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Photoreflectance study of coupling effects in double quantum wells*

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A double quantum well (DQW) molecular beam epitaxy (MBE) grown GaAs/$Al_xGa_{1-x}As$ structure was studied. To investigate the coupling effects in such a system 1 monolayer (ML) thick AlAs barrier was inserted at the centre of the GaAs/$Al_xGa_{1-x}As$ single well. Due to the strong coupling between wells each confined state splits into two: symmetric and antisymmetric ones. At room temperature photoreflectance (PR) spectrum features related to transitions between all these states were observed. Theoretical considerations based on the envelope function approximation were performed to obtain the energies of expected optical transitions. An excellent agreement between experiment and theory was obtained.

Keywords: $GaAs/Al_xGa_{1-x}As$ double quantum wells, coupling effects, photoreflectance spectroscopy

1. Introduction

Investigations on coupled double quantum wells in semiconductor heterostructures have gained considerable interest during the last decade. This interest arises in part from the expectation that their electronic properties might be utilized in optoelectronic devices. On the other hand, the physical interest in these systems is strongly related to their excitonic properties, which have attracted attention both with respect to the single-exciton problem and the exciton-exciton interaction.

Here we have investigated the double quantum well (DQW) system by modulation spectroscopy. Because of its derivative nature, this is very sensitive method for investigation of optical transitions in semiconductor reduced dimensionality system even at room temperature. Particularly in photoreflectance spectroscopy (contactless form of electromodulation spectroscopy) modulation of the built-in electric field in the sample is caused by photoexcited electron-hole pairs created by a pump source (laser or other light source) which is chopped at frequency f_m. This procedure results in sharp derivative-like spectral features in the region of intersubband transitions. In reduced-dimensional systems, it has been shown that PR produces a line shape that is the first derivative of the unmodulated optical constants [1,2].

2. Experimental

We have used a standard PR apparatus with a silicon photodiode as a detector. The 488 nm line of an Ar^+ laser chopped at frequency 120 Hz has been used as a pump beam. More experimental details have been described in [3].

Undoped symmetric $GaAs/Al_{0.3}Ga_{0.7}As/Al_{0.35}Ga_{0.65}As$ DQW separated by thin AlAs spike was grown by solid source molecular beam epitaxy along [001] direction on semi-insulating substrate. The scheme of the conduction band edge profile and the thicknesses of layers are shown in Fig. 1.

3. PR results

In Fig. 2 the room temperature photoreflectance spectrum for investigated structure is shown. We can see a lot of transitions above the energy of the feature related to GaAs band gap transition. We connect them

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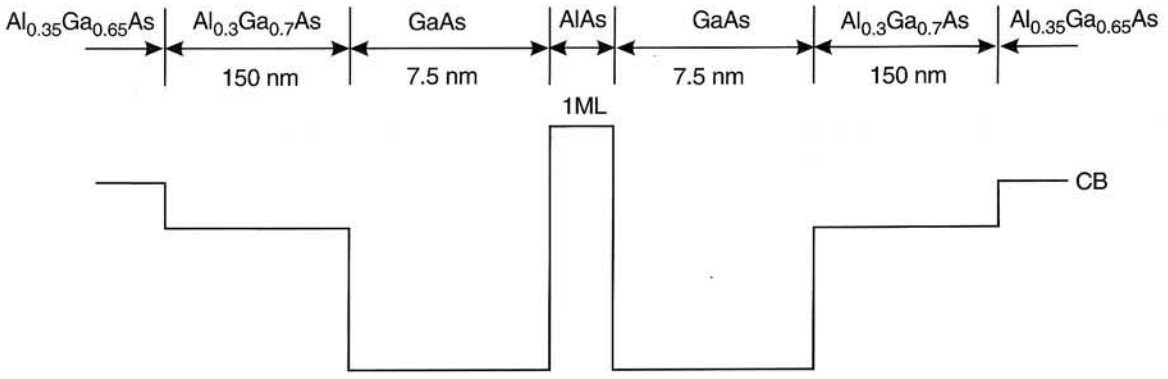

Fig. 1. Sketch of the conduction band edge of investigated structure.

with transitions between confined states in the DQW. Arrows indicate the experimental energies of these confined transitions. The energies were obtained from the least-square fitting procedure according to the first derivative of Gaussian line shape, the most appropriate profile of the PR signal in the case of confined transitions at room temperature [1,2]. The transitions are labeled according to the notation H(L)mn which denotes a transition between the m-th conduction and n-th valence subbands of heavy (H) or light (L) holes, respectively. The index s means the transition between symmetric and a antisymmetric states.

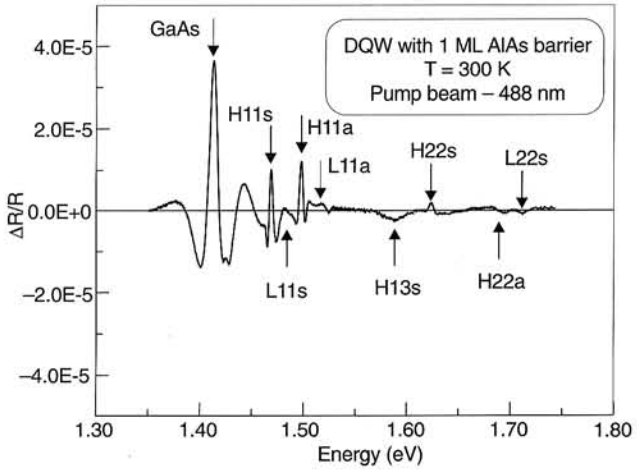

Fig. 2. PR spectrum of investigated DQW structure. The experimental transition energies are indicated by arrows.

4. Theoretical considerations and discussion

To calculate the energies of the states we considered a motion of a particle in a double quantum well in a semiconductor heterostructure consisting of two quantum wells separated by a thin potential barrier. All the calculations were performed in the effective-mass approximation. To account the band nonparabolicity we introduced the energy dependent electron mass as follow [4]

$$\frac{m^*(E)}{m_e^*} = \frac{(E+E_g)(E+E_g+\Delta)(E_g+2\Delta/3)}{E_g(E_g+\Delta)(E+E_g+2\Delta/3)} \qquad (1)$$

where E_g is the band gap energy and Δ the Γ spin-orbit coupling energy.

The single particle Schrödinger equation was solved in a standard Bastard way [4]. The material parameters used in calculations are presented in Table 1 [5,6]. The material constants for $Al_xGa_{1-x}As$ were obtained by linear interpolation of values shown in Table 1. The room temperature band gap energy was taken to be [5]

$$E_g(Al_xGa_{1-x}As) = 1.425 + 1.155x + 0.37x^2 \text{ (eV)} \qquad (2)$$

The valence band offset was assumed to be 40% of the total band gap difference. The holes masses are determined from the Luttinger parameters: $m_{hh}^* = (\gamma_1 - 2\gamma_2)^{-1}$ and $m_{lh}^* = (\gamma_1 - 2\gamma_2)^{-1}$.

Table 1. Material parameters

Parameter	GaAs	AlAs
a (Å)	5.6533	5.6611
γ_1	6.85	3.45
γ_2	2.10	0.68
γ_3	2.90	1.29
E_g(eV)	1.425	3.02
$E_g + \Delta$(eV)	1.765	3.32

In Table 2, the comparison of experimental and theoretical transition energies is presented. Generally,

quite good agreement was obtained. Our results are also in good agreement with those ones reported previously by Bayer [7]. The theory slightly overestimates the experimental energies. It may be related to the exciton binding energy that was not included in the calculations. Therefore we calculated also the difference between transition energies of respective a and s states (see Table 2). Now, the agreement is almost excellent. The small disagreement might result from the difference in the exciton binding energy for antisymmetric and symmetric states. It can be seen, from Table 2, that the splitting energy between antisymmetric and symmetric transitions is smaller for H11 transitions than for L11 ones. It is connected with difference in masses of heavy and light holes and can be understood on the base of the following relation, which gives us the splitting energy between the symmetric and antisymmetric single-particle states

$$\Delta_{a-s} = E_a - E_s = \frac{E}{\pi}\exp\left(-\sqrt{\frac{2mE}{\hbar^2}}L\right) \qquad (3)$$

In equation (3) E is the energy of electron or hole in the decoupled single quantum well, m is the electron/hole effective mass and L is the separating barrier width. We can see from this relation that the splitting energy Δ_{a-s} is strongly dependent on the barrier width, the carrier mass and via E on the barrier height.

Table 2. Experimental and theoretical transition energies

Transition	Transition energy (eV)		Δ_{a-c} (eV)	
	Experiment	Theory	Experiment	Theory
H11s	1.467	1.471	0.013	0.014
L11s	1.480	1.485		
H11a	1.496	1.502	0.025	0.033
L11a	1.521	1.535		
H13s	1.585	1.562		
H22s	1.615	1.629	0.070	0.073
H22a	1.685	1.702		
L22s	1.697	1.704		

5. Conclusions

In summary, we have measured the photoreflectance spectroscopy on the DQW structure at room temperature. All the confined states in such a system are split into two, symmetric and antisymmetric one, because of the strong coupling between the wells due to a very thin AlAs barrier. We have obtained the transition energies between respective states and compared them with the results of numerical calculation based on the envelope function approximation. The theory slightly overestimates the experimental transition energies but the energies of the difference between the antisymmetric and symmetric transitions are in good agreement. This is probably due to the exciton binding energy, which was not included in the calculations.

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