 2-(A) shows the energy levels of two isolated quantum wires with a sufficiently thick barrier. Figure 2-(B) shows those of coupled quantum wires separated by a barrier narrow enough that the wave function of the electron and the hole states in the conduction and valence bands in adjacent wells overlap. We assume the heavy holes (hh) like states and light holes (lh) like state in the quantum wire, since the cross sectional ratio of width to thickness of the quantum wires is large. These hh-like and lh-like states are shown in Fig.2.

For the coupled quantum wires, the energy level splitting occurs due to the coupling. We can call the energy difference between the two coupled-states as the " splitting energy ". Also we can call the coupled lower energy state as the " symmetric state ", and the coupled higher energy state as the "anti-symmetric state ".

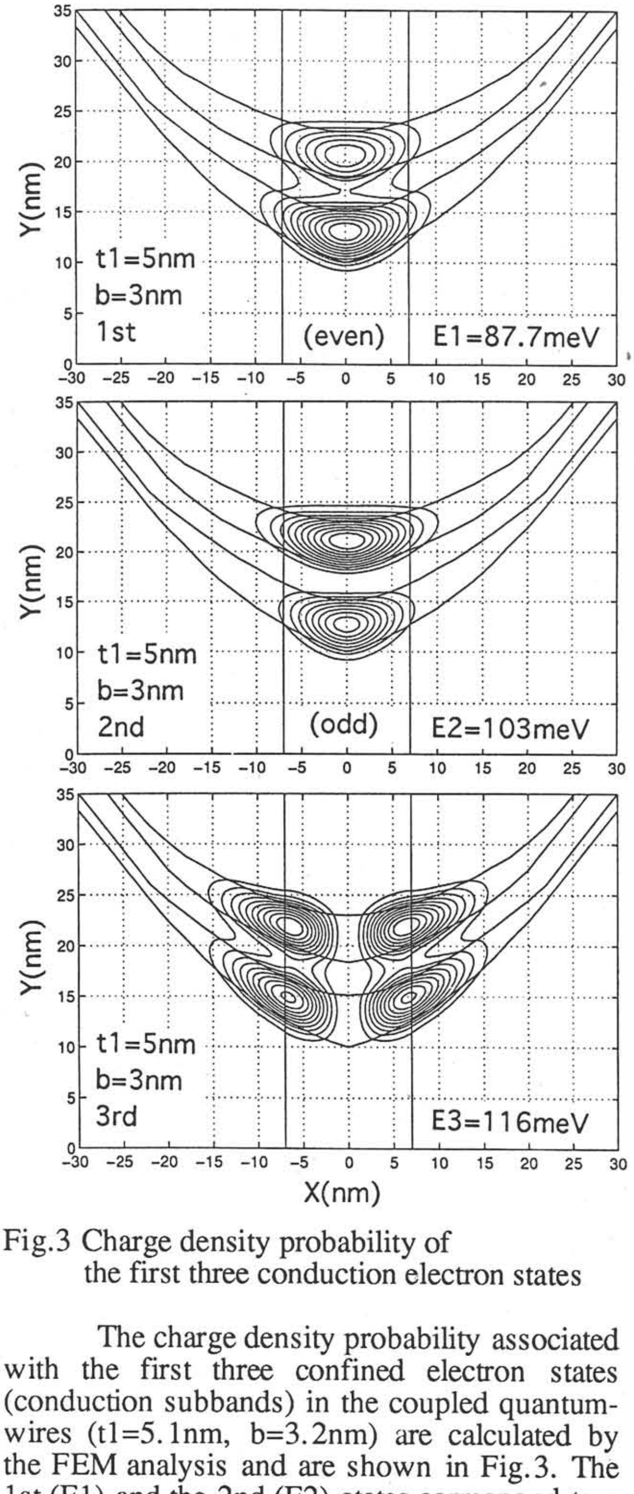

Fig.3 Charge density probability of the first three conduction electron states

The charge density probability associated with the first three confined electron states (conduction subbands) in the coupled quantum-wires (t1=5.1nm, b=3.2nm) are calculated by the FEM analysis and are shown in Fig.3. The 1st (E1) and the 2nd (E2) states correspond to a symmetric state and an antisymmetric state of the coupled systems[7] while the 3rd state (E3) is the transverse electron-wave state due to the confinement in the transverse (x) direction. The energy splitting between 1st and 2nd state is explained by the coupling effect.

In order to obtain the transition energy of the coupled quantum-wires, the heavy hole -like states are calculated by the FEM analysis.

4. Experiment and Discussions

Figure 4 shows the temperature characteristics of PL from the coupled and the single quantum-wires. At low temperature, the sharp single peak around 760nm is the PL from the quantum-wires, while those around 660nm and 670nm are the PL from the vertical quantum-film and the (111) quantum-film, respectively. The single peak from the coupled quantum-wires at low temperature is considered as the transition of the symmetric coupled states of electron and hole. The PL peak from the coupled quantum-wires shows the shoulder on the higher energy side of the main peak as the temperature increase and it changes into two peaks at room temperature.

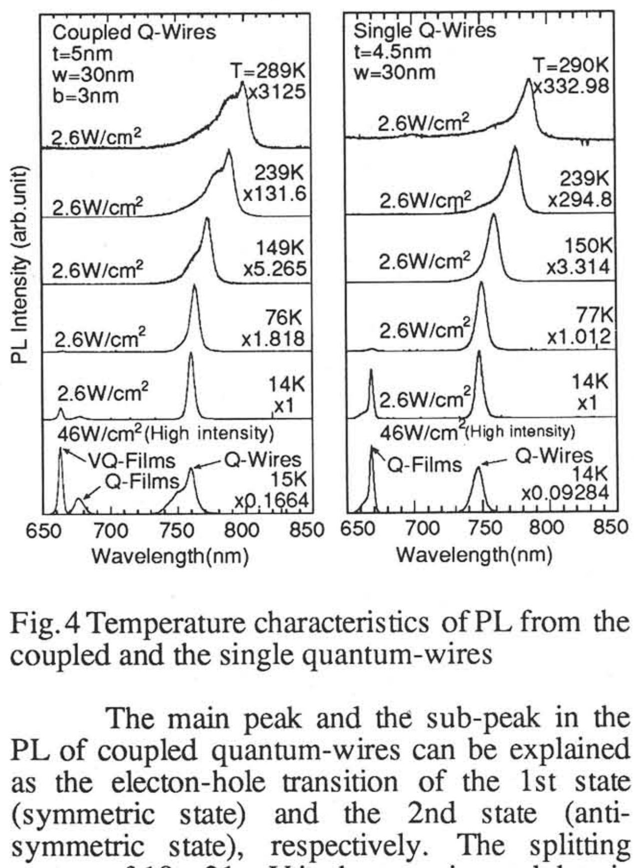

Fig.4 Temperature characteristics of PL from the coupled and the single quantum-wires

The main peak and the sub-peak in the PL of coupled quantum-wires can be explained as the electon-hole transition of the 1st state (symmetric state) and the 2nd state (anti-symmetric state), respectively. The splitting energy of 18 - 21meV in the experimental data is well explained by the FEM results of 17meV for the coupled quantum-wires with a barrier thickness of 3nm. Thus, this splitting can be explained as the coupling effect in the coupled quantum-wires.

In the PL spectra of single quantum-wires, very small sub-peak appeared at the shorter wavelength side of the main peak. This is considered as the transverse electron-wave state transition, which is also explained by the results of FEM analysis of the single quantum wires.

Conclusions

We have investigated the electron states in crescent GaAs coupled quantum-wires fabricated on V-grooved substrate by using both the theoretical analysis of finite element method (FEM) and the experiment on photoluminescence (PL) characteristics. Coupling effects as well as one dimensional quantum effect in the cresent GaAs coupled quantu-wires are clarified by the FEM analysis and the PL characteristics.

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