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ELECTRON COUPLING IN InGaAs/GaAs QUANTUM DOT-PAIRS FABRICATED WITH InP ISLAND STRESSORS

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Abstract

Coupled quantum dot (QD)-pairs were fabricated by stressing the near-surface InGaAs/GaAs coupled quantum wells (QWs) with self-assembled InP islands. The coupling strength in the dot-pair was studied by varying the barrier layer width separating the two dots and the indium composition in the lower dot. Strong coupling was observed at a barrier less than 4 nm. Anti-bonding of the two ground states as well as all the bonding states were observed by state filling in the photoluminescence spectra. By tuning the indium composition in the lower QW to adjust the lower QD state energies before coupling relative to those in the upper QD, crossing of the bonding and anti-bonding states is achieved.

I. Introduction

Recent years, zero-dimensional semiconductor quantum dots (QDs), being artificial atoms, have attracted considerable attention (1-6). Fabrication of artificial molecules by coupling two or more quantum dots opens a new way to investigate the quantum phenomena over a wide range of configuration. Electronic coupling processes have been investigated in coupled dot-pair or dot-chain structures (4-7), and the formation of bonding and anti-bonding states has been observed in symmetric dot-pairs (8). In order to avoid non-radiative recombination defects caused by nano-fabrication processes, a one step growth process is desired. Stranski-Krastanow growth of self-assembled quantum dots (SADs) can be vertically self-aligned and electronically coupled (4,5). However, the diversity of the actual size, shape and composition of SADs and the strain effect of one SAD to its paired one make it difficult to control the electronic structure in the coupled SADs. In contrast, strain-induced quantum dots (SIDs) formed by locally straining a near-surface quantum well (QW) with self-assembled islands have nearly equal energy spacing of the state levels which is normally larger than the inhomogeneous broadening (6,9,10). By tensile stressing of the near-surface coupled quantum wells (QWs), a quantum dot-pair can be formed. The coupling strength in the dot-pair can be studied by tuning the barrier layer width separating the two dots and the relative state levels in both dots. In this study, we systematically investigated both the lateral and vertical quantum confinements in InGaAs/GaAs SIDs and coupling in the dot-pair by tuning the GaAs caplayer thickness, barrier width, quantum well width and composition.

II. Experimental

Samples were fabricated in an EMCORE D-75 MOVPE chamber at 60 torr. The substrates were semi-insulating GaAs (001) ± 0.5° rotating at 1400 revolutions per minute during growth. Triethylgallium, trimethylindium, arsine, phosphine and tertiarybutylphosphine were used as the sources. After the growth of an $In_xGa_{1-x}As$ QW or coupled QWs covered by a GaAs caplayer, InP islands with 4ML nominal supply were deposited as stressors. The sample structures were studied by atomic force microscopy (AFM), transmission electron microscopy (TEM) and double crystal X-ray diffraction. The InP island size and shape grown at 610°C are highly reproducible and uniform. The base diameter and height are 50 nm and 18 nm, respectively with standard deviations of about 8%. The areal density of the InP stressors is about 3×10^9 cm^{-2}. The state

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levels were obtained by photoluminescence (PL) at 77K with 514.5 nm line of an Ar^+ laser as the excitation source.

III. Results and Discussion

Figure 1(a) shows the schematic diagrams of the strain-induced coupled QD-pair structure and (b) the resulted vertical confinement of electronic states along the symmetric axis. Because the lattice constant of InP is larger than that of GaAs, the GaAs lattice right below the InP stressor is tensile strained while that around the edges are compressive strained. Such a strain field below the InP stressor produces laterally confining potentials for both electrons and holes in the GaAs/InGaAs QWs below the stressor (6,9). Because the distortion is gradually recovered with increasing displacement into the bulk, such a CQD is asymmetric due to the decay of the strain field (6,11).

In order to study the vertical profile of strain field, a serious of samples containing a single QW but different GaAs caplayer thickness that separates the QW from the stressor were investigated. Figure 2 shows the PL of SIDs in a 4 nm $In_{0.2}Ga_{0.8}As$/GaAs QW in relation to the GaAs caplayer thickness. The thin QW can be used as a probe to measure the average strain field at certain depth. From an almost equal spacing of neighboring state energies ΔE, the lateral confining potential is believed to be parabolic (6). Both E_r and ΔE_r decrease with increasing the caplayer thickness. The strain-induced confining potential, or the energy barrier from the bottom of the parabolic potential to the QW ground state, can be estimated as $V = V_e + V_{hh} = E_r + \Delta E_r$. Fitting the experimental results of the confining potential V in Fig. 2 reveals an exponential decay profile of the strain field below the stressor with a penetration depth of 25 nm. It is possible to make coupled quantum dot-pairs by stressing on coupled QWs within this depth.

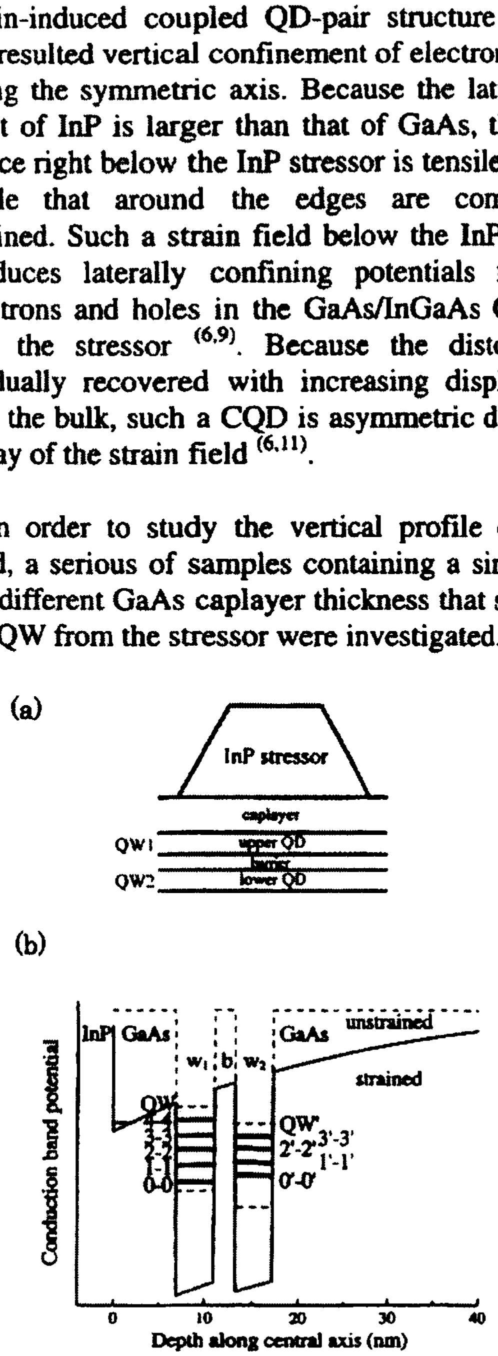

Fig. 1. Schematic diagrams of (a) the structure of strain-induced coupled QD-pair and (b) the resulted vertical confinement of electronic states. The levels labeled 0-0, 1-1, 2-2, and 0'-0', 1'-1', etc. are before coupling.

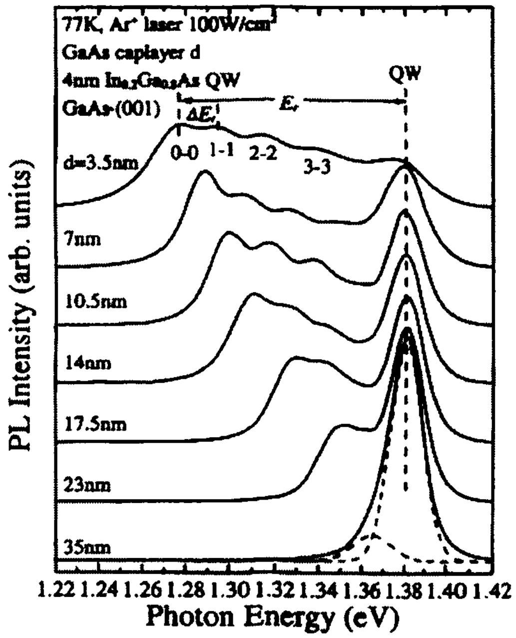

Fig.2. 77K PL showing the transition energies of strain-induced 4 nm $In_{0.2}Ga_{0.8}As$/GaAs QDs in relation to the GaAs caplayer thickness.

Figure 3 shows the PL of CQDs in two 4 nm $In_{0.2}Ga_{0.8}As$ QWs separated by a GaAs barrier of various widths. The top GaAs caplayer is kept at 7 nm. PL of a sample with only the upper QD was also given for reference. As the PL from the QWs can be distinguished by selectively etching away InP stressors, doublet-peak feature is observed from the near surface coupled QWs as shown in dot lines.

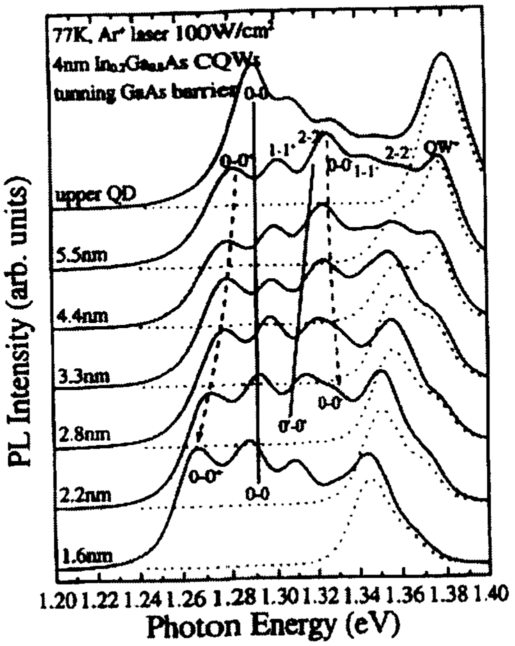

Fig.3. 77K PL spectra of strain-induced quantum dot-pairs by straining two 4 nm $In_{0.2}Ga_{0.8}As$ QWs separated by a GaAs barrier of various widths. The GaAs caplayer is kept at 7nm. PL spectra from CQWs without stressors are shown in dash lines.

For a barrier width larger than 4 nm, the PL spectra from CQDs seem to be an overlap of two nearly isolated upper and lower QDs due to weak coupling and large state energy differences. They can also be considered as bonding and anti-bonding states of the 0th, 1st, 2nd, ... states in CQDs and are labeled $0\text{-}0^+$, $1\text{-}1^+$, $2\text{-}2^+$, ..., and $0\text{-}0^-$, $1\text{-}1^-$, $2\text{-}2^-$, ... respectively. For reference, the ground state energy position from the sample with only the upper dot is plotted in a solid line labeled 0-0. That from samples with only the lower dot (by replacing the upper 4 nm $In_{0.2}Ga_{0.8}As$ QW with 4 nm GaAs) is also plotted in a solid line and labeled 0'-0', it increases with the barrier width as can be derived from Fig.2. With decreasing the barrier width, electronic coupling is greatly enhanced as the bonding state energies labeled $0\text{-}0^+$, $1\text{-}1^+$, $2\text{-}2^+$, ...decrease remarkably. A new excited state is resolved at the shoulder of $2\text{-}2^+$ at a barrier width of 2.2 nm or 2.8 nm. By connecting this peak with that of the anti-bonding states at larger barrier width $0\text{-}0^-$, the shoulder peak is obviously a result of the anti-bonding of the two ground states at strong coupling. By plotting both bonding and anti-bonding states in dash lines labeled $0\text{-}0^+$ and $0\text{-}0^-$, their state labeled $0\text{-}0^+$ and $0\text{-}0^-$, their state energies E_+ and E_- are related to the 0-0 and 0'-0' state energies E and E' by the formula

$$E_{\pm} = \frac{1}{2}(E + E') \mp \sqrt{V_i^{\,2} + (\Delta E)^2} \qquad (3.1)$$

here V_i is the interaction Hamiltonian or overlap parameter representing the coupling strength and

$$\Delta E = \frac{1}{2}(E' - E) \qquad (3.2)$$

Better evidence showing the formation of bonding and anti-bonding states is to see their crossing. This can be achieved by tuning the relative state energies in the two dots by either the QD size or the composition. The state levels in SIDs decrease sublinearly with increasing the indium composition as well as the QW width [11]. In order to modify the coupling behavior in the strain-induced QD-pair, A series of samples with fixed structure but varying indium composition in the lower QW are investigated. The upper QW is 4 nm $In_{0.2}Ga_{0.8}As$ while the lower one is 4 nm $In_xGa_{1-x}As$ (x=0.2, 0.21, ..., 0.3). The GaAs barrier separating the two wells is 3 nm and the GaAs caplayer is 7 nm. Figure 4 shows their PL spectra in addition to those from only CQWs in

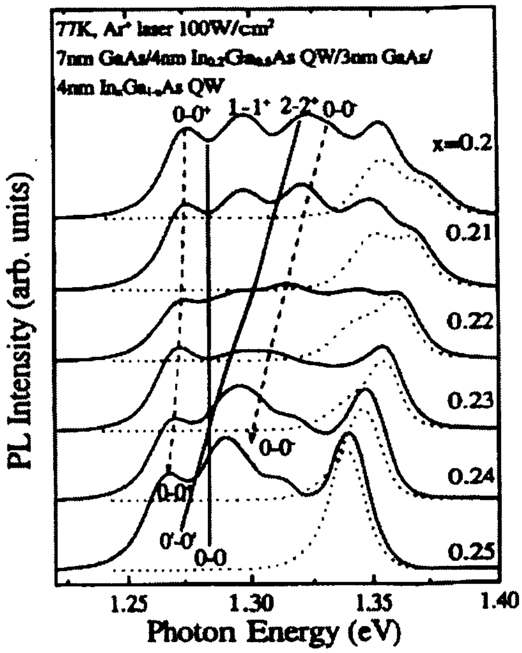

Fig.4. 77K PL spectra of the CQD-pairs having different indium compositions in the lower QD. Both QWs are 4 nm, the GaAs barrier width is 3 nm and the caplayer thickness is 7 nm.

dot lines. In order to understand the origin of the peaks, the ground state energies of the upper and lower SIDs without coupling (obtained separately with samples containing only the upper or lower QD by replacing the other layer with GaAs) in relation to the QW composition x are plotted in solid lines and labeled 0-0 and 0'-0', respectively. Their coupled states are traced in dash lines. Since coupling takes place only between the states in the two dots with equal quantum numbers, resonant coupling takes place when the state energy in the lower dot meets the one with equal quantum numbers in the upper dot, or $\Delta E = 0$. With increasing x, crossing takes place in the range x=0.23~ 0.245 first between higher states, and finally between the two ground states. Beside their bonding states labeled 0-0^+, 1-1^+, 2-2^+, ... that can be identified easily, the peak whose energy reduces fast with x as was indicated by an arrow in Fig.4 is also identified to be the anti-bonding of the two ground states and was labeled 0-0^-. The bonding state 0-0^+ is dominating in the upper dot when $x<0.245$ while is dominating in the lower one when $x>0.245$. As the level spacing in the lower QD is smaller, the coupled state energy spacing is reduced when the electron bonding state starts dominating in the lower dot. Higher order anti-bonding states shall be present but are not clearly resolved in Fig. 4.

Finally, the doublet feature of PL spectra from the near-surface coupled QWs deserves an explanation. It is well known that Fermi level pinning at the semiconductor surfaces leads to band bending in the near-surface QW region. Since the GaAs/InGaAs materials grown by MOVPE are unintentionally n-type doped, the near-surface band is considered to bend upward. For weakly coupled QWs, the lowest transition occurs between the electron ground state in the lower QW and hole ground state in the upper QW (Type II transition), while direct transitions occur in each QW at higher energies. The type II transition is suppressed with increasing the barrier width or the indium composition in the lower QW so that one peak from CQWs becomes dominant.

IV. Conclusions

It is found that the total strain field below the InP self-assembled island decays exponentially with a penetration depth of about 25 nm, which is enough to strain two near surface quantum wells into a coupled quantum dot-pair. Coupling strength between the QD states having equal quantum numbers in each dot was investigated by varying the barrier width separating the two dots, and the indium composition in the lower QD. Anti-bonding of the two ground states as well as all the bonding states are resolved in the PL spectra. To our knowledge, this is the first experiment revealing the formation of not only the bonding but also the anti-bonding states of coupled quantum dots by conventional optical state filling.

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