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Negatively charged exciton X^- and donor bound exciton D^0X in planar doped $CdTe/Cd_{1-x}Zn_xTe$ quantum well heterostructures

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Abstract: A comparative luminescence and magneto-transmission study is made of donor bound excitons D^0X and negatively charged excitons X^- in planar doped $CdTe/Cd_{1-x}Zn_xTe$ quantum wells of 100\AA width. As the dopant plane is removed from the well centres to 450\AA distance in the barriers, D^0X evolves continuously into an X^- species weakly localised in random potential fluctuations. The exciton localisation energy in D^0X transforms into the second electron's binding energy in X^- .

The use of precision planar doping techniques [1] allows accurate studies of impurity related and electron-gas related exciton transitions. In the previous conference in this series, we identified the donor bound exciton line D^0X in $CdTe/Cd_{1-x}Zn_xTe$ quantum wells planar doped with Indium donors in the wells [2]. A more recent investigation of "modulation doped" multi-QWs (that is QWs doped in the barriers) has led to the first clear observation of the negatively charged exciton line, X^- (two electrons bound to one hole) [3]. The binding energy of the second electron of species X^- , very low in 3D (only ≈ 0.05 Rydbergs), is dramatically increased in 2D [4]. The quantum confinement effect, together with the rather large CdTe Rydberg (14 meV), makes it relatively easy to observe X^- in $CdTe/Cd_{1-x}Zn_xTe$ QWs. In the present paper we compare these two species, D^0X and X^- , studying the evolution of the D^0X line into the X^- line as a donor plane is removed from the centre of the well to 450\AA distance in the barrier.

$CdTe/Cd_{1-x}Zn_xTe$, strained layer, 10 period multi-QW structures, planar doped with Indium donors, were coherently grown by Molecular Beam Epitaxy directly on (001) orientation $Cd_{0.88}Zn_{0.12}Te$ substrates (see Table). The average lattice parameter matches that of the substrates. The samples all have identical CdTe well width (100\AA) and, except for ZD141, identical 450\AA wide $Cd_{0.84}Zn_{0.16}Te$ barriers. Sample ZD141 has $Cd_{0.86}Zn_{0.14}Te$ barriers 900\AA wide.

Sample ZD139 is doped in the centre of the wells ($10^{11}\text{ In cm}^{-2}$). Sample ZD140 is doped at spacing distance $s=30\text{\AA}$ from each well edge with $5 \cdot 10^{10}\text{ In cm}^{-2}$ per dopant plane. Samples ZD138 and ZD141 are doped in the centre of the barriers to 10^{11} cm^{-2} , that is the dopant plane is placed at $s=225$ and $s=450\text{\AA}$ from the well edges respectively. The concentrations quoted in this paper are nominal. SIMS profiling shows that any broadening of the dopant plane is small at the scale of the SIMS resolution (40\AA). ZD130 is an undoped reference sample.

For $s=30$ and 225\AA all the donors' electrons should transfer into the wells, giving a two dimensional electron gas (2DEG) in the wells with a concentration of 10^{11} cm^{-2} . But for $s=450\text{\AA}$, only $4.5 \cdot 10^{10}\text{ cm}^{-2}$ donors should transfer their electrons to the wells because the electrostatic field induced by the ionised donors and the 2DEG prevents further transfer (that is the donor level in the barrier at the doping plane is then pulled down to the Fermi level).

Our $\text{Cd}_{0.88}\text{Zn}_{0.12}\text{Te}$ substrates are transparent to about 1.656 eV so that the confined excitons can be seen in transmission. Transmission experiments were performed at $1.7\text{--}80\text{K}$ in the Faraday configuration along the QW growth direction in the magnetic field of a superconducting coil. The samples were illuminated by a tungsten source from the substrate side and the transmitted light is detected through a circular polarizer and a monochromator by a GaAs photomultiplier.

We begin with luminescence spectra at 0T , 1.7 K , see Fig.1. For ZD139 (doped at the well centres), we observe the usual $E_1\text{HH}_1$ excitonic line, X, and the donor bound exciton line, D^0X . The exciton localisation energy ($E_{\text{loc}}=\text{X}-\text{D}^0\text{X}$ separation) is $E_{\text{loc}}=4.65\text{ meV}$. The luminescence of the undoped sample ZD130 shows the X line and another line 2.5 meV lower in energy. We have shown that this line (usually called line Y [5]) is associated with the presence of metastable photoelectrons in the wells. It is much stronger for modulation doped samples, its intensity increasing with the concentration of dopant in the barriers. From its magnetic properties (see later) we have attributed this line to the recombination of a negatively charged exciton [3]. The binding energy of the second electron ($\text{X}-\text{X}^-$ separation) is $E_b=2.5\text{ meV}$.

In sample ZD141, dopant planes were placed at 450\AA from the well edge ($=7.5$ times the 3D donor Bohr radius for CdTe, $a_B=60\text{\AA}$) to ensure no or very weak interaction of the electrons with their parent donors. In this case the luminescence spectrum shows only the X^- line (FWHM= 1.45 meV). When $s=225\text{\AA}$ the 2DEG becomes denser and the luminescence line broadens (FWHM= 3.8 meV). For $s=30\text{\AA}$ the 2DEG is apparently very sensitive to the fluctuation of the potential induced by the positive donor cores: this causes a tail in the low energy side of the luminescence line (FWHM= 3.9 meV)

Magnetic splittings and polarization effects are easy to interpret in the $\text{CdTe}/\text{Cd}_{1-x}\text{Zn}_x\text{Te}$ system because the built-in biaxial strain, due to lattice mismatch, splits the degeneracy of the valence band maximum into two well decoupled heavy and light hole states (separation= 35 meV in our structures). Fig. 2b shows circularly polarised, absolute absorption spectra in an 11 T magnetic field. Sample ZD139 gives the X line with its Zeeman splittings and at lower energy the D^0X line. The donor electron doublet $|\pm 1/2\rangle$ is split in the 11 T magnetic field and at 1.7 K only the lower level $|+1/2\rangle$ is populated (see insert of Fig. 2b). So the D^0X transition can appear in σ^+ polarisation only. The absorption spectra of samples

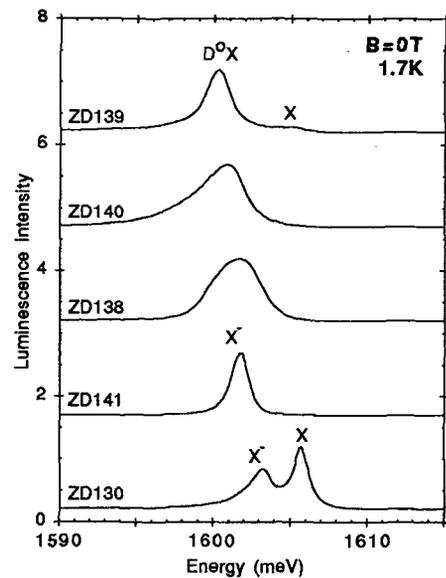


Fig. 1 Normalised luminescence spectra at 1.7 K and $B=0\text{ T}$ for undoped sample ZD130, modulation doped samples ZD141, ZD138, ZD140 and well-centre doped sample ZD139.

ZD141, ZD138 and ZD140 also show a distinct line below line X at 11T. For ZD140, this line can be called a $D^0_{\text{barrier}}X$ line since the dopant plane is so near the well edge that an electron in the well is still bound to its parent donor ($s < a_B$). That is, the label $D^0_{\text{barrier}}X$ represents an exciton confined in the well bound to a donor of the barrier. For samples ZD138 and ZD141, where $s \gg a_B$, X^- becomes a more appropriate label for the lower energy line. Like D^0X , absorption lines X^- and $D^0_{\text{barrier}}X$ are polarised σ^+ at 1.7 K (see Fig. 2b) because an electron is involved in the initial state in each case. Temperature-dependent measurements show that the lines D^0X , $D^0_{\text{barrier}}X$ and X^- appear in σ^- polarization as expected when the temperature is increased.

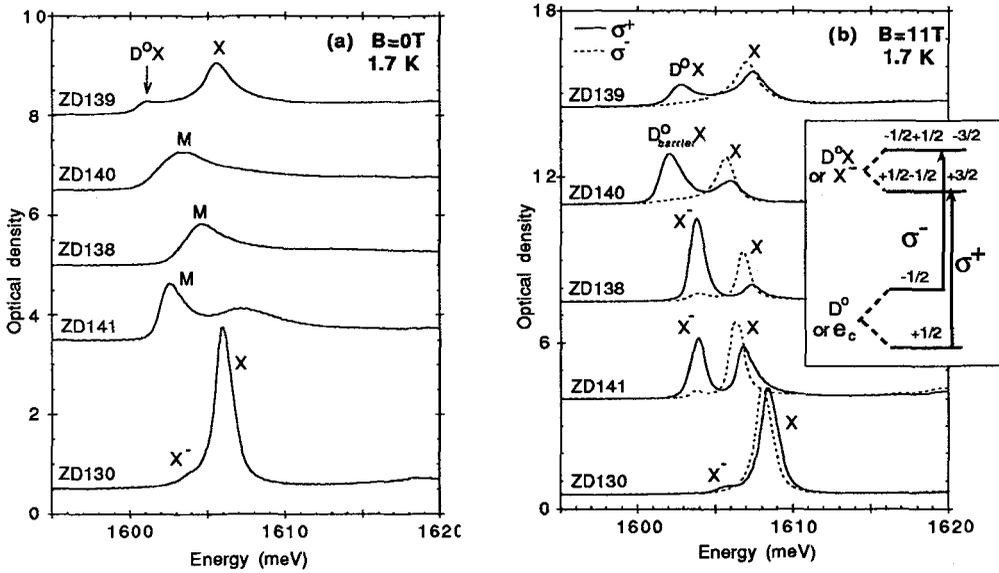


Fig. 2: Absolute optical density spectra ($\ln(1/\text{transmission})$) of the five samples at 1.7 K. (a) Zero-field spectra showing the E_1HH_1 exciton line, X, and D^0X for sample ZD139 (doped at well centres) and X and X^- lines for ZD130 (undoped). M labels the "Mahan" exciton in the electron gas in the modulation doped samples. (The feature at 1607 meV for ZD141 is unexplained.) (b) 11T spectra in σ^+ (solid lines) and σ^- (dashed lines) polarization. The insert shows the polarisation selection rules where the total angular momenta of the ground and excited states are $\pm 1/2$ and $\pm 3/2$ respectively (the two electrons of the excited state having anti-parallel spins)

The main difference between absorption lines D^0X and X^- is their energy position with regard to line X and their relative intensity for the same dopant concentration (see Table). Measured at 11 T, the line separation varies from 4.7 meV for D^0X to 2.9 meV for X^- at $s=450\text{\AA}$. Comparing equal concentrations of electrons and donors, the oscillator strength of X^- is much higher than that of D^0X .

Table : s is the dopant plane position with regard to the well edge. Line separation is X- D^0X or X- X^- separation.

Sample	ZD139	ZD140	ZD138	ZD141	ZD130
Dopant plane position: s (\AA)	well centre	30	225	450	
Planar doping concentration (10^{10} cm^{-2})	10	2×5	10	10	undoped
Line separation at 11T (meV)	4.7	4.0	3.6	2.9	2.7
Integrated optical density (meV per well)	0.1626	0.2870	0.3294	0.2802	

Another difference is seen in the zero-field absorption spectra of Fig. 2(a). The D^0X line is distinctly observed at 0T whereas modulation doped samples ZD138, ZD140 show only a "Mahan exciton" feature [6], labelled M, which results from many body interactions in the electron gas. (Sample ZD141 constitutes a difficult to interpret, intermediate case, where the absorption has some 2DEG features but the emission (Fig.1) appears excitonic.) The X^- absorption is not resolved at 0T because the second electron's binding energy is drastically decreased by screening in the 2DEG. It seems paradoxical that the formation of the X^- species needs an excess of electrons but electronic screening can prevent the observation of X^- . However, our detailed measurements show that with increasing magnetic field, peak M evolves into the two distinct lines X and X^- . The denser the 2DEG the higher the magnetic field needed to separate out these two lines.

We believe that the effect of the magnetic field is to suppress dynamic screening by localising the electrons into the potential fluctuations generated by the distant donor planes. At 11T, each electron in the QWs of sample ZD140 can be considered as frozen out into the potential of a single ionised donor situated in the barrier, the dopant plane being placed at only 30\AA from the well edge. Hence our label $D^0_{\text{barrier}}X$ for a bound exciton in this case. For ZD138 and ZD141, we must speak instead of potential fluctuations in the well [7], caused by the whole plane of randomly distributed, ionised donors at $s=225\text{\AA}$ and 450\AA respectively. These fluctuations are smoother than for the previous case and are screened by the electrons. If an electron localised by such a shallow potential fluctuation is involved in the formation of a bound exciton, the excitonic species should be considered as a localised X^- , the binding energy of the second electron ($\approx 3\text{meV}$) being larger than the mean depth of the localising potential.

In conclusion, the observation of the X^- absorption above a certain value of magnetic field in the above modulation-doped samples probably results from the effect of magnetically induced freeze out of the 2DEG into potential fluctuations; thus the X^- species created in these samples are probably localised. On the other hand the X^- absorption is visible in zero-field at low electron concentration (doping $2 \cdot 10^{10} \text{ cm}^{-2}$ at $s=225\text{\AA}$, not shown here). This may mean that the electrons are localised by potential fluctuations already in zero field at such low concentrations. But we note that free X^- ought to exist in a dilute gas in the absence of any disorder when the mean distance between the electrons is sufficiently large compared to the radius of X^- ; in this case screening of X^- would be inefficient because its negative charge repels electrons[8]. A conclusive proof of the presence of free negatively charged excitons would be the observation of their cyclotron energy since they are charged particles [9]. This has not been seen yet in the samples investigated.

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