PHYSICAL REVIEW B VOLUME 57, NUMBER 11 15 MARCH 1998-I

Magnetoluminescence study of a two-dimensional electron gas confined in diluted-magnetic-semiconductor quantum wells

M. S. Salib, G. Kioseoglou, H. C. Chang, H. Luo, and A. Petrou
Department of Physics, State University of New York at Buffalo, Buffalo, New York 14260

M. Dobrowolska and J. K. Furdyna
Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556

A. Twardowski
Institute of Experimental Physics, Warsaw University, Hoza 69, 00681 Warsaw, Poland

(Received 10 September 1997)

We have carried out a photoluminescence study of an n-type modulation-doped ZnSe/$Zn_{0.825}Cd_{0.14}Mn_{0.035}Se$/ZnSe single quantum well structure (electron areal density $n_A=1.6\times10^{12}$ cm^{-2}) in magnetic fields up to 30 T. In the presence of a magnetic field, the broad emission band in the vicinity of the gap evolves into a series of discrete features. These are attributed to interband transitions of electrons occupying Landau levels to photogenerated holes. The Landau transitions associated with both electron spin states ($m_j=\pm\frac{1}{2}$) are clearly resolved due to the large electron and hole g factors exhibited by the magnetic wells. An analysis of the Landau-level occupation as a function of magnetic field yields the electron concentration. [S0163-1829(98)05111-X]

The optical properties of two-dimensional electrons confined in heterostructures based on III-V semiconductors have been studied in detail over the past 15 years.[1–5] The luminescence from these structures at zero magnetic field is broad and featureless; it is attributed to radiative transitions between electrons populating the lowest conduction subband with photogenerated holes. When a magnetic field is applied perpendicular to the structure layers, the degeneracy of the electrons associated with the motion in the x-y plane is removed and their energy spectrum becomes discrete, with the appearance of Landau levels. This quantization manifests itself as a disappearance of the continuous emission band and its evolution into a series of discrete interband transitions, with all excitonic effects screened by the electron gas. More recently[6] the magnetoluminescence from n-type modulation-doped $Zn_{1-x}Cd_xSe$/ZnSe(Cl) quantum wells has been studied. The phenomena in this II-VI system are very similar to those observed earlier in III-V-based structures. These include the screening of excitons, band-gap renormalization, and the dependence of the Landau-level occupancy on magnetic field. Magnetotransport studies have been reported by Smorchkova *et al.*[7] of a two-dimensional electron gas confined in $Zn_{1-x}Cd_xSe$ wells that incorporate fractional monolayers of MnSe. Quantum transport in these structures is strongly influenced by the spin-exchange interaction between electrons and the localized Mn ions in the MnSe monolayers.

In this paper we report a magnetoluminescence study of an n-type modulation-doped ZnSe(Cl)/$Zn_{1-x-y}Cd_xMn_ySe$/ZnSe(Cl) single quantum well structure. The well layers belong to a class of materials known as ‘‘diluted magnetic semiconductors’’ (DMS) due to the presence of transition-metal ions randomly substituting the nonmagnetic cations.[8,9] The most striking feature of DMS is the enhanced electron and hole g factors resulting from the strong exchange interaction between the spins of band electrons and those of the magnetic ions. The zero-field photoluminescence (PL) spectra from n-type magnetic samples are very similar to those from nonmagnetic II-VI structures.[6] In the presence of a magnetic field, significant differences are observed; the emission band splits into two strongly circularly polarized components that are associated with transitions between the $m_j=-\frac{1}{2}$ ($m_j=+\frac{1}{2}$) electrons and $m_j=-\frac{3}{2}$ ($m_j=+\frac{3}{2}$) holes. The energy of the two components does not change for magnetic fields $B>10$ T due to the saturation of the magnetization in the magnetic well layer. For magnetic fields $B>12$ T, the lower PL component exhibits further splitting due to the emergence of Landau levels. The magnetic-field dependence of the Landau-level occupancy allows the determination of the electron density. This work demonstrates the realization of a system that confines electrons, for which the size of the electron spin-splitting ΔE_s can be varied with respect to the cyclotron gap $\Delta E_c=\hbar\omega_c$.

EXPERIMENT

We have used two ZnSe/$Zn_{0.825}Cd_{0.14}Mn_{0.035}Se$/ZnSe single quantum well structures in this work. Sample 1 was doped n-type with chlorine in the ZnSe barriers; sample 2 was not intentionally doped and was used as a reference. Both structures were grown using molecular-beam epitaxy on (100) GaAs substrates on which a 2400-Å-thick undoped ZnSe buffer layer was deposited. The ZnSe barriers were 3600 Å thick, and the $Zn_{0.825}Cd_{0.14}Mn_{0.035}Se$ wells 100 Å. In sample 1, 240-Å undoped ZnSe spacers were incorporated between the well and the doped barriers.

0163-1829/98/57(11)/6278(4)/$15.00

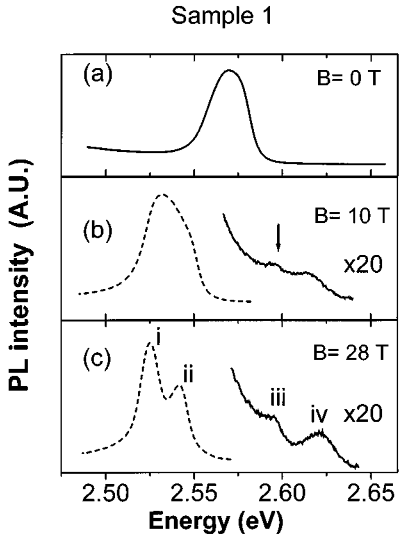

FIG. 1. Photoluminescence spectra from sample 1; $T=4.2$ K, (a) $B=0$ T. (b) $B=10$ T. (c) $B=28$ T. In (b) and (c), the solid (dashed) line indicates luminescence analyzed as σ_- (σ_+).

The PL spectra were recorded in magnetic fields up to 30 T at the National High Magnetic Field Laboratory. The magnetic field was generated by a water-cooled resistive magnet; the samples were mounted in an exchange gas cryostat that was placed inside the magnet bore. Luminescence was excited by the 3638-Å line of an argon-ion laser. The laser beam was transmitted via a 200-μm-diam UV optical fiber and the emitted light was collected by a 600-μm-diam optical fiber. The luminescence was analyzed by a grating spectrometer equipped with single-channel photon counting electronics as well as a multichannel cooled charge-coupled device detector. All measurements were carried out at 4.2 K in the Faraday geometry, with the magnetic field applied perpendicular to the structure layers. The polarization of the luminescence was analyzed as σ_+ or σ_- by a combination of a quarter-wave plate followed by a linear polarizer with its transmission axis at 45° with respect to the quarter-wave plate fast axis. The assembly was placed at the tip of the collection fiber and transmitted left circularly polarized light (σ_+) when the magnetic field direction was pointing up. Reversal of the magnetic field (magnetic field pointing down) resulted in transmitting right circularly polarized light (σ_-). The emission spectra were studied using two methods. The first was to fix the magnetic field and measure the luminescence intensity as a function of detected photon energy; we refer to these spectra as ‘‘energy scans.’’ The second technique consisted of fixing the detected photon energy and recording the luminescence intensity as the magnetic field was ramped from 0 to 30 T; we refer to these spectra as ‘‘field scans.’’ Field scans are more sensitive to interband transitions with higher slopes (dE/dB).

DISCUSSION

The zero-field PL spectrum from sample 1 is shown in Fig. 1(a). It consists of a broad (width=40 meV) band in the vicinity of the lowest-energy interband transition (e_1h_1). The zero-field emission feature is attributed to radiative recombination processes between electrons occupying states at the bottom of the e_1 subband and photogenerated holes. All excitonic effects are screened by the electrons. In the presence of a magnetic field up to 10 T applied perpendicular to the structure's layers, the luminescence splits into two components that are circularly polarized as σ_+ [dashed line in Fig. 1(b)] and σ_- [solid line in Fig. 1(b)]. The σ_+ (σ_-) component is attributed to band-to-band recombination processes between the $m_j=-\frac{1}{2}$ ($m_j=+\frac{1}{2}$) electrons and $m_j=-\frac{3}{2}$ ($m_j=+\frac{3}{2}$) holes. The weak feature indicated by the vertical arrow in Fig. 1(b) is associated with transitions between $m_j=-\frac{1}{2}$ electrons and $m_j=+\frac{1}{2}$ light holes.

Even though the energy separation of the two heavy-hole PL components (90 meV at 10 T) is well above kT, the upper (σ_-) component is still observable in the PL spectra. This has been reported earlier in other strained quantum well structures and epilayers[10] and has been attributed to the long spin-relaxation lifetime τ_h of the holes that becomes comparable to the recombination time. The increase in τ_h is due to the strain-induced separation of the heavy- ($m_j=\pm\frac{3}{2}$) from the light- ($m_j=\pm\frac{1}{2}$) hole states; the matrix element for the $|+\frac{3}{2}\rangle \rightarrow |-\frac{3}{2}\rangle$ transition at $k=0$ vanishes if we assume a Heisenberg-type coupling between the spins of the holes and those of the Mn ions.[11] Both samples used in this study incorporate thick ZnSe layers (buffer plus barrier=6000 Å) that impose a compressive strain on the much thinner (100 Å) $\mathrm{Zn_{0.825}Cd_{0.14}Mn_{0.035}Se}$ well layers of approximately 1%.[12] The presence of strain does not affect the electron-spin-relaxation time τ_e, which remains well below the recombination time.[10,13] The intensity of the σ_- component in sample 1 is 60 times stronger than the same transition in the undoped sample 2. This difference is understood as follows: In sample 2 both electrons and holes participating in the σ_- recombination process are photogenerated, with τ_e and τ_h affecting the luminescence intensity. In sample 1, which contains a dense two-dimensional electron gas however, both electron-spin states ($m_j=\pm\frac{1}{2}$) are occupied and the recombination intensity is only affected by the spin-relaxation time (τ_h) of the holes. This stronger relative intensity of the σ_- component in sample 1 is a signature of the two-dimensional electron gas.

For magnetic fields greater than 10 T a series of distinct features emerges from the lower-energy branch [dashed line in Fig. 1(c) for $B=28$ T]. Features (i) at 2.525 eV and (ii) at 2.542 eV are attributed to transitions from the $m_j=-\frac{1}{2}$, $l=0$ and $l=1$ conduction-band Landau levels, respectively, to the $m_j=-\frac{3}{2}$ hole state. Feature (iv) at 2.621 eV is associated with the transition from the $m_j=+\frac{1}{2}$, $l=0$ conduction-band Landau level to the $m_j=+\frac{3}{2}$ hole state. Feature (iii) at 2.593 eV is identified as due to transitions between $m_j=-\frac{1}{2}$ electrons and $m_j=+\frac{1}{2}$ light holes. In sample 2 transitions associated with Landau levels are not observed; only the two e_1h_1 excitonic components (σ_+ and σ_-) are observed up to 30 T.

In Fig. 2 we plot the energies of the interband transitions from sample 1 as a function of magnetic field. Circles and crosses indicate features analyzed as σ_+; triangles represent PL features analyzed as σ_- recorded using energy scans. Circles (crosses) correspond to PL features recorded using

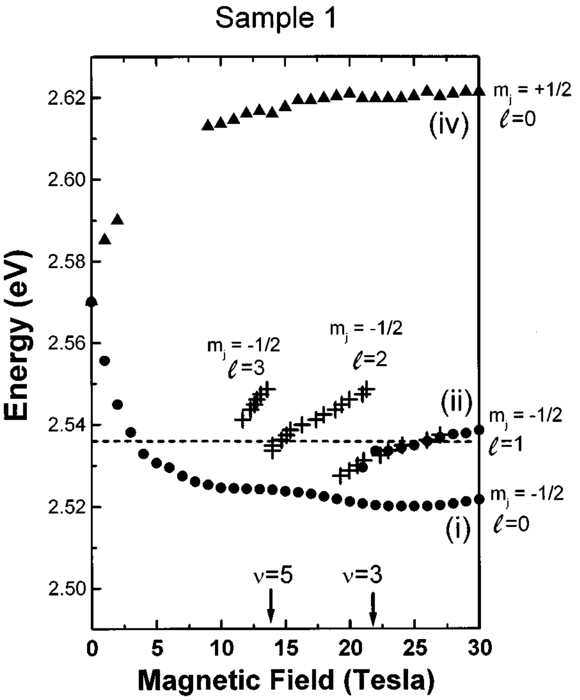

FIG. 2. Energies of the PL features from sample 1 plotted as a function of magnetic field at $T=4.2$ K. Triangles, energy scans (σ_-); circles, energy scans (σ_+); crosses, field scans (σ_+). The vertical arrows indicate the magnetic field positions for filling factors $\nu=3$ and 5.

energy (field) scans. An example of a field scan is given in Fig. 3. The spectrometer was fixed at 2.536 eV as indicated by the horizontal dashed line in Fig. 2, while the magnetic field was ramped from 0 to 30 T. The field scan in Fig. 3 contains three features: (a) at 3.6 T, (b) at 15 T, and (c) at 25.5 T. Feature (a) results from the redshift of the lower PL branch (σ_+) as it crosses the detected energy (see Fig. 2). Features (b) and (c) are identified as the interband transitions associated with the $m_j=-\frac{1}{2}$, $l=2$ and $l=1$ conduction-band Landau levels, respectively. The energies of the PL features recorded using both energy and field scans are in good agreement [see feature (ii) in Fig. 2]. The energy of the lowest transition in Fig. 2 [feature (i)] exhibits a step at ~ 17.5 T that nearly matches the field at which a similar step occurs in bulk $\mathrm{Zn}_{1-x}\mathrm{Mn}_x\mathrm{Se}$.[14] This behavior has been attributed to the first (of five) magnetization steps resulting from the Mn-Mn pairs.

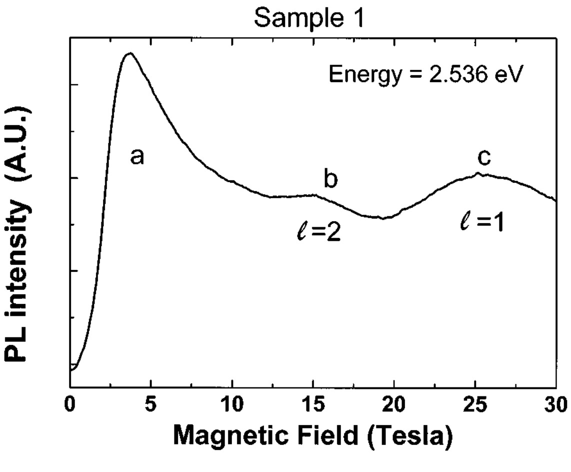

FIG. 3. Field scan from sample 1 taken with the spectrometer tuned at 2.536 eV (dashed horizontal line in Fig. 2); $T=4.2$ K.

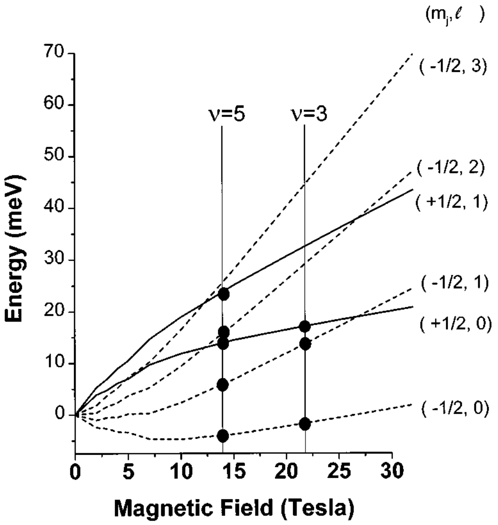

FIG. 4. Calculated energies of the conduction-band Landau levels plotted as a function of magnetic field. The spin (m_j) and Landau-level (l) quantum numbers are shown to the right. Dashed (solid) lines are used for the $m_j=-\frac{1}{2}$ $(m_j=+\frac{1}{2})$ electron-spin states. The vertical lines indicate the magnetic field positions for filling factors $\nu=3$ and 5.

In Fig. 4 we plot the calculated energies of the lowest six energy Landau levels in the conduction band as functions of magnetic field. Dashed (solid) lines indicate $m_j=-\frac{1}{2}$ $(m_j=+\frac{1}{2})$ electron-spin states. The energies were determined by adding the Landau energy term $[(l+1/2)\hbar\omega_c]$ to the electron-spin contribution. The electron spin splitting was taken to be 17% of the total splitting associated with heavy-hole transitions.[15] As can be seen in Fig. 2 the $m_j=-\frac{1}{2}$, $l=3$ transition vanishes at $B=14$ T $(\pm 0.5\ \mathrm{T})$. This results from the depopulation of the $m_j=-\frac{1}{2}$, $l=3$ state due to the finite electron occupancy per unit area of each spin-state (Be/h). Similarly at $B=22$ T $(\pm 0.5$ T) the $m_j=-\frac{1}{2}$, $l=2$ transition disappears. Both field values are shown in Fig. 4 using vertical lines and correspond to filling factors $\nu=5$ $(B=14\ \mathrm{T})$ and $\nu=3$ $(B=22\ \mathrm{T})$. The occupied states are indicated by solid circles. An electron areal density $n_A=(1.6\pm 0.1)\times 10^{12}\ \mathrm{cm}^{-2}$ was determined from these filling factors.

CONCLUSION

We have studied the band-edge PL spectra from an n-type modulation-doped $\mathrm{ZnSe/Zn_{0.825}Cd_{0.14}Mn_{0.035}Se/ZnSe}$ single quantum well structure (electron areal density $n_A=1.6\times 10^{12}\ \mathrm{cm}^{-2}$) in magnetic fields up to 30 T. Interband transitions that involve electrons occupying Landau levels associated with both $(m_j=\pm\frac{1}{2})$ spin states have been observed. An analysis of the Landau-level occupancy as a function of magnetic field allows a determination of the electron gas density. The physical system studied is unique because the electron spin splitting ΔE_s is much larger than the corresponding splitting in nonmagnetic II-VI and III-V structures.

In addition, the saturation value ($B > 10$ T) of ΔE_s can be tailored by varying the transition-metal ion concentration in the magnetic wells. Also the relative size of the spin splitting ΔE_s and the cyclotron gap ΔE_c at a fixed magnetic field can be continuously changed by varying the angle between the applied field with the perpendicular to the structure layers.

ACKNOWLEDGMENTS

A portion of this work was carried out at the National High Magnetic Field Laboratory, which is supported by NSF Cooperative Agreement No. DMR 9527035 and by the State of Florida. The work at SUNY was supported by ONR under the MFEL program.

---

[1] A. Pinczuk, J. Shah, R. C. Miller, A. C. Gossard, and W. Wiegmann, Solid State Commun. **50**, 735 (1984).

[2] C. H. Perry, J. M. Worlock, M. C. Smith, and A. Petrou, in *High Magnetic Fields in Semiconductor Physics*, edited by G. Landwehr (Springer-Verlag, Berlin, 1987), p. 202.

[3] M. S. Skolnick, J. M. Rorison, K. J. Nash, D. J. Mowbray, P. R. Tapster, S. J. Bass, and A. D. Pitt, Phys. Rev. Lett. **58**, 2130 (1987).

[4] E. D. Jones, H. Ackermann, J. E. Schirber, T. J. Drummond, L. R. Dawson, and I. J. Fritz, Solid State Commun. **55**, 525 (1985).

[5] D. Heiman, B. B. Goldberg, A. Pinczuk, C. W. Tu, A. C. Gossard, and J. H. English, Phys. Rev. Lett. **61**, 605 (1988).

[6] G. Kioseoglou, J. Haetty, H. C. Chang, H. Luo, A. Petrou, T. Schmiedel, and P. Hawrylak, Phys. Rev. B **55**, 4628 (1997).

[7] I. P. Smorchkova, N. Samarth, J. M. Kikkawa, and D. D. Awschalom, Phys. Rev. Lett. **78**, 3571 (1997).

[8] J. K. Furdyna, J. Appl. Phys. **64**, R29 (1988).

[9] J. P. Lascaray, in *Semimagnetic Semiconductors and Diluted Magnetic Semiconductors*, edited by M. Averous and M. Balkanski (Plenum, New York, 1991), Vol. 55, pp. 169–190.

[10] W. C. Chou, A. Petrou, J. Warnock, and B. T. Jonker, Phys. Rev. B **46**, 4316 (1992).

[11] R. Ferreira and G. Bastard, Phys. Rev. B **43**, 9687 (1991).

[12] H. J. Lozykowski and V. K. Shastri, J. Appl. Phys. **69**, 3235 (1991).

[13] C. D. Powleit, L. M. Smith, and B. T. Jonker, in *Proceedings of the 22nd International Conference on the Physics of Semiconductors*, edited by D. J. Lockwood (World Scientific, Singapore, 1994), Vol. 3, pp. 2561–2564.

[14] Y. Shapira, in *Semimagnetic Semiconductors and Diluted Magnetic Semiconductors* (Ref. 9), pp. 121–168.

[15] A. Twardowski, T. Dietl, and M. Demianiuk, Solid State Commun. **48**, 845 (1983).