Crossing of Zeeman levels in quantum Hall systems of CdMnTe

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Abstract. Magnetoluminescence properties have been studied for 2 dimensional electron systems in a CdMnTe/ CdMgTe single quantum well for dilute Mn concentration at high steady magnetic fields up to 35T. Singlet and triplet charged excitons are observed with varying the applied magnetic field, and a splitting of a luminescence peak based on the crossing of Zeeman levels have been found out around \( B = 12 \)T. It is also found that anomalous photoluminescence peaks appear under the high magnetic field above \( B = 25 \)T.

1. Introduction
In II-VI diluted magnetic semiconductors, optical properties, e.g., the giant Zeeman splitting and the giant Faraday rotation, have been investigated extensively from a viewpoint of the controllability of effective \( g^* \)-factor. Recent progresses of the growth technique enable us to study transport properties [1,2] (the quantum Hall effect in CdMnTe QW) or magnetic properties [3,4] (the ferromagnetism in ZnCrTe) for high quality doped systems in various II-VI compounds. These progresses of sample quality mean that detailed optical studies are also possible to be performed in 2 dimensional electron gases (2DEGs) of II-VI diluted magnetic semiconductors [5-7].

Optical properties of the 2DEGs have already been studied in high quality GaAs heterojunction systems at low temperatures and at high magnetic fields. However, optical spectra of 2DEGs under the magnetic field depend strongly on several parameters such as the carrier density, the mobility, the Zeeman splitting and the structure of samples. Thus, the optical nature in quantum Hall systems have not been understood well yet.

The advantage of II-VI diluted magnetic semiconductors for studying the optical properties in 2DEGs is the controllability of the \( g^* \)-factor through introducing magnetic ions. The controlling of the Zeeman splitting by the Mn concentration in CdMnTe affects the spin population of Landau levels. We have already studied the quantum Hall systems of CdMnTe with moderate Mn concentration in the high magnetic field [8], and 2DEGs are found to be polarized even at \( \nu \geq 1 \) because of the giant Zeeman splitting. In this study, we have concentrated the photoluminescence (PL) spectra in the quantum Hall systems of CdMnTe/CdMgTe for dilute Mn concentration, and the stability of the charged excitons will be studied in case of the small Zeeman gap in the conduction band even under the high magnetic field.
2. Experimental
Magneto PL experiments in CdMnTe/CdMgTe single quantum well (SQW) were performed at $T=0.5\text{K}$ or $1.5\text{K}$ with an excitation by a CW-solid state green laser (=532nm). The steady magnetic field was generated up to $B=15\text{T}$ by a superconducting magnet and up to $B=35\text{T}$ by the hybrid magnet in National Institute for Materials Science, respectively. A sample was grown by molecular beam epitaxy method on a (100) GaAs substrate with doping iodine donors in the center of a CdMgTe barrier layer. The well width of the sample is 10nm and the Mn concentration of the quantum well is estimated less than 0.3% from the PL energy under no magnetic fields. The carrier density was estimated $4\times10^{10}\text{cm}^{-2}$ from the magnetic field of $\nu=1$.

3. Results and Discussions
Figure 1 and 2 show the magnetic field dependence of PL spectra and PL energies of the CdMnTe/CdMgTe SQW at $T=0.5\text{K}$, respectively. The magnetic field is applied perpendicular to growth layers up to $B=15\text{T}$. A red shift of the PL peaks caused by the s(p)-d exchange interaction between carriers and Mn local spins, is observed clearly at low magnetic fields, and the blue shift occurs at higher magnetic fields. The main PL observed at $B=0\text{T}$ is the recombination of the singlet charged exciton (Open circles in Figure 2). The PL intensity of the singlet charged exciton is suppressed drastically with increasing the magnetic field, and a exciton peak appears at the higher energy side instead of the singlet charged exciton peak. These features are common in the magnetic field dependence of PL in both CdMnTe [8] and ZnMnSe [9], and the shift of the PL energy in 2DEGs of CdMnTe was found to occur at $\nu=1$ [8]. In the sample, the PL energy of the main peak shifts to the lower energy around $B=1.6\text{T}$. Thus, the carrier density of the sample can be estimated about $4\times10^{10}\text{cm}^{-2}$. This shift of the PL energy at $\nu=1$ is correspondent to the switching of the ground state from the singlet charged exciton or exciton to the triplet one. This is due to the electron spin polarization occupied in the lowest Landau spin sub-level at $\nu \leq 1$. The larger PL intensity of the exciton than the one of the singlet charged exciton means that the localization degree of valence excited holes is larger in the sample at low magnetic fields.

![Figure 1. Magneto photoluminescence spectra in CdMnTe/CdMgTe SQW at $T=0.5\text{K}$ up to $15\text{T}$. A splitting of the triplet charged exciton peak is found out above $B=12\text{T}$.](image1)

![Figure 2. Magnetic field dependence of PL energies in CdMnTe/CdMgTe SQW at $T=0.5\text{K}$. The size of the each symbol shows the PL intensity.](image2)
Below $\nu=1$, the triplet charged exciton peak is stable up to $B=15T$ except a splitting of the PL peak above $B=12T$ in figure 1. This feature is not observed in the conventional CdMnTe SQW [8], and this anomaly is due to the realization of the zero Zeeman gap by crossing spin sub-levels of conduction electrons for dilute Mn concentration. The effective g-factor of CdTe is negative ($g^*\sim-1.6$) and the contribution of the s-d exchange interaction to the $g^*$-factor in CdMnTe is positive. Thus, in dilute Mn concentration, both contributions are balanced in a magnetic field. The splitting of the triplet charged exciton peak means that both up-spin and down-spin electrons are survived at $\nu \leq 1$ even though the spin sub-levels are switched around $B=12T$.

In figure 3, Landau levels for the conduction band are calculated with the use of the modified Brillouin function. We used the electron effective mass $m^*=0.105m_0$ and the Mn concentration $x=0.2\%$ as the parameter for the calculation. The crossing of the spin sub-levels in the conduction band is found to occur around $B=12T$ in the case, and the critical magnetic field is found to be in good agreement with the obtained data from figure 2.

The magnetic field dependence of the luminescence at high magnetic field up to $B=35T$ not at $T=0.5K$ but 1.5K is shown in figure 4. The crossing behavior around $B=12T$ is not clear at the temperature. Moreover, other photoluminescence peaks appear above $B=25T$. This is probably due to the crossing between the heavy hole state and the light hole state at high magnetic fields because the two states are estimated to cross each other around $B=25T$ (not shown here) under the assumption of the heavy hole mass $m^*_{hh}=0.81m_0$, the light hole mass $m^*_{lh}=0.12m_0$ and the splitting between the heavy and light hole states 10meV. Thus, the origin of four PL peaks above 25T can be explained as triplet charged exciton (+, heavy hole), singlet charged exciton (-, light hole), singlet charged exciton (+, heavy hole) and singlet charged exciton (+, light hole), respectively from the comparison with the calculation of the Landau levels including the s(p)-d exchange interaction. However, the real structure of the valence band in the magnetic field is complicated, and further theoretical and experimental studies at high magnetic fields are needed to clarify the origin of the optical recombination at high magnetic fields in figure 4 and also to understand the stability of the triplet and the singlet charged exciton in the quantum Hall systems under the small Zeeman gap.

4. Conclusion
We have performed magnetoluminescence experiments in CdMnTe SQW for dilute Mn concentration with dilute 2DEGs at high magnetic fields up to $B=35T$. The splitting of the
triplet charged exciton peak is observed around $B=12\,\text{T}$ owing to the crossing between up-spin and down-spin Zeeman levels. Above $B=25\,\text{T}$, we also found that other PL peaks appear at the lower energy side instead of the triplet charged exciton peak. From the comparison with a calculation of Landau levels by using the modified Brillouin function with some assumption, the appearance of these PL peaks at high magnetic fields are probably due to the crossing between the heavy hole state and the light hole state. In the sample of low Mn concentration, the competition among the binding energy of the charged exciton, crossing of the Zeeman levels and crossing between the heavy hole state and the light hole one, make the magnetoluminescence spectra quite complicated in particular at the high magnetic field.

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6. References
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