# Electron tunneling effects on radiative recombination in modulation n-doped ZnSe/BeTe type-II quantum wells*

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We have studied the cyclotron-resonance absorption and photoluminescence properties of the modulation n-doped ZnSe/BeTe/ZnSe type-II quantum wells. It is shown that only the doped sample shows electron cyclotron-resonance absorption. Also, the undoped sample shows two distinctive peaks in the spatially indirect photoluminescence spectra, and the doped one shows only one peak. The results reveal that the high concentration electrons accumulated in ZnSe quantum well layers from n-doped layers can tunnel through BeTe barrier from one well layer to the other. The electron concentration difference between these two well layers originating from the tunneling results in a new additional electric field, and can cancel out a built-in electric field as observed in the undoped structures.

**Keywords:** type-II quantum wells, cyclotron resonance, photoluminescence, electron tunneling
**PACC:** 7320D, 7125H, 7855, 7335C

## 1. Introduction

During the past years remarkable progress has been made in the fundamental research and practical applications of III–V heterostructures.[1−5] Recently, type-II ZnSe/BeTe quantum wells (QWs) structures have received considerable attention due to a number of interesting properties: the good lattice match (mismatch smaller than 0.5%), a type-II band alignment with large band offsets for both conduction (∼2.3 eV) and valence (∼0.9 eV) bands,[6−8] and strong in-plane optical anisotropy.[9] Such deep potential wells for carriers result in a very small penetration of the electron and hole wave functions into the neighbouring layers.[10,11] Due to the long recombination lifetimes of spatially separated electrons and holes, type-II QWs are considered to be good candidates for observing high-density excited states.[12,13]

The information, such as how many carriers are actually injected or accumulated in the QWs under either modulation doping or conventional photoexcitation, is important for a complete understanding of high-density effects of the excited states. The cyclotron-resonance (CR) was considered to be a powerful tool to determine the parameters of the accumulated carriers in an equilibrium state in the QWs, such as carrier effective mass and carrier concentration.[14−17] However, to our knowledge, there has been no detailed experimental report on the direct observation of the modulation n-doped in ZnSe/BeTe QWs under high magnetic fields up to 180 T.

In this paper, the infrared CR measurements are carried out as mid-wave infrared (MWIR) power absorption from the electrons which occupy the conduction band of the ZnSe layers and the electron concentration and effective mass are estimated. At the same time, the spatially direct transition photoluminescence (PL) is measured. The physical mechanism of the electron tunneling effects on spatially indirect radiative recombination is explained by the established physical model.

## 2. Experimental details

The samples (undoped, #237, n-doped, #288) were grown on (001) GaAs substrates by molecular beam epitaxy (MBE). The QWs in the samples consisted of one set (for #237), and three sets (for #288) of symmetrical ZnSe (28 ML) /BeTe (10 ML)/ZnSe

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(28 ML) layers as described in detail in Refs. [15], [18] and [19], where 1 ML was approximately equal to 0.28 nm. In the n-doped sample, the doped layers ($ZnCl_2$) were separated from the QWs by 10 nm-thick barrier layers as shown in Fig. 3 (see below). Other parameters of the two samples were identical.[15,18,19] The samples were grown in Ultrafast Photonic Devices Laboratory of AIST in Japan.

For the infrared CR measurements, MWIR laser ($CO_2$ laser, 10.6 $\mu$m) was used as a probe light source. The magnetic fields were applied parallel to the growth ($z$) direction of the QWs. The magnetic fields up to 180 T were generated by using the single-turn-coil technique with 10-mm bore coils.[20,21] A fast pulsed current was discharged from a 200-kJ capacitor bank into a single-turn copper coil. The pulse duration was about 8 $\mu$s. The magnetic field was measured by a pick-up coil wound around the sample. A HgCdTe photodiode cooled down at liquid nitrogen temperature was used as the fast MWIR detector for the $CO_2$ laser. The signals of the transmission and magnetic fields were sent to a digital recorder through an optical fibre. More details about the single-turn coil technique and the data-acquisition system are described in Refs. [20] and [21]. The infrared CR measurements were taken in the International MegaGauss Science Laboratory, Institute for Solid State Physics, University of Tokyo.

For the type-II PL spectra measurements, a frequency-doubled mode-locked Ti:sapphire laser was used as an excitation light source. The excitation wavelength is 370 nm. A liquid-nitrogen cooled charge coupled device (CCD) array was used as a detector.

## 3. Experimental results and discussion

Figure 1 shows the magneto-transmission spectra of 10.6 $\mu$m radiation in the undoped (#237) and n-doped (#288) samples at 296 K. Every CR valley is observed twice on the rising and falling slopes of the magnetic field. It should be noted that good coincidence of the two slopes ensures a sufficiently fast response of the detector system and the accuracy of the measurement. Figure 1(a) shows no CR absorption valley of the electrons in ZnSe layers due to the absence of free electron in undoped sample. The CR valley at around 80 T in Fig. 1(a) is the transition of the free electrons in GaAs substrates.[22] However, transmission spectrum of the n-doped sample shows a broad CR valley at around 148 T, in Fig. 1(b). In order to estimate the electron effective mass $m^*$ and electron concentration $n_e$ in QWs, we use a dielectric function model to fit the transmission spectra (Fig. 1(b)) The dielectric function is expressed as $\varepsilon(B) = 1 - \omega_p^2/(\omega - \omega_c(B) + \mathrm{Im}(1/\tau)$, where $\omega = 2\pi \times 10^{10}/\lambda$ is the frequency of the radiation, $\omega_p = (4\pi n_e^2/m^*)^{1/2}$ the plasma frequency, $\omega_c$ the cyclotron frequency, and $\tau$ is the scatting time. The electron effective mass $m^*$ is estimated to be 0.146 $m_0$ from $\omega_c = eB/m^*$, in good agreement with the value 0.15 $m_0$ of the electron mass in the ZnSe QW.[23] Based on this result, the electrons are considered to be located in the ZnSe layers in our structures. The electron concentration $n_e$ is roughly estimated to be $\sim 1.2\times10^{12}/\mathrm{cm}^2$ from the CR absorption intensity, which is consistent with our doping level.

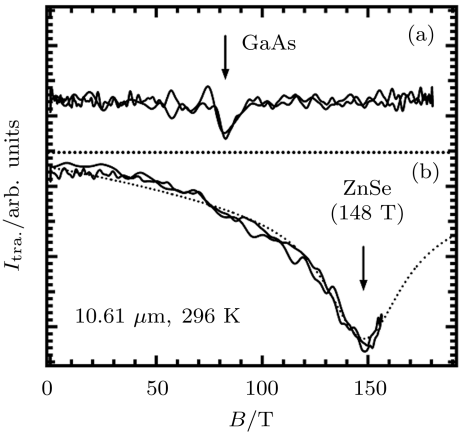



**Fig. 1.** Magneto-transmission of undoped sample #237 (a) and n-doped sample #288 (b) at 10.61 $\mu$m radiation. The dotted line in (b) presents a fitting curve calculated using the by dielectric function model.

Figure 2 shows the measurement results of the type-II spatially indirect PL spectra obtained for these two samples at $T = 5$ K. For the macro PL spectra (solid lines in Fig. 2), which were measured without linear polariser, there are two distinctive peaks at 1.882 eV (peak $L$) and 1.912 eV (peak $H$) for the undoped sample #237, while only one main peak at 1.870 eV ($M$) for n-doped sample #288. The PL spectra, the dashed and dotted lines, show the type-II transitions with a linear polarisation along the [110] and [1$\bar{1}$0] axes, respectively. As reported in our previous work[15,19] the two separated macro PL peaks $L$ and $H$ of the undoped sample in Fig. 2(a) correspond to the type-II transitions of different interfaces

since the two peaks have opposite linear polarisation, and the energy interval $\Delta E$ of 30 meV of the two peaks originates from a strong Stark effects induced by a built-in electric field $F$. The single main peak obtained from the doped sample in Fig. 2(b), can be explained by the screening of a built-in electric field $F$ with n-doping. In order to investigate the dependence of the indirect PL of modulation n-doped structures on the n-doping density, we discuss the screening mechanism of the built-in electric field $F$ by electron tunneling as follows.

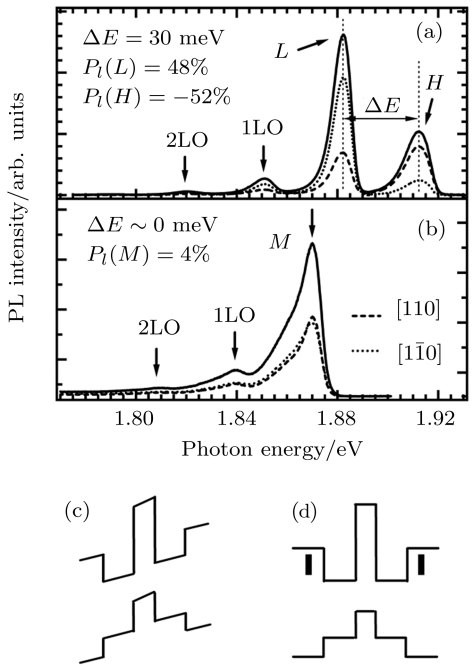



**Fig. 2.** PL spectra and the polarisation properties of the two samples: (a) undoped, #237; (b) n-doped, #288. Solid lines present macro PL spectra (measured without polariser). Dashed and dotted lines present spectra, polarised along the [110] axis and the [1$\bar{1}$0] axis, respectively. The two weak peaks denoted by 1 LO and 2 LO are phonon replicas of the main peak. $\Delta E$ presents the energy interval of the two peaks from different interfaces; (c) and (d) the conduction and valence band diagrams of the undoped (#237) and n-doped (#288) ZnSe/BeTe/ZnSe type-II QW structures, respectively.

BeTe is an indirect semiconductor, with the minimum of the conduction band at the $X$ point.[24] Figures 2(c) and 2(d) only show the conductor-band diagram of the single barrier at the $\Gamma$ point of the Brillouin zone, and they correspond to the cases of the undoped sample and doped sample, respectively. Due to the indirect gap of BeTe, $\Gamma$ electrons might tunnel through indirect states in BeTe into the QW. The tunneling through indirect-gap semiconductor barriers has also been observed in other heterostructures, such as $Ga_{1-x}Al_xAs/GaAs/Ga_{1-x}Al_xAs$.[25] For the undoped sample #237, the tunneling effect can be neglected due to the absence of free electron without photo-excitation, or due to the low free electron concentration with moderate-intensity excitation. Therefore, the built-in electric field $F$ existing in the undoped structure is inclined to become energy band alignment, and thus results in the peak separation of $\Delta E = 30$ meV of the indirect PL spectra, as shown in Figs. 2(a) and 2(c), respectively. The built-in electric field $F$ is estimated to be $2.8\times10^4$ V·cm$^{-1}$ from $F = \Delta E/e\Delta d$, where $\Delta d = W_{\rm ZnSe}/2 + W_{\rm BeTe} + W_{\rm ZnSe}/2 = 10.7$ nm is the mean distance between the centres of the two QWs, $W_{\rm ZnSe}$ and $W_{\rm BeTe}$ are the widths of the ZnSe and BeTe layers, respectively. For the doped sample #288, however, the electron tunnel effect will result in an additional electric field, which can cancel out the built-in electric field $F$. Therefore, the doped sample has a flatter energy band alignment as shown in Fig. 2(d), and only the single PL peak, involving the contributions from both sides of the interfaces, is observed, as shown in Fig. 2(b).

In order to quantitatively estimate the electron concentration difference between the two QWs, the ZnSe/BeTe/ZnSe QW structures can be approximately equivalent to a parallel-plate capacitor. Assume that the electric charges situated in the two QWs are $-Q - \delta Q$ and $-Q + \delta Q$, respectively as shown in Fig. 3(a). The charge and charge density on the two plates are assumed to be $-\delta Q$, $-\delta\sigma$, and $-\delta Q$, $+\delta\sigma$, respectively, as shown in Fig. 3(b). Then, the carrier concentration $\delta n_{\rm e}$ on the plates are given by $\delta n_{\rm e} = \delta\sigma/e = F\varepsilon/e \approx 1.4\times10^{11}$ cm$^{-2}$, where $F = 2.8\times10^4$ V·cm$^{-1}$, $\varepsilon = 9.15\varepsilon$($\varepsilon_0$ : permittivity of vacuum) is the permittivity of the space between these two plates, being approximately equal to the permittivity of ZnSe material.[26] As the electron concentration $n_{\rm e}$ in the QWs under the photo-excitation is much larger than $1.2\times10^{12}$/cm$^2$, the electron concentration difference of $2\delta n_{\rm e} = 2.8\times10^{11}$ cm$^{-2}$ between the two QWs is considered to be reasonable. In other words, the electron concentration difference of $2.8\times10^{11}$ cm$^{-2}$ between the two QWs, originating from the electron tunneling through BeTe barrier, results in a new additional electric field, and the new electric field can cancel out the built-in electric field in the QW structure.

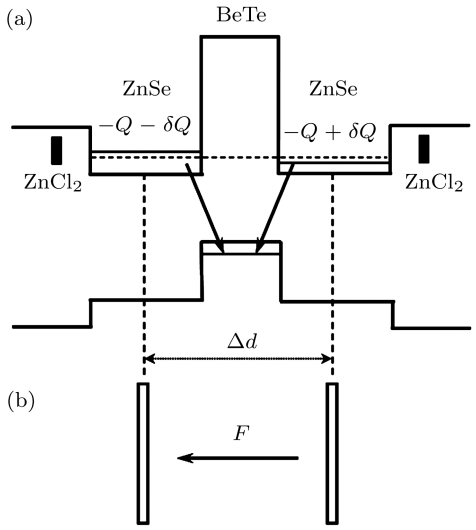



**Fig. 3.** (a) The electrons into the conduction band of the ZnSe layers after tunneling through BeTe barrier. (b) Parallel-plate capacitor that was equivalent to a ZnSe/BeTe/ZnSe structures shown in (a).

# 4. Summary

In order to investigate the dependence of spatially indirect PL transition on the n-doping density in modulation n-doped ZnSe/BeTe/ZnSe type-II QW structures, the CR absorption and indirect PL have been measured. The CR absorption measurements show that a high concentration two-dimensional electron gas can be formed in ZnSe layers only in the n-doped sample. While the spatially indirect PL measurements indicate that the high concentration electrons can cancel out a built-in electric field in the n-doped sample. These features are explained by the electron tunneling through the BeTe barrier. This tunneling results in the difference of the electron concentrations between the two QWs, and hence a new additional electric field forms, which cancels out the built-in electric field, and as the result, a flatter energy band alignment in the doped structure is evidently observed.

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