Optical de Haas oscillations of charged excitons in type-II ZnSe/BeTe quantum wells

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Abstract. We have studied the optical properties of the modulation n-doped ZnSe/BeTe/ZnSe type-II quantum wells. The reflection spectra have shown typical negatively charged exciton features only in a doped sample. The electron density as well as the mass was determined in high magnetic field (up to 160 T) cyclotron-resonance measurements. Photoluminescence (PL) measurements were performed in pulsed high magnetic fields (up to 42 T) with a Faraday configuration. We found oscillations in both the PL intensity and the peak energy in the doped sample. These oscillations were originated from optical de Haas oscillations. It was found that the observed indirect PL transition occurs via the charged excitons in a type-II quantum configuration.

1. Introduction
Recently type-II ZnSe/BeTe quantum well (QW) 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 [1], and strong in-plane optical anisotropy [2]. Such deep potential wells for carriers result in a very small penetration of the electron and hole wave functions into the neighboring layers [3, 4]. Due to the long recombination lifetimes of spatially separated electrons and holes, type-II QW’s are considered to be good candidates for the observation of high density excited states [5,6]. However, to our knowledge, there have been few experimental reports on the radiative properties of n-type ZnSe/BeTe/ZnSe type-II QW structures in high magnetic fields.

In this paper, in order to investigate the origin of the PL, we have examined the magnetic field effects on reflectivity and radiative recombination in modulation n-doped ZnSe/BeTe/ZnSe type-II QWs.

2. Experimental details
All of the four types of samples were grown on (001) GaAs substrates by molecular beam epitaxy (MBE) and consist of ZnSe/BeTe/ZnSe QW structures. Both the non-doped (#237) and the light-
doped (#239) samples have symmetrical ZnSe/BeTe/ZnSe (28 ML/10 ML/28 ML) QW structures [7], and the non-doped (#287) sample has an asymmetrical (28/10/14) structure. The heavily-doped (#288) sample has three sets of symmetrical (28/10/28) structures separated from each other by 90-nm-thick Zn_{0.77}Mg_{0.15}Be_{0.08}Se barriers. The QW layers in all samples were sandwiched by 200 nm-thick Zn_{0.77}Mg_{0.15}Be_{0.08}Se barrier layers. The thickness of the doped layers (ZnCl₂) separated from the QWs by 10 nm-thick barrier layers is 1 nm for sample #239 and 5 nm for sample #288. The other parameters for the four samples are identical. Special growth conditions were chosen to form the Zn-Te (or Te-Zn) chemical bonds at respective interfaces by devising shutter cycles in the effusion cells [7,8]. The schematic diagram of quantum structure of the symmetrical sample is shown in the inset to Fig. 1.

For infrared cyclotron-resonance (CR) absorption measurements, the megagauss magnetic fields were generated by the single-turn coil technique, and a CO₂ laser of wavelength 10.78 μm was used [9]. For the magneto-PL measurements, the pulsed magnetic fields were produced by a capacitor discharge, applied parallel to the growth (z) direction. An Ar-ion laser was used as an excitation source. The light from the Ar-ion laser was introduced to the sample via an optical fiber system with a core diameter of 200 μm, and the luminescence signal was transferred to a spectrometer with a CCD array [10].

3. Experimental results and discussion

The reflection measurements with right- and left-circular (σ⁺ and σ⁻) polarizations in the magnetic fields (0-7 T) were performed at 5 K. As seen in Fig. 1, these spectra in non-doped (#237) and light-doped (#239) samples have shown heavy- and light-hole exciton transitions with discernible structures at an energy around 2.835 eV, which value is typical of a direct band gap in the ZnSe. On the low energy side of the heavy-hole peak, there was observed a shoulder only in the doped sample (#239). The shoulder peak became more enhanced with an increasing magnetic field only for the σ⁻ polarization, while it disappeared in the σ⁺ polarization, obeying the typical spin selection rule for negatively charged excitons having a singlet spin configuration.

Recently, we reported the results of reflection, absorption, and PL measurements performed on other samples of this structure system [7]. We found that only for the doped samples did the reflection and the absorption spectra of a direct transition in the ZnSe layer show a typical negatively charged exciton feature in spin-dependent polarization under a magnetic field. At the same time the radiative recombination of the spatially indirect transition between the electrons in a ZnSe layer and the holes in
a BeTe layer showed a lower polarization degree and a weaker built-in electrostatic field in the doped sample than in the non-doped one.

The magneto-transmission spectrum of a 10.78 μm radiation in the heavily-doped sample (#288) displayed a broad CR at 144 T, as shown in Fig. 2. The electron effective mass $m^*$ was estimated to be 0.144$m_0$ from $\omega_c = eB/m^*c$, in rather good agreement with the value 0.141$m_0$ of the electron mass determined for the bulk n-ZnSe [11]. Based on these results, the electrons are considered to be efficiently doped in the ZnSe layers in our structures. The electron density is roughly estimated to be $\sim 5 \times 10^{11}$/cm$^2$ from the fit between the CR absorption spectrum and a dielectric function model, which is consistent with our estimate of the doping level. In addition, the mobility $\mu$, as estimated from the line-width corresponding to $\tau = 0.02$ ps, is about 244 cm$^2$/V·s.

Fig. 3 shows the magnetic field effects of the type-II PL spectra in sample #288 to be 2 K with $P = 8$ W/cm$^2$. We found the oscillations in both the PL integrated intensity and the peak energy under the magnetic fields to be as seen in the inset to Fig. 3. In contrast, such oscillation behavior was not observed in the non-doped sample #287 (Fig. 4), where the PL intensity decreases and the peak energy increases consistently. This tendency could be explained by an effect of Zeeman splitting in higher fields, which caused the inter-band transition to be prohibited between -1/2 electrons, and the +3/2 holes occupied only at the lowest energy levels. Together with the negatively charged exciton features of the absorption and reflection spectra of a direct optical transition in the ZnSe layer, as stated above, the observed oscillations in doped samples are regarded as optical de Haas (OdH) oscillations. These oscillations have been observed also in type-I structures [12-15].

The PL oscillation behavior is well understood by considering the many-body interaction of electrons and holes reported by both Tsuchiya et al. [16] and S. Katayama et al. [17]. The oscillation of a peak position is considered to be the result of self-energies associated with 2D electrons and holes. In our case, however, the oscillation period is somehow shifted from those expected from the Fermi-level derived from the doping level or from the value expected from the CR data. The electron density was estimated to be $\sim 7 \times 10^{11}$/cm$^2$ in region of the low magnetic fields (below 18 T), and $\sim 2 \times 10^{12}$/cm$^2$ in region of the high magnetic fields (above 18 T), respectively, from the oscillation period. Due to an extremely long life time of the optically excited electron-hole pairs, which is magnetic field dependent, we expect that the Fermi level under optical illumination defers from that of dark condition. Based on these facts mentioned above, the observed indirect PL spectra in doped samples are ascribed to the charged exciton transition [7].
4. Summary
The modulation n-doped ZnSe/BeTe/ZnSe type-II QW structures were studied by magneto-optical
experiments in pulsed high magnetic fields. The reflection spectra of a direct transition in the ZnSe
layer showed typical negatively charged exciton features under a magnetic field. A carrier
concentration of the ZnSe QWs was estimated from a clear signal of an ultra-high magnetic field CR
conducted by a single-turn coil technique. The PL of indirect transition exhibited oscillatory features
of both intensity and energy, which is considered as an OdH oscillation, peculiar to the type-II
structures.

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Figure 4. PL spectra in magnetic fields for the non-doped asymmetrical sample #287. A streak image (a)
and plots (b) of the PL intensities and the peak energies, at $T = 4.2$ K and $P = 11$ W/cm².