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OPTICALLY DETECTED SdH OSCILLATIONS IN CdTe/(CdMg)Te AND CdTe/(CdMnMg)Te MODULATION DOPED QUANTUM WELLS

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Oscillations of photoluminescence properties in external magnetic fields are investigated in CdTe modulation doped quantum wells. The oscillatory behaviour of the luminescence intensity, the line width and the g factor is due to many-body effects in the 2-dimensional electron gas. The oscillation of photoluminescence intensity can be easily used as optically detected Shubnikov de Haas effect to determine the electron concentration in quantum wells without contacts.

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1. Introduction and mechanism

The determination of the charge carrier concentration is one of the most important tasks to characterise the electronic properties of semiconductor devices. The intensity oscillation of the photoluminescence (PL) spectra as a function of the magnetic field can be used to detect the electron concentration [1, 2]. In this paper we report, for the first time, on oscillations of the PL properties in II–VI heterostructures which are directly correlated to many-body effects of the 2-dimensional electron gas (2DEG).

The many-body effects determining the PL intensity oscillation observed for 2DEGs can be summarised as follows [3]. The Landau level half width, and so the density of states, is a function of the Fermi level position. According to the theory within the self-consistent Born approximation, the half width will be narrow when the Fermi level lies in the centre of the Landau level where extended states are located and it will be broad when the Fermi level lies between two Landau levels. When the Landau levels pass successively through the Fermi level, the half width oscillates. As the total number of states does not change, the density of states oscillates as a function of the magnetic field with a period of $1/B$, resulting in an oscillation of the PL intensity, with the same period and phase as the electrical Shubnikov de Haas (SdH) oscillation.

2. Experiment and discussion

A typical PL spectrum of a modulation doped QW with $L_z = 10$ nm is shown in Fig. 1a. From the magnetic field shift of the peak position in external magnetic fields and from the line shape analysis, we know that this line is associated with a band-to-band transition. The line shape fit assuming a band to band transition exhibits a perfect agreement with the observed spectrum. As can be seen from Fig. 1a the quasi Fermi level for the electrons is, approximately, in the middle of the edge-like structure in the PL spectrum (Fig. 1).

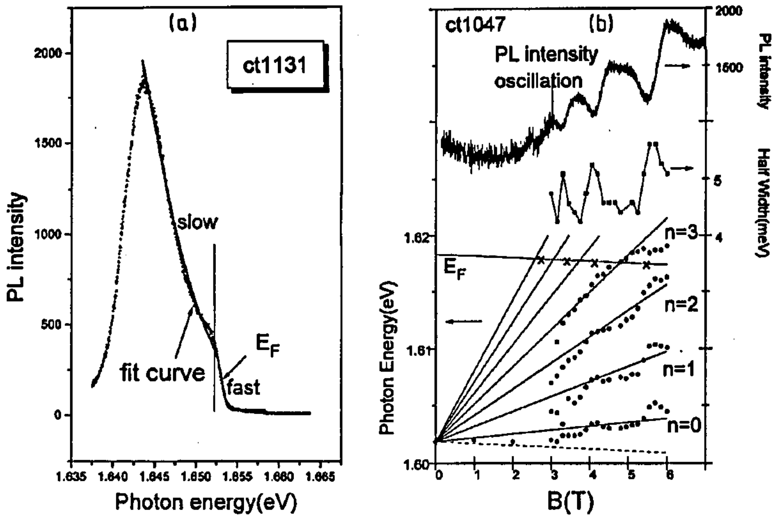

Fig. 1. (a) Photoluminescence signal in a QW ($B = 0$). The solid line is a line shape fit of the PL signal assuming a band to band transition. The vertical line separates the region, where the line shape is dominated by the thermal distribution of holes (slow) and electrons (fast), respectively. The Fermi level is indicated by the arrow. (b) Comparison of OdSdH, half width oscillation and Landau level oscillation. The solid circles represent the Landau level energies obtained from the experiment. The crosses on the Fermi level E_F represent magnetic fields where the half width reaches a maximum.

If the laser power is very low, the concentration of photoexcited carriers will be much less than the intrinsic carrier concentration. At low temperatures, the high energy side of the PL line shape is determined by a slow and a fast (approximately 1.6 times faster) decreasing part which is related with the thermal distribution of holes and electrons. The line shape of the conduction band Landau level can thus be deduced from the PL spectrum as a function of the magnetic field.

Sweeping the magnetic field and keeping the spectrometer fixed on the transition of the lowest Landau level ($n = 0$) in the conduction band we are able to detect the intensity change of the PL as a function of the magnetic field (Fig. 1b). The Fermi level and Landau levels are drawn with the consideration of self-energy correction and with the effective mass of $0.122m_0$. We deduce that the PL intensity minimum occurs at magnetic field strengths where the Fermi level lies between two Landau levels (Fig. 1b). As can be seen, the intensity of the PL line shows a well-resolved $1/B$ oscillation. The electron concentrations determined by this optically detected Shubnikov de Haas (OdSdH) oscillations are listed in Table. For samples whose carrier concentrations could be determined by electrical means, we obtained values in good agreement with OdSdH data.

TABLE

The list of the samples investigated.

Sample	CdTe/(CdMnMg)Te	QW [Å]	Spacer [Å]	n_{OdSdH} [10^{11}/cm^2]	n_{Hall} [10^{11}/cm^2]
ct1047	Mg = 27%, Mn = 0	100	50	7.7	8.0
ct1089	Mg = 34%, Mn = 0	100	50	8.6	–
ct1091	Mg = 32%, Mn = 0.5	100	50	7.0	–
ct1103	Mg = 25%, Mn = 0.5	60	60	8.2	9.2
ct1130	Mg = 26%, Mn = 0	60	120	4.02	–
ct1131	Mg = 26%, Mn = 0	60	90	4.5	–
ct1133	Mg = 26%, Mn = 0	60	60	5.3	–
ct1132	Mg = 26%, Mn = 0	60	30	5.2	–

A series of samples, ct1130, ct1131, ct1133 and ct1132 have been grown under identical conditions, but with different spacer thicknesses. With increasing thickness of the spacer we obtain a decreasing electron concentration in the QW demonstrating a reduced charge transfer with increasing spacer thickness.

There might be a small contribution to the oscillation of the PL intensity by the oscillation of Landau level energy as can be seen in Fig. 1. The Landau level energy oscillates because the dielectric constant, which determines the electron self energy, is a function of the density of the electrons near the Fermi level. In our experiments the difference between the detection wavelength and the wavelength of the luminescence maximum is kept always smaller than 2 Å. Therefore, a contribution to the PL intensity by the non-linear variation of he photon energies can be neglected.

We have also recorded the PL signal with respect to σ^+ and σ^- polarization of the detected light (Fig. 2). From the well resolved sets of the Landau level fan diagrams for the different polarization, the g factor can be deduced. The g factor oscillates and reaches its maxima when a spin down Landau level lies above the Fermi level and a spin up level lies below. In this situation, the electron or hole concentration difference of the two-spin directions is at its maximum. Thus the total PL intensity of σ^+ and σ^- polarization oscillates with the same period of SdH effect. So the total PL intensity oscillation can also be used as OdSdH to measure electron concentration.

To further understand the relation between optical and electrical properties, we have measured both properties simultaneously for the sample ct1103 (Fig. 3).

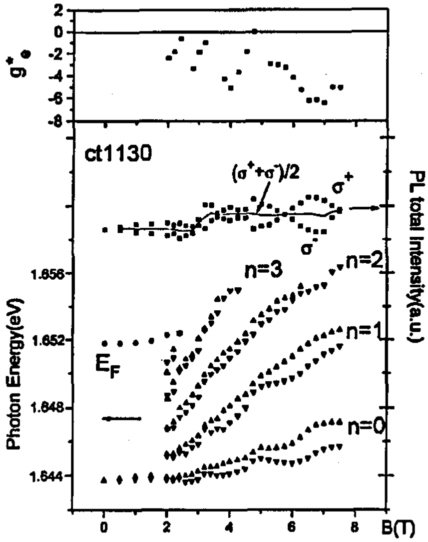

Fig. 2. Oscillatory behaviour of the electron g factor, total PL intensity of σ^+ and σ^- polarization and Landau level energy. The total PL intensity oscillates in phase with the g factor oscillation. The solid line is the average value of σ^+ and σ^- PL intensity. The up and down triangles in the Landau levels represent the σ^+ and σ^- Landau level transition energies.

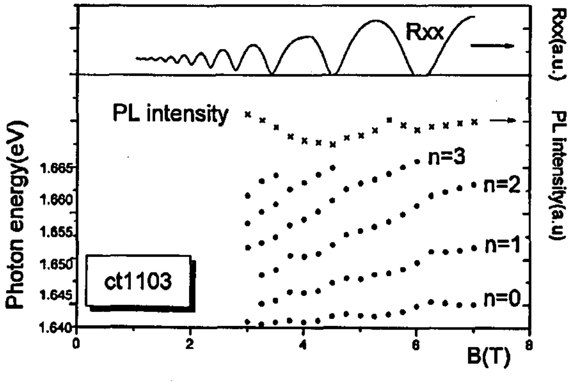

Fig. 3. Comparison of the oscillatory behaviour of SdH with OdSdH and Landau level energy.

Magneto-resistance R_{XX} minima perfectly coincide with the minima of the PL intensity at magnetic fields where the half width has a maximum, the Landau level energy shows the strongest increase and the g factor has the smallest value. All of these extrema occur at the field strength where the Fermi level lies in the band tails of the Landau levels as theoretically predicted [4].

3. Conclusion

Various kinds of magneto-photoluminescence oscillations have been observed and are explained by many-body interactions. The electron concentration, measured by OdSdH, agrees very well with the data obtained by transport measurement. The oscillation of the σ^+ and σ^- PL intensities are explained by the oscillations of the g factors. Details are published elsewhere [5]. All oscillations observed in the PL experiments are related to the Fermi level position and have the same oscillation period as observed in SdH experiments.

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References

[1] V.E. Kirpichev, I.V. Kukushkin, V.B. Timofeev, V.I. Fal'ko, K. von Klitzing, K. Ploog, *JETP Lett.* 54, 637 (1991).

[2] I.V. Kukuschkin, K. von Klitzing, K. Ploog, *JETP Lett.* 47, 599 (1988).

[3] T. Ando, in: High Magnetic Fields in Semiconducter Physics, Ed. G. Landwehr, in series *Solid State Sciences*, Vol. 87, Springer Verlag, Berlin 1989, p. 164.

[4] *The Quantum Hall Effect*, Eds. R.E. Prange, S.M. Girvin, Springer Verlag, New York 1987.

[5] J.X. Shen, W. Ossau, F. Fischer, A. Waag, G. Landwehr, in: *Eleventh Intern. Conf. on the Electronic Properties of Two-Dimensional Systems, Nottingham (1995)*, to be published.