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# Study of extending carrier lifetime in ZnTe quantum dots coupled with ZnCdSe quantum well

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ABSTRACT

We demonstrated the growth of a self-assembled type-II ZnTe/ZnSe quantum dot (QD) structure coupled with a type-I $Zn_{0.88}Cd_{0.12}Se$/ZnSe quantum well (QW) on the (001) GaAs substrate by molecular beam epitaxy (MBE). As the spacer thickness is less than 2 nm, the carrier lifetime increasing from 20 ns to nearly 200 ns was successfully achieved. By utilizing the time-resolved photoluminescence (TRPL) and PL with different excitation power, we identify the PL emission from the coupled QDs consisting of two recombination mechanisms. One is the recombination between electrons in ZnSe barrier and holes confined within ZnTe QDs, and the other is between electrons confined in $Zn_{0.88}Cd_{0.12}Se$ QW and holes confined within ZnTe QDs. According to the band diagram and power-dependent PL, both of the two recombinations reveal the type-II transition. In addition, the second recombination mechanism dominates the whole carrier recombination as the spacer thickness is less than 2 nm. A significant extension of carrier lifetime by increasing the electron and hole separation is illustrated in a type-II ZnTe/ZnSe QD structure coupling with a type-I ZnCdSe/ZnSe QW. Current sample structure could be used to increase the quantum efficient of solar cell based on the II-VI compound semiconductors.

## 1. Introduction

Quantum structures of magnetic semiconductors offer an interesting material system to manipulate the spin for the application in the spintronic devices [1]. Spin precession and spin-valve effect were observed in the spinronic device employing *p*+-GaMnAs/*n*+-GaAs ferromagnetic Esaki diodes [2]. Room temperature electric field controlled ferromagnetism was also illustrated in the $Mn_{0.05}Ge_{0.95}$ quantum dot (QD) system [3]. J. Kobak et al. studied the magneto-optical spectroscopy of CdSe QD with single $Mn^{2+}$ ion and CdTe QD with single $Co^{2+}$ ion [4]. They identified the optimal magnetic-ion quantum dot systems for implementation of a single-ion-based spin memory. Recently, we had demonstrated the dynamics of magnetic polaron formation in the ZnTe/ZnMnSe and ZnMnTe/ZnSe QD systems [5]. The long electron and hole recombination time due to the type II band alignment of QD, holes are confined in the QDs and electrons situate outside the QD, enables us to observe the slow formation dynamics of magnetic polaron. The type II ZnTe/ZnSe, ZnTe/ZnMnSe and ZnMnTe/ZnSe QD systems resemble the type II GaSb/GaAs QD system [6,7] and had been studied in details previously [8–11]. There is about 7% of lattice mismatch between ZnTe and ZnSe, which is similar to that between GaSb and GaAs.

In current study, an extra ZnCdSe quantum well is inserted into the ZnTe/ZnSe QD structure in order to extend the electron and hole recombination time. The photon generated electrons are expected to carry out a relaxation process to the lower energy state in the nearby quantum well. This further increases the spatial separation of the electron and hole. The spatial separation of electron and hole could be manipulated by controlling the spacer thickness to achieve the extension of recombination lifetime. The long recombination time is essential for the future manipulation of spin in magnetic semiconductor QD as well as the possible application in the high efficiency solar cell employing this QD structure.

## 2. Experiments

ZnCdSe QW and ZnTe QD coupled with ZnCdSe QW samples were grown on GaAs (001) substrates by SVTA molecular beam epitaxy (MBE) system. The substrates were cleaned by $NH_4OH:H_2O_2:H_2O=1:5:50$ solutions and de-ionized water with supersonic rinse for two minutes and then rinsed in flow de-ionized water. 650 °C was used for desorption of oxide on the substrate surface until

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**Table 1**
The growth parameters for (a) ZnCdSe film, (b) ZnCdSe QW and (c) ZnTe QD coupled with ZnCdSe QW.

(a)

| T (sub) | ZnCdSe film | | | | | | |
|---|---|---|---|---|---|---|---|
| (°C) | Zn (°C) | BEP ($\times10^{-7}$ torr) | Cd (°C) | BEP ($\times10^{-7}$ torr) | Se (°C) | BEP ($\times10^{-7}$ torr) | Con. (%) |
| 320 | 278 | 1.4 | 190 | 4.73 | 177 | 2.08 | 12 |
| | 285 | 1.68 | 200 | 9.45 | 160 | 1.96 | 19 |
| | 275 | 1.42 | 210 | 16 | 160 | 2.01 | 37 |

(b)

| T (sub) | ZnSe barrier | | ZnCdSe QW | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (°C) | Zn (°C) | Se (°C) | Zn (°C) | BEP ($\times10^{-7}$ torr) | Cd (°C) | BEP ($\times10^{-7}$ torr) | Se (°C) | BEP ($\times10^{-7}$ torr) | Con. (%) |
| 320 | 270 | 180 | 278 | 1.4 | 190 | 4.73 | 177 | 2.08 | 12 |
| | | | 285 | 1.68 | 200 | 9.45 | 160 | 1.96 | 19 |
| | | | 275 | 1.42 | 210 | 16 | 160 | 2.01 | 37 |

(c)

| T (sub) | ZnSe barrier | | ZnTe QDs | | ZnCdSe QW | | | ZnSe spacer |
|---|---|---|---|---|---|---|---|---|
| (°C) | Zn (°C) | Se (°C) | Zn (°C) | Te (°C) | Zn (°C) | Cd (°C) | Se (°C) | thickness. (nm) |
| 320 | 270 | 180 | 270 | 330 | 278 | 190 | 177 | 1 |
| | | | | | | | | 2 |
| | | | | | | | | 5 |
| | | | | | | | | 10 |

the clear reflective high energy diffraction (RHEED) pattern was observed. The substrate temperature was then decreased to 320 °C for growth. In this study, three ZnCdSe thick epilayers and quantum wells (QWs) with different cadmium (Cd) concentration, which was controlled by beam equivalent pressure (BEP) ratio, were grown for reference. ZnTe QDs coupled with ZnCdSe QW with different spacer thickness were grown to study the extension of carrier lifetime. The growth parameters of these three series samples are listed in Table 1.

The Cd concentrations of three $Zn_{1-x}Cd_xSe$ thin films, $x$=0.12, 0.19 and 0.37, were confirmed by the energy dispersion spectroscopy (EDS). The growth parameters of the thin films were used to grow the 10 nm ZnCdSe QW with ZnSe barrier for reference. Finally, ZnCdSe QWs were grown to couple with ZnTe QDs. The ZnTe QDs were grown above ZnCdSe QW with ZnSe spacer thickness of 1, 2, 5 and 10 nm. The schematic sample structures were shown in Fig. 1. In the previous study of the growth of ZnTe QDs on ZnSe, the RHEED pattern demonstrates the Stranski-Krostanov (SK) growth mode. The streaky RHEED patterns illustrate the two dimensional growth for the growth coverage below 2.4 mono-layers (MLs) and the spotty patterns reflect the self-assemble of QDs at the growth coverage above 2.4 MLs [11]. The SK growth mode with critical thickness of about 2.4 MLs was also confirmed by the atomic force microscopy (AFM) [11,12] and transmission electron microscopy (TEM) [8] measurements. Therefore, the coverage thicknesses of ZnTe QDs are kept at 2.8 MLs to guarantee the formation of QDs. ZnSe capping layer was then capped on ZnTe QDs for improving the optical properties.

For the photoluminescence (PL) study, the He-Cd continuous wave mode laser with wavelength 325 nm (3.815 eV) line is used as the excitation light source. The samples were mounted in a closed-cycle refrigerator to adjust the sample temperature from 10 K to 300 K. The PL signal was analyzed by a Horiba-Jobin Yvon *i*HR550 (1800 grooves/mm grating) spectrometer with a liquid nitrogen cooled charge-coupled device (CCD) detector, the energy resolution of PL spectrometer is about 0.3 meV.

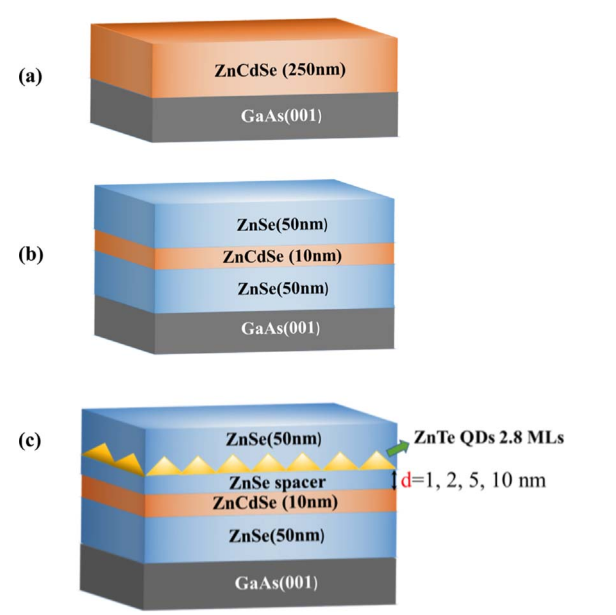


**Fig. 1.** Schematic ample structures for (a) ZnCdSe film, (b) ZnCdSe QW and (c) ZnTe QD coupled with ZnCdSe QW.

The time-resolved photoluminescence (TRPL) is used to study the decay dynamics of exciton. The GaN diode laser with 50 ps pulses and a repetition rate of 40 MHz at a wavelength of 377 nm was used as an excitation source. The average power of the pulse was estimated to be below 0.1 mW. The iHR550 spectrometer equipped with a high-speed photomultiplier tube was used to detect the TRPL signal. The overall temporal resolution of the setup was about 300 ps.