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Dissociation Energy of Positively Charged Excitons in Semimagnetic CdMnTe Quantum Wells

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We present a transmission study of the energies of neutral and positively charged excitons in modulation doped $Cd_{1-x}Mn_xTe$ quantum wells with variable concentration of the hole gas. Application of the semimagnetic semiconductor as the QW material gives the opportunity to control independently the total hole concentration and its distribution between the two spin subbands (by a small magnetic field). The positively charged exciton dissociation energy is found to be a linear function of the concentration in only one hole spin subband (the one with the spin opposite to that of photocreated hole). This can be seen as a consequence of the fact that a charged exciton is not simply a three particle complex, but it consists of an exciton interacting with many holes.

Optical effects resulting from the exciton–carrier interactions in the presence of 2D carrier gas of low density, recently became a subject of intensive investigations. This interest has been stimulated by the observation of negatively and positively charged excitons in several types of quantum wells [1 to 6]. One of the issues that attracted much attention is the charged exciton dissociation energy defined as the difference between energies of charged and neutral excitons. This was extensively studied in several systems both experimentally [5, 6] and theoretically [7].

In this paper we focus on the dissociation energy of positively charged excitons in the presence of hole gas. Choosing a quantum well of semimagnetic material ($Cd_{1-x}Mn_xTe$) gives us the unique opportunity to tune independently the total hole concentration (through barrier illumination) and its distribution among the two Zeeman split $\pm 3/2$ spin subbands (by applying a weak magnetic field) [8, 9]. Therefore we were able to analyze independently effects of total population and carrier spin polarization, as opposed to the direct influence of the magnetic field, present in most studies of similar systems. In particular, we are able to distinguish spin-independent effects from spin-dependent ones.

In our experiment, we used MBE grown samples consisting of a single 80 Å quantum well (QW) of $Cd_{1-x}Mn_xTe$ embedded between $Cd_{0.66}Mg_{0.27}Zn_{0.07}Te$ barriers grown pseudomorphically on a [100] $Cd_{0.88}Zn_{0.12}Te$ substrate. Such a layout assures a large confinement energy for the holes in the quantum well, minimising at the same time the

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effects of lattice mismatch. A low Mn concentration in the QW ($x = 0.0018$) assured that the line broadening characteristic for mixed semimagnetic material was kept as low as possible, but was large enough to provide a significant Zeeman splitting ($\approx$5 meV in magnetic field of 5 T and at temperature 1.5 K). A nitrogen doped region in the front barrier was located at the distance which determined the equilibrium hole gas concentration and was chosen from 200 Å to 700 Å. The nominal hole concentration in the doped structure with 200 Å spacer, evaluated from a self-consistent solution of the Poisson and Schrödinger equations, was 2×10^{11} cm^{-2} [10].

In order to control the total carrier concentration we used above-barrier illumination, which reduces the concentration of hole gas in the quantum well. The mechanism of this effect [11] is based on the diffusion of electrons created by light into the quantum well. These electrons neutralize the hole gas and under continuous illumination the system approaches a stationary state with lowered hole gas concentration.

In order to determine carrier concentrations in the range where sharp X and X^+ absorption lines are observed, we applied a simple model describing the neutralization of the hole gas, by the photo-created carriers. We assume [10, 12] that the current of photo-created electrons recombining in the quantum well (participating in the hole gas neutralization) is proportional to the illumination, and in the steady state, it is equal to the current of holes tunneling from acceptors into the quantum well. Therefore the hole concentration is determined by the probability of the hole tunneling through the potential barrier between the quantum well and doped region. The model has two parameters which define the relation between the illumination and the electron current as well as the probability of the tunneling from acceptor to the quantum well. These parameters were obtained empirically [10] from the high concentration range, where the Moss-Burstein shift (the distance between well-resolved PL line and the energy of the absorption edge) gives directly the hole gas concentration.

The magnetooptic measurements were performed in the Faraday configuration with the magnetic field perpendicular to the sample surface. The sample was mounted strain-free in a superconducting magnet and immersed in liquid helium which was pumped to achieve 1.5 K. PL and PLE spectra were measured using an Al_2O_3:Ti laser providing about 2 mW/cm^2.

The typical zero field transmission spectra as a function of the hole gas concentration are presented in Fig. 1. The two lines are related to neutral (X) and positively charged exciton (X^+) formation. At the lowest concentration displayed, both lines are sharp and the X line is much stronger than X^+. When the carrier concentration increases, the low-energy line (X^+) becomes more intense while the other one (X) weakens and finally disappears at a hole concentration of about 8×10^{10} cm^{-2}. The energies of the lines move slightly when the hole gas concentration is changed. The energy of X^+ transition decreases by 0.5 meV when concentration is increased from 1.3×10^{10} to 6×10^{10} cm^{-2}. Simultaneously the X energy increases by 0.4 meV. This corresponds to an increase of the X–X^+ splitting from 2.7 to 3.6 meV as it is presented in Fig. 2 (empty symbols). Note that in Fig. 2 the hole concentration in only one spin subband (+3/2) is used as abscissa, and in zero field it is equal to half of the total concentration ($p_{+3/2} = (1/2)\, p$).

The energies of both X and X^+ transitions as a function of the magnetic field are shown in Fig. 3 for various total hole concentrations. For the neutral exciton X the shape of the magnetic field dependence does not vary with hole concentration. It reproduces well the bulk CdMnTe Zeeman effect which is described by a modified Brillouin function [9]. This shows that any spin-dependent effects (such as phase space filling) have

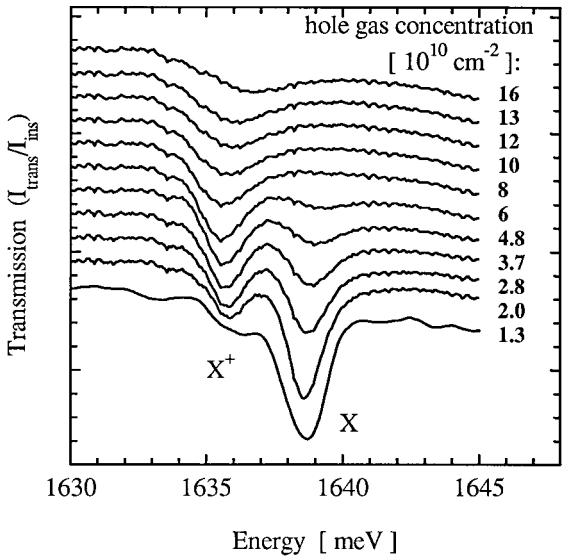

Fig. 1. Zero-field transmission spectra (transmitted intensity/incident intensity) for different hole gas concentrations (controlled by additional blue light illumination)

negligible influence on the neutral exciton energy. Therefore the observed slight increase with hole concentration of the X transition energy should be understood as an influence of spin-independent screening on the exciton binding energy [13, 14], partially balanced by band gap renormalization and by a variation of the electrostatic potential in this asymmetric modulation doped quantum well. The significance of the last contribution has been tested by growing a pair of samples having the same hole gas concentration, but one symmetric and one asymmetrically doped. The measurements of the X energy versus hole gas concentration showed exactly the same dependence on both samples.

Much more interesting is the field dependence of the charged exciton energy. At relatively high magnetic fields, high enough to completely spin polarize the hole gas ($p_{+3/2} = p$), one finds that in σ^- polarization, the energy of X^+ varies with field almost parallel to that of the neutral exciton. Thus, the X–X^+ distance (the X^+ dissociation energy) is constant for each hole concentration but it increases linearly with the concentration (Fig. 2, closed symbols). At lower field, the dissociation

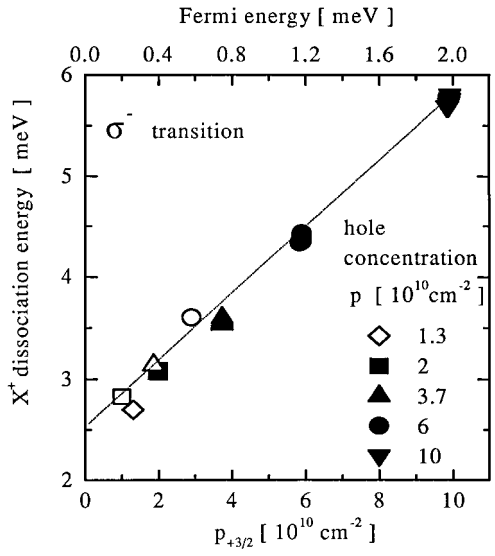

Fig. 2. Charged exciton dissociation energy (difference between the X and X^+ energy) as a function of the hole gas concentration in the spin subband promoting the X^+ formation (full symbols: complete spin polarization of holes, open symbols: no applied field)

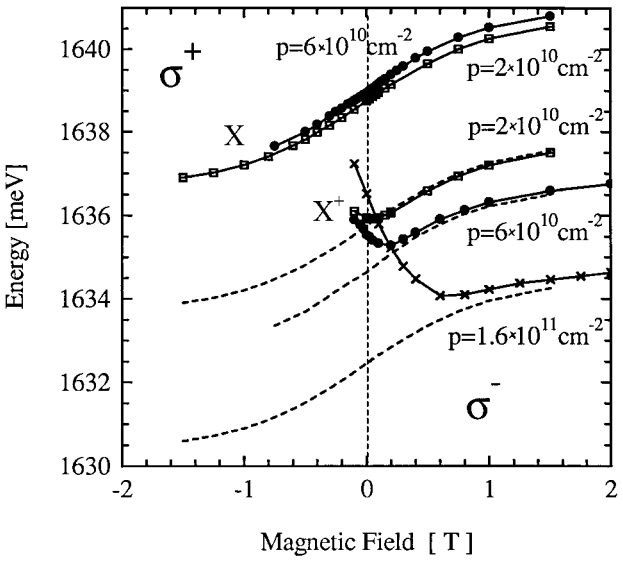

Fig. 3. Energies of the absorption lines versus magnetic field (left side: σ^+ polarization, right side: σ^- polarization), measured under different blue light illumination. Dashed lines represent the giant Zeeman effect of the X state (the same as in a bulk CdMnTe) shifted by an appropriate energy

energy suddenly gets smaller. This appears below a characteristic field, which increases with the hole density, and which corresponds to the field necessary to fully polarize the hole gas. If we then plot together the zero-field dissociation energy and the dissociation energy in the magnetic field versus population of holes in one spin subband (containing carriers necessary for X^+ formation), we find that the dependence is equal. An extrapolation to vanishing hole concentration gives a value of 2.5 meV. This is slightly smaller than the value 2.7 meV measured on samples with a low (but non-zero) doping [3].

The first consequence of the variation of the charged exciton dissociation energy is the remark that sufficient care must be taken when evaluating the trion binding energy and comparing it to any calculations. Most theoretical models are valid in the limit of vanishing density [7]. Our present extrapolation, 2.5 meV, is slightly smaller than the energy 2.7 meV measured previously in a similar quantum well at small but finite hole gas concentration [3].

The observed increase of the X^+ dissociation energy with the concentration of holes with the relevant spin (preexisting carriers only) requires a deeper analysis. Theoretical results of Hawrylak and coworkers [15] predict in fact a linear increase of the splitting between neutral and charged exciton, as the population increases in the absence of spin splitting. In a simple intuitive picture, both the neutral exciton and the charged exciton are due to the existence of a bound level which appears in the 2D gas in the presence of a carrier of opposite sign (i.e., of a hole in the case of an electron gas as described by Hawrylak, or of an electron in the present case of a hole gas). The neutral exciton then corresponds to a single occupancy of this level. The charged exciton involves, in addition to the creation of the exciton, the transfer of a carrier of opposite spin from the Fermi level down to the bound level. If we assume that the bound level exhibits the same giant Zeeman splitting as the band, we obtain that the $X–X^+$ splitting exhibits, in addition to the binding energy, an energy proportional to the population of the subband of preexisting carriers. Although the theory described in [15] has been developed principally for an electron gas and dispersionless holes, it would need to be extended to

the case where the photocreated carrier has a finite mass (which in the present case is smaller than the mass of the majority carriers), and to include spin splitting.

In summary, we show that the energy of the neutral exciton exhibits no influence of phase space filling and follows the giant Zeeman splitting of the bulk $Cd_{1-x}Mn_xTe$ material. The behaviour of the charged exciton is different: its dissociation energy, measured as the distance between the X and X^+ lines, is not constant with the hole gas concentration. It increases by a factor of two, when the hole concentration increases from 1×10^{10} up to 1×10^{11} cm^{-2}. Surprisingly the dissociation energy is found to be a linear function of the concentration in only one hole spin subband (the one with the spin opposite to that of the photocreated hole). This can be seen as a consequence of the fact that a charged exciton is not simply a three particle complex, but it consists of an exciton interacting with many holes. We find a qualitative agreement with the theoretical results of Hawrylak and coworkers [15] predicting such an effect but further theoretical analysis is necessary.

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References

[1] K. Kheng, R. T. Cox, Y. Merle d'Aubigné, F. Bassani, K. Saminadayar, and S. Tatarenko, Phys. Rev. Lett. **71**, 1752 (1993).
[2] G. Finkelstein, H. Shtrikman, and I. Bar-Joseph, Phys. Rev. Lett. **74**, 976 (1995).
[3] A. Haury, A. Arnoult, V. A. Chitta, J. Cibert, Y. Merle d'Aubigné, S. Tatarenko, and A. Wasiela, Superlattices and Microstructures **23**, 1097 (1998).
[4] T. Wojtowicz, M. Kutrowski, G. Karczewski, J. Kossut, F. J. Teran, and M. Potemski, Phys. Rev. B **59**, R10437 (1999).
[5] B. E. Cole, T. Takamasu, K. Takehana, R. Goldhahn, D. Schulze, G. Kido, J. M. Chamberlain, G. Gobsch, and M. Henini, Physica **249/251B**, 607 (1998).
[6] V. Huard, R. T. Cox, K. Saminadayar, C. Burgognon, A. Arnoult, J. Cibert, and S. Tatarenko, Proc. 13th EP2DS Conf., Ottawa, July 1999, to be published in Physica E.
[7] B. Stébé, E. Feddi, A. Ainane, and F. Dujardin, Phys. Rev. B **58**, 9926 (1998).
[8] A. Haury et al., Phys. Rev. Lett. **79**, 511 (1997).
[9] J. A. Gaj, W. Grieshaber, C. Bodin-Deshayes, J. Cibert, G. Feuillet, Y. Merle d'Aubigné, and A. Wasiela, Phys. Rev. B **50**, 5512 (1994).
J. A. Gaj, R. Planel, and G. Fishman, Solid State Commun. **29**, 435 (1979).
[10] P. Kossacki, J. Cibert, D. Ferrand, Y. Merle d'Aubigné, A. Arnoult, A. Wasiela, S. Tatarenko, and J. A. Gaj, unpublished.
[11] A. J. Shields, J. L. Osborne, M. Y. Simmons, D. A. Ritchie, and M. Pepper, Semicond. Sci. Technol. **11**, 890 (1996).
[12] E. F. Schubert and K. Ploog, Phys. Rev. B **29**, 4562 (1984).
[13] G. D. Sanders and Yia-Chung Chang, Phys. Rev. B **35**, 1300 (1987).
[14] A. B. Henriques, Phys. Rev. B **44**, 3340 (1991).
[15] P. Hawrylak, Phys. Rev. B **44**, 3821 (1991).
S. A. Brown, J. F. Young, J. A. Brum, P. Hawrylak, and Z. Wasilewski, Phys. Rev. B **54**, R11082 (1996).