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1994 J. Phys.: Condens. Matter 6 10391

(http://iopscience.iop.org/0953-8984/6/47/021)

J. Phys.: Condens. Matter 6 (1994) 10391–10396. Printed in the UK

The Fermi-edge singularity in $CdTe/Cd_{1-x}Mn_xTe$:In multiple quantum wells

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Received 24 May 1994, in final form 30 August 1994

Abstract. The observation of a many-body, Fermi-energy-edge singularity in low-temperature photoluminescence spectra of $CdTe/Cd_{1-x}Mn_xTe$:In multiple quantum wells is reported. A strong enhancement of the photoluminescence intensity towards the electron Fermi edge, which is caused by multiple-electron–hole-scattering processes, is observed. The temperature dependence of the Fermi-edge singularity has been measured and discussed. The mechanism of the Fermi-edge singularity can be explained in terms of hole localization and indium migration.

1. Introduction

In modulation-doped multiple-quantum-well (MQW) structures, the carriers and the impurities are separated in real space and a many-electron–one-hole (or many-hole–one-electron) Fermi sea system can be obtained. This system is of interest both in theory and in experiment. The many-electron–one-hole interaction in the Fermi sea system was initially considered by Mahan [1, 2] for bulk semiconductors in the framework of the final-state electron–hole scattering. He showed that in spite of static screening by the equilibrium electrons an exciton-like effect still survives at moderate electron densities and there is a bound state slightly below the Fermi edge (now called a Mahan exciton). This bound state results from the sharpness of the Fermi surface and the Pauli exclusion principle restriction on the electron's scattering. Later theory included the dynamic response of the Fermi sea to the creation of the photohole, as well as the exchange effect due to the increased carrier density [3, 4], to show how the bound state eventually becomes unbound and merges with the continuum.

The Mahan exciton effect was first found in the soft-x-ray emission and absorption spectra of metals such as Na, Al, and Mg [5, 6] where it was referred to as the many-body 'x-ray edge singularity'. However, such a Fermi-edge singularity is very difficult to observe in semiconductors, as there is a great sensitivity to any broadening mechanisms, such as the finite-hole mass (in metals the hole mass is very large, so it is easy to see the many-body enhancement), the lifetime contribution from the optical hole, and temperature. Any of these effects can broaden and even smear out the enhancement in photoluminescence (PL) and absorption spectra. In order to observe the Fermi-edge singularity (FES) experimentally (especially in PL) one must either keep the broadening at a minimum or enhance the interaction of the electrons at the Fermi level with the photoholes. One example of the

0953-8984/94/4710391+06$19.50

former case can be found in [7] and the latter case can be found in [8]. However, both of the examples are obtained in InGaAs QWs. In this system the FES can only be observed at very low temperature, because of the lower quasi-2D excitonic binding energy and weaker localization of holes.

In this paper we report PL experimental results for a 2D electron system in a (Cd, Mn)Te QW structure. A strong enhancement of the PL intensity towards the electron Fermi energy (E_F) is observed at 12.5 K, and even at 77 K the enhancement is clearly visible. The experiment also shows that the localization of holes in the (Cd, Mn)Te system is stronger than that in III–V compound QW structures, due to indium migration, alloy fluctuations and more defects in the sample.

2. Experiments and results

The CdTe/$Cd_{0.72}Mn_{0.28}$Te:In MQW structures used in the experiment were fabricated by photoassisted molecular-beam epitaxy (MBE) on an undoped $Cd_{0.86}Mn_{0.14}$Te buffer layer with a thickness of 1 μm grown on the undoped (001) CdTe substrate. The structure of the sample was such that $x = 0.28$, $L_z = L_b = 120$ Å, and $n = 100$; here x, L_z, L_b and n are the Mn^{2+} concentration, the well thickness, the barrier thickness, and the number of periods, respectively. The $Cd_{0.72}Mn_{0.28}$Te layers are heavily n-type doped by In and the barriers are doped right up to the well edges; the doping level is about 2×10^{18} cm^{-3}.

In the PL experiments, the sample was mounted on a cold finger of an intra-cyclic refrigerator, model PAB 32-2A, whose temperature can be changed from 12.5 K to 300 K. The PL signals were excited by the 514.5 nm line of an argon-ion laser, whose power is 30 mW cm^{-2}, and the signals were dispersed by a SPEX 1403 monochromatar with a cooled GaAs photomultiplier tube detector. The analog signals were amplified by a lock-in amplifier and the PL spectra were displayed using an IBM PC computer.

A low-temperature (12.5 K) PL spectrum obtained for the sample is shown in figure 1. The PL spectrum is composed of a low-energy onset at about 1.60 eV, a slowly increasing region, then a strong increase towards the high-energy cut-off at about 1.64 eV. The overall width of the PL band is about 40 meV, and the line shape is strongly asymmetric.

The PL spectra from 12.5 K to 150 K are shown in figure 2. It can be seen from figure 2 that the intensity of the sharp peak on the high-energy side of the PL band is strongly reduced and the full width at half maximum (FWHM) of the peak is increased with increasing temperature from 12.5 K to 77 K, but the asymmetry of the PL band can be seen clearly even at 77 K. When temperature is further increased to 150 K, the asymmetry of the PL band disappears. The energy of PL peak and its shift with temperature are shown in figure 3.

3. Discussion

As we know [9], the energy gap (E_g) of $Cd_{1-x}Mn_xTe$ varies with x as

$$E_g \text{ (eV)} = 1.528 + 1.316x. \tag{1}$$

Thus $Cd_{1-x}Mn_xTe$ layers are the barriers and CdTe layers are the wells. It is easy to obtain $E_g(Cd_{0.72}Mn_{0.28}Te) - E_g(CdTe) = 0.37$ eV from (1).

In $Cd_{1-x}Mn_xTe$/CdTe MQW, the conduction band states can be calculated on the basis of a simple Krönig–Penney model. Even though the strain causes some valence band offset, the strain-induced shifts are negligible compared with the CdTe band gap of about 1.6 eV. Therefore, the strain has little effect on the position of the quantized conduction band

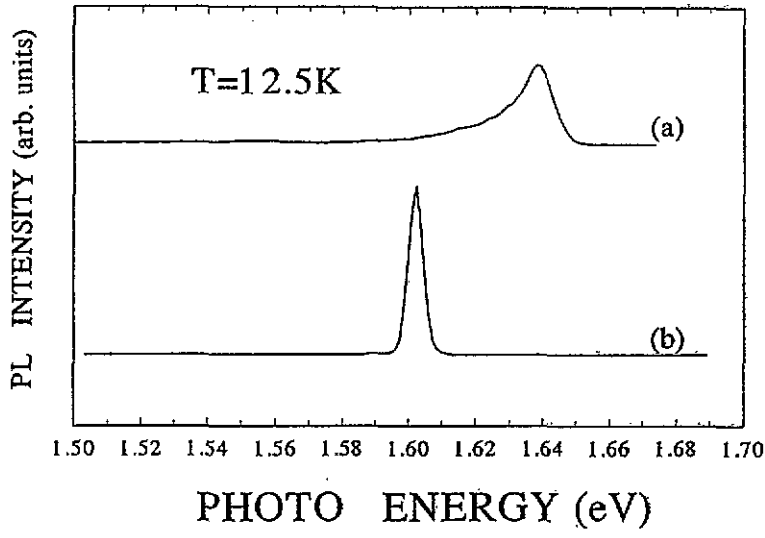

Figure 1. The PL spectra of CdTe/CdMnTe at 12.5 K: (a) shows the PL spectrum of CdTe/Cd$_{0.72}$Mn$_{0.28}$Te:In; (b) shows the PL spectrum of a sample that has the same structure as that in (a), but is not doped.

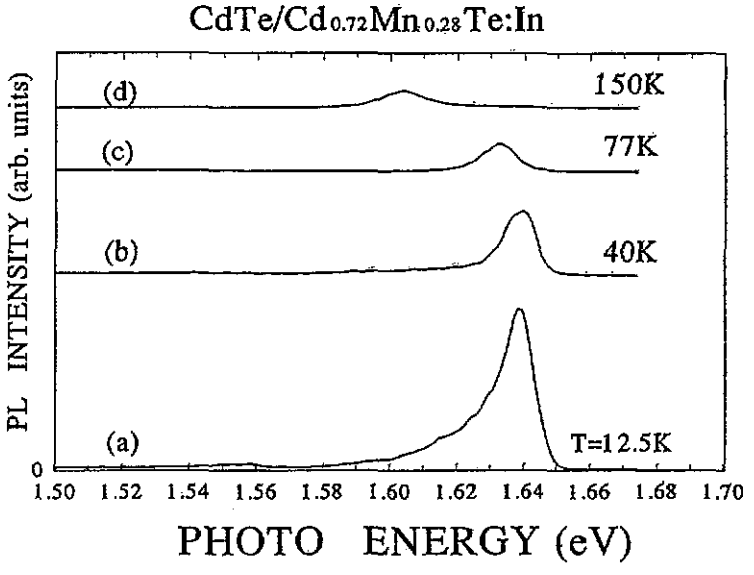

Figure 2. The PL spectra of CdTe/Cd$_{0.72}$Mn$_{0.28}$Te:In MQWs at different temperatures.

states. Up to now, many papers have shown that the valence band offset of CdMnTe/CdTe heterostructures is very small [10, 11, 12, 13, 14]. In the calculation of the conduction band states ΔE_v (the valence band offset) = 0 is assumed, and the other parameters used in calculation are $L_z = L_b = 120$ Å, ΔE_c (the conduction band offset) = 0.37 eV, and $m^* = 0.11m_0$. The calculated result shows that the energy of the HH1–E1 interband transition is about 1.601 eV. However, in figure 1 we find that 1.6 eV is only the beginning of the PL band; the strong peak of the PL band is at 1.637 eV, which is obviously different from the calculated result.

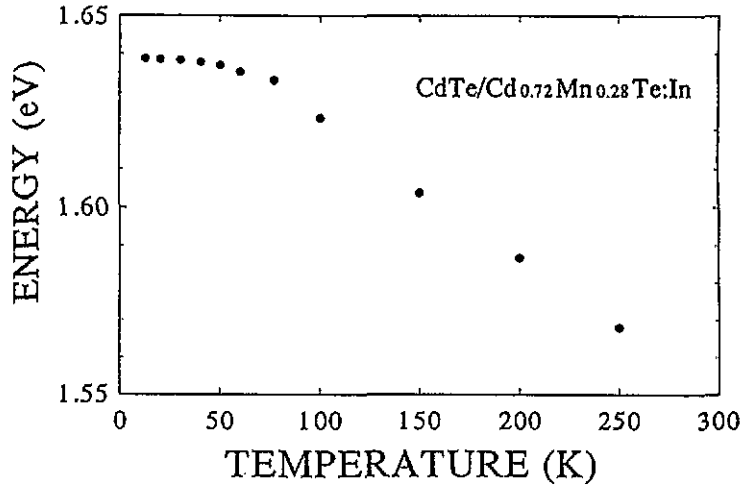

Figure 3. The energy of the PL peak at different temperatures.

In order to compare the theory and experiment, we also measured the PL spectrum of a sample, that has the same structure as the one that we used above but that is undoped, and the result is also shown in figure 1. It can be found from figure 1 that the energy of the PL peak of the undoped sample is 1.603 eV, which is in good agreement with the calculated result. It is also found that the PL peak is very sharp—its full width at half maximum is about 5 meV—but the PL peak of the doped sample is much wider and weaker than that of the undoped one. Comparing the two PL bands in fig.1 it is easy to see that the PL peak of the undoped sample is corresponding to the 11H transition, but the PL band of the doped sample is not caused by 11H transition.

We think that the PL band of the doped sample is caused by the transition from electrons throughout the Fermi sea to the holes at the top of the valence band, with maximum PL intensity occurring for electrons at E_F. The Fermi energy can be obtained from $E_F = 1.637$ eV $- 1.603$ eV $= 0.034$ eV, which is in agreement with the low-temperature Hall measurements and photomodulation spectra measurements. However, if we want to explain the enhancement of the PL band at E_F, we must consider the multiple e–h scattering in the Fermi sea. In a neutral e–h plasma system, theoretical calculation [4] has shown that an enhancement of the e–h oscillator strength occurs at the Fermi energy (E_F) at low temperatures. This arises because the e–h multiple scattering is favoured at the Fermi surface and the e–h multiple scattering is suppressed by exclusion effects for $E \ll E_F$. This effect is much stronger in 2D and quasi-2D systems compared to 3D systems because of the enhancement of e–h pair fluctuations under quantum confinement and the reduction of the effect of screening. However, in our experiment, a non-thermalized free-hole distribution with a temperature of the order of 250 K would be required to give efficient recombination for electrons at E_F if only vertical, k-conserving transitions between free-particle states occurred. However, the temperature is only 12.5 K, so in our experiment the e–h recombination is dominated by transitions between the high-density electrons and low-density holes. In this condition we have multiple scattering and recombination arising from $k_e < k_h$ thus 'breaking' the k selection rule. In general this process is much smaller than the vertical, k-conserving process, and this is why the FES effect is difficult to observe in a doped quantum well structure, such as in GaAs/GaAlAs systems. If we consider the

material properties of CdTe/Cd$_{1-x}$Mn$_x$Te:In QWs we can understand why the FES effect is so strong in our experiment. Bassani *et al* have shown that at doping levels around 10^{18} cm^{-3}, there is substantial migration of indium on pure CdTe, depending on the MBE growth temperature [15]. So there may be some indium in the well; for our sample in particular the barriers are only 120 Å and there is no spacer layer at the surface. This, and also the indium in the barriers, would produce strong potential fluctuations that lift the k selection rule. In addition, alloy disorder and impurity effects in Cd$_{1-x}$Mn$_x$Te are much stronger than in III–V materials [16]. A strong hole localization can be caused by the disorder and impurities in CdTe/Cd$_{1-x}$Mn$_x$Te:In QWs. The localization of a hole in real space can cause a strong expansion in momentum space, and k_h can be increased to a large enough value to give efficient recombination, without k restriction, for electrons in all states up to E_F. Hence the FES effect can be easily observed in our sample.

Rorison has calculated the many-body effects in optical spectra of n-doped alloy semiconductor quantum well structures [17]. In her calculation she considered the effect of multiple e–h scattering and the hole localization in a Bethe–Salpeter equation, and got a PL shape of the following form:

$$I(\omega) = I_0(\omega)\left\{\frac{1-\Lambda_2(p)}{1+\Lambda_1(p)}\right\}^2 \tag{2}$$

where the term in curly brackets is the excitonic enhancement factor, and Λ_1 and Λ_2 are defined in [1] and [2]. The calculation results show a strong enhancement of the PL intensity towards the electron Fermi energy, which can give a good qualitative explanation for our experimental results. Full details of the theory can be found in [17].

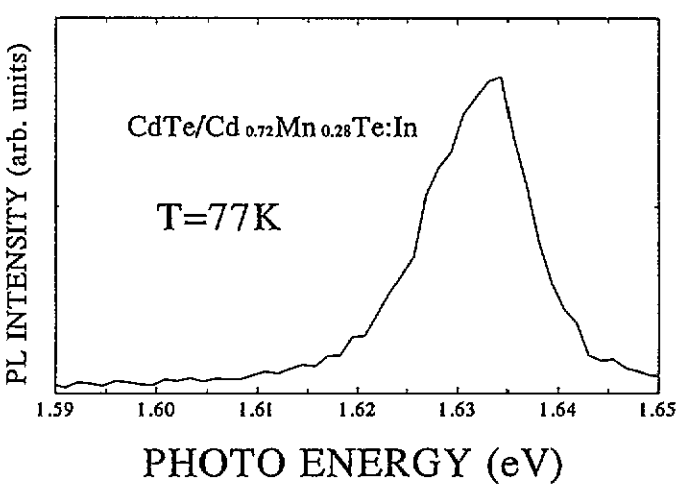

Figure 4. The PL spectrum of CdTe/Cd$_{0.72}$Mn$_{0.28}$Te:In at 77 K.

FES effects have already been observed in some n-type modulation-doped III–V semiconductor QWs [7, 8]. However, in a III–V QW system the lattice has high quality, the hole localization is weak, and the excitonic binding energy is low, so in general the FES effect is weak and difficult to observe in these materials. The FES effect can only be observed clearly at very low temperatures ($T < 10$ K) in III–V QW structures. As has been discussed in [7], with increasing temperature the sharp Fermi level is broadened out, and the enhancement at E_F will be strongly reduced at a temperatures of the order of E_b/K_B. As we know, E_b is much larger in II–VI semiconductors than in III–V semiconductors, so the

FES effect is stronger in II–VI compounds than in III–V compounds. In order to compare our result with the result obtained by Skolnick *et al*, we have shown the PL spectrum of the sample in figure 4 (this was shown in figure 2, but in figure 2 it is difficult to see the shape clearly). In figure 4 we can see that even at 77 K the singularity of the PL peak is still clear, but in [7] when the temperature is higher than 60 K the singularity has basically disappeared. Hence the FES effect is much stronger in our sample than that in the III–V case.

4. Conclusion

In conclusion, we have demonstrated that the FES effect is very strong in CdTe/CdMnTe:In; it can be found clearly at temperatures from 12 K to 40 K, and even at 77 K the FES effect can still be observed. The physical mechanism that causes the FES effect has been analyzed and discussed. In addition, we have compared our experimental results with the theoretical results obtained by Rorison, and the theoretical results can give a good explanation for our experimental results. We have also demonstrated that due to the migration of indium at the interface and the higher excitonic binding energy in CdTe/CdMnTe:In systems, the FES effect is much stronger in our sample than that in III–V materials.

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