The Exciton Tunneling in ZnCdSe/ZnSe Asymmetric Double Quantum Well

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Photoluminescence spectra of asymmetric double-quantum-well structure are studied in this paper. We show the excitation power dependence of exciton tunneling. Due to the different tunneling time of electrons and holes, space-charge effect is observed.

Key words: Asymmetric double quantum well (ADQW), exciton, tunneling

INTRODUCTION

The dynamics of carrier tunneling through a thin barrier in semiconductor heterostructures was a topic of research interest in the last years, since this process was not only of basic physical interest but also of fundamental importance for application. In an asymmetric double quantum well (ADQW) structure, which consists of two different width wells coupled with a thin barrier, the subbands in each well have different energies under flat band condition, therefore, the carrier tunneling from the narrow quantum well (QWn) to the wide quantum well (QWw) becomes easy and notable. In III-V compound semiconductors ADQW, the carriers tunneling process has been investigated widely.[1,2] Due to weak Coulomb interaction between electrons and holes in III-V ADQW, the electrons and holes tunnel independently rather than as excitons. But in II-VI compound semiconductors ADQW, exciton binding energy is large, which make the Coulomb interaction between electrons and holes not be neglected in tunneling process.[3] In this paper, we report excitation power dependence of the exciton tunneling in the ADQW by photoluminescence (PL) spectra and using optical measurements, and demonstrate photoinduced space-charge buildup in the ADQW caused by the tunneling process.

EXPERIMENT

The ADQW samples studied were grown on Si-doped (100) GaAs substrates by low pressure (LP) metalorganic chemical vapor deposition (MOCVD) at 350°C with reactor pressure at 38 Torr. The structure consists of a 1 μm ZnSe buffer layer followed by a five-period $Zn_{0.72}Cd_{0.28}Se$/ZnSe ADQW, and then a 100 nm ZnSe cap layer. Each period of the ZnCdSe/ZnSe ADQW includes one narrow ZnCdSe quantum well (QWn), one thin ZnSe barrier and one wide ZnCdSe quantum well (QWw), which will be denoted later as $L_n/L_b/L_w$, where L_n, L_b, and L_w are the widths of the narrow well, barrier and wide well, respectively. PL spectra were excited by the 337.1 nm line of a N_2 laser worked at 10 Hz and the signal was measured at 77K using a 44W grating monochromator with a RCA-C31034 cooled photomultiplier.

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RESULTS AND DISCUSSION

Figure 1 shows the photoluminescence of the sample 3nm/4nm/7nm ADQW structure under different excitation. At low excitation (<0.2KW/cm^2), there is only one luminescence peak due to n = 1 heavy hold (HH1) excitonic transition from the wide well (not present in the figure), and with the excitation increasing, HH1 excitonic emission from narrow well is observed and shows redshift. Figure 2 shows the excitation intensity dependence of the luminescence intensity of the wide well and narrow well. The changing of the emission intensity from the narrow well is smooth with excitation, but the emission intensity from the wide well has a strong change process in low excitation range, and then trends to smooth.

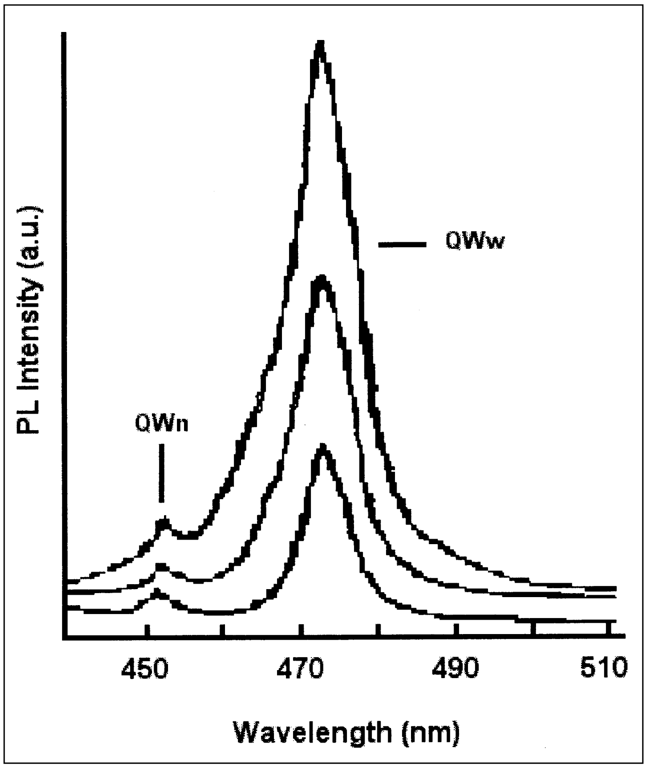

Fig. 1. The PL spectra of ADQW under different excitation from top: 2.9KW/cm^2, 0.9KW/cm^2, 0.2KW/cm^2.

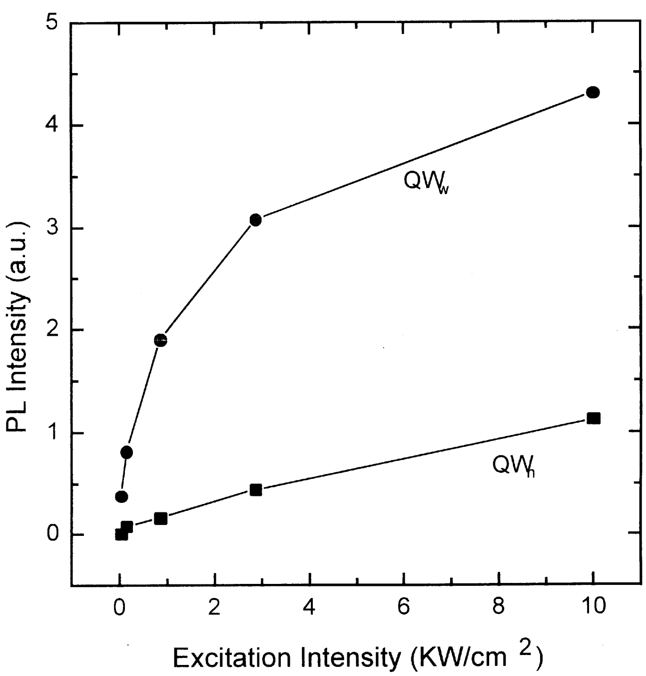

Fig. 2. The emission intensity from the wide well and narrow well dependence on excitation density of the 3nm/4nm/7nm structure.

In ADQW, the transition process should include following steps: a. Electron-hole pairs are excited, and excitons are formed (for II-VI compounds, because of the larger exciton binding energy, the electron-hole pair exists as exciton). b. Electrons in excitons tunnel from narrow well to wide well, which means direct excitons (electrons, holes in the same well) tranfer to indirect excitons (electrons, holes not in the same well), c. Holes in the excitons tunnel from narrow well to wide well (from indirect excitons transferring to direct excitons), d. Excitons recombinate in wide well.

This process can be described by the rate equations

$$\frac{dn_n}{dt} = G_n - \frac{n_n}{T_{te}} - \frac{n_n}{T_r} \tag{1}$$

$$\frac{dp_n}{dt} = G_n - \frac{p_n}{T_{th}} - \frac{p_n}{T_r} \tag{2}$$

$$\frac{dn_w}{dt} = G_w + \frac{n_n}{T_{te}} - \frac{n_w}{T_r} \tag{3}$$

$$\frac{dp_w}{dt} = G_w + \frac{p_n}{T_{th}} - \frac{p_w}{T_r} \tag{4}$$

where n_n, n_w, p_n, p_w are the densities of the electrons and holes in the narrow well and wide well, respectively, G_n and G_w are the generation rates of the electron-hole pairs in narrow well and wide well, T_{te}, T_{th}, T_r are the tunneling times of the electrons, holes and excitons recombination time, respectively. Here, we assume that all carriers exist as excitons due to the larger Coulomb interaction between electrons and holes and then the carriers densities used in rate equations are the densities of electrons or holes in excitons.

According to our calculation, for the sample 3nm/4nm/7nm $Zn_{0.72}Cd_{0.28}Se/ZnSe$ ADQW structure, the difference of n = 1 electron subbands between the wide well and narrow well ΔE_{1e} is about 60 meV, and the difference of n = 1 heavy hole subbands ΔE_{1h} is about 9 meV (see Fig. 3a), therefore $\Delta E_{1e} > E_{LO}$[3] (E_{LO} is the energy of LO phonon) and $\Delta E_{1h} < E_{LO}$, and then the electrons in the narrow well could tunnel to the wide well by phonon-assistant but the holes could not. Additionally, because of the binary barrier, the alloy-tunneling is neglected. So that the relationship $T_{te} < T_{th} < T_r$ is obtained.[4] At low excitation, n_n is so small that $\frac{n_n}{T_r}$ could be neglected in Eq. (1), and almost all of the electrons in the narrow well tunnel to the wide well before recombination with holes, as a result, no emission from narrow well is observed. With higher excitation, n_n, p_n become larger, and $\frac{n_n}{T_r}$, $\frac{p_n}{T_r}$ could not be neglected, which leads to part of electrons would recombinate with holes in the narrow well, and consequently results in the emission from the narrow well. Because of $T_{te} < T_{th}$, tunneling of electrons is faster than that of holes, so electron is the minority, which decides the emission intensity in the narrow well. Therefore, $I_n \propto \frac{n_n}{T_r}$ is obtained, where I_n is the emission intensity of narrow well. At our excitation range, the changing of the electrons density excited with excitation intensity is nearly linearly, which is the same as the experiment results shown in Fig. 2.

The minority which decides emission intensity in the wide well is hole which come from two sources, one is excited by photo in the wide well, the other one is that tunneling from the narrow well [see the Eq. (4)]. As discussion above, the densities of both kinds of the holes would change linearly with excitation intensity,

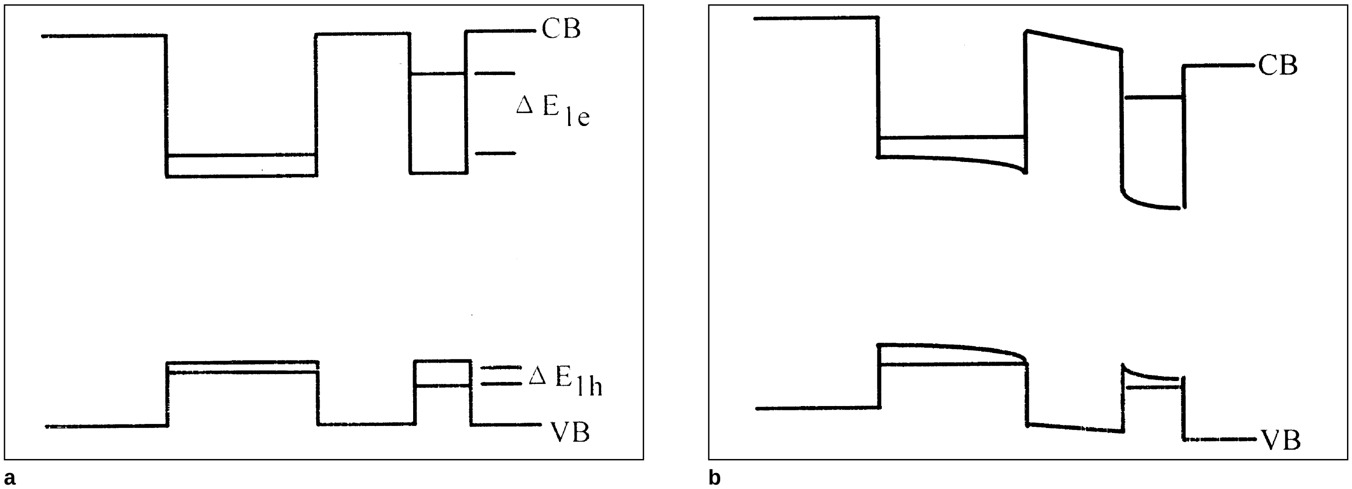

Fig. 3. The diagrams of band offest for electrons and holes in ADQW (a) flat band condition, and (b) under internal electric field.

therefore the emission intensity in wide well I_w should change linearly with excitation; however, from Fig. 2, we see that it is not this situation. For the reason of low excitation range, PL saturation phenomena could be excluded (In normal quantum structure, even at high excitation intensity, there would not appear PL saturation phenomena). We attribute it to space-charge effect. Because of $T_{te}<T_{th}$, electrons must be more than holes in the wide well, while holes must be more than electrons in narrow well, and then an internal electric field is formed from the narrow well to the wide well, which is different from the external electric field. The external electric field passes through the whole sample, but the internal electric field only passes through the thin ZnSe barrier in which the electrons or holes tunnel and the electric field across the thick barrier is neglected. With increasing of the excitation, the internal electric field becomes strong and the ΔE_{1e} is smaller while ΔE_{1h} is larger (see Fig. 3b), which would cause band bending and block the tunneling of carriers. For the reason of the thin barrier between the two wells in ADQW, the hole wave functions are delocalized, and due to disordered alloys, the hole subbands are spread; on the other hand, because ΔE_{1h} is only 9 meV at flat band condition in the sample 3nm/4nm/7nm structure (as said above), the n = 1 heavy hole wave functions would be overlapped partly. Therefore, the two n = 1 heavy hole subbands could be thought as nearly resonant. But when the internal electric field increases, the difference between the two heavy hole subbands increase while the overlap of the two wave functions decreases, which induces that the tunneling of the holes becomes slower. The detailed calculation will be found elsewhere. For the sample 3nm/4nm/8nm structure, depending on our calculation, ΔE_{1h} is about 10 meV and larger than that for the sample 3nm/4nm/7nm. In experiment, we really found that the excitation intensity related to inflection point of emission intensity from strong changing to smooth changing in the sample 3nm/4nm/8nm structure is lower than that in the 3nm/4nm/7nm structure. (For 3nm/4nm/7nm structure, the infection point was at about 2.8KW/cm^2, while it was at about 2.1KW/cm^2 for the 3nm/4nm/8mn structure.)

Another phenomena caused by the internal electric field is Stark effect. Figure 1 shows that the emission peak from narrow well shifts to the red side with increasing of excitation intensity. According to the calculation of Bastard et al.[5] for a finite quantum well, the energy shift of the ground state induced by the field can be expressed as

$$\Delta E \propto (n_n - p_n)^2 \tag{5}$$

Depending on the Eq. (5), ΔE should be in the range of several meV,[6] which tallies with the experiment. But the shift of the emission peak from the wide well was not observed, and the reason is not clear, maybe this is because the well width is larger and Stark effect only affects the carriers on interfaces between the barrier and well.[6]

CONCLUSION

We have studied the excitation intensity dependence of the emission intensity in the ADQW structure. The exciton tunneling causes different effects on the narrow and wide well. Space charges caused by different tunneling rate between electrons and holes leads to the foundation of the internal electric field which affects carriers tunneling and produces Stark effect.

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