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OPTICAL TRANSMISSION UNDER MAGNETIC FIELDS IN CdTe/CdMnTe SUPERLATTICES

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Abstract: We have measured the optical transmission in CdTe/CdMnTe superlattices at 1.6K and under magnetic field up to 50kOe. The transmission spectra exhibit step-like characteristics, which can be identified with subband transitions in the CdTe wells. In the presence of a magnetic field, conduction and valence bands of CdMnTe are split because of the large exchange interaction which modifies the transmission near its absorption edge. The observed spectra show that the transition associated with the highest subband vanishes, as a result of the reduction of the effective gap of CdMnTe, but lower energies remain essentially unchanged.

Dilute magnetic semiconductors (D.M.S) are II-VI (or IV-VI) semiconductors such as CdTe (or PbTe) with a fraction of the group II (or IV) element substituted by a transition metal such Mn. These materials have generated a great deal of interest. The free carriers in the conduction and valence bands interact strongly, via an exchange interaction with the localized $3d^5$ electrons of the magnetic Mn$^{2+}$ ions, giving rise to a large Zeeman splitting of the bands.

The growth of good quality CdTe/(CdMn)Te quantum wells has been realized by molecular beam epitaxy and magnetic tunable laser emission has already been reported in Cd$_{(1-x)}$Mn$_x$Te/Cd$_{(1-y)}$Mn$_y$Te superlattices. More recently, the growth of In doped CdTe/(CdMn)Te superlattices has also been successful. However, problems related to the valence band offset and the effects of a magnetic field on the energy levels remain to be answered. J.A. Brum and $\alpha$ suggested that magneto-luminescence in a double quantum well would be suitable to yield information about the valence band offset. Recently, luminescence excitation data performed on CdTe/Cd$_{1-x}$Mn$_x$Te (x<0.45) have been successfully interpreted solely on the basis of strain valence band offset leading to a splitting of heavy and light hole states. These results are consistent with angle-resolved U.V. photoemission measurements which indicate a zero valence band offset with an accuracy of $\pm$50 meV.

In luminescence, beside the free and defect bound excitons associated with the CdTe quantum wells, the spectra in CdTe/(CdMn)Te superlattices exhibit lines at smaller energies which are also magnetic field dependent. These lines shift to lower energies in the presence of a magnetic field in contrast to those associated with the Landau levels, which shift to higher energies. This behavior suggests a penetration of hole and electron wave functions in the (CdMn)Te layers, resulting in interface localized excitons.

In this letter, we report the first optical transmission measurements in CdTe/(CdMn)Te superlattices with two different CdTe thickness layers. The effect of a magnetic field is also reported.

The CdTe/Cd$_{1-x}$Mn$_x$Te multilayers were grown by molecular beam epitaxy on a 2um CdTe buffer layer which was grown on a (100) oriented GaAs substrate. The superlattices were (111) oriented. Two superlattice configurations were investigated. The first configuration #1 consisted of Cd$_{(1-x)}$Mn$_x$Te (x=0.07) layers with a thickness of 100Å and CdTe layers with a thickness $L_2=80Å$. In the second configuration #2 corresponding values were x=0.013, 100Å and $L_2=250Å$. The GaAs substrate thickness was reduced to about 200μm by mechanical polishing and a window of 3mm$^2$ was produced by etching in $H_2O_2$-NH$_4$OH (20:1). The buffer layer of CdTe and a

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part of the superlattice were etched off in a 0.1% solution of bromine methanol (etching rate 1500Å/min). The final thickness of the superlattice was about 1000Å-1500Å. The optical transmission was measured at 1.6K. Unpolarized light was used in the experiments.

Figure 1 displays the optical transmission spectra for both #1 and #2 superlattices. Both spectra exhibit step-like characteristics, with two and six transitions observed in #1 and #2 samples respectively. These are labeled n=1,2,..., demonstrating the presence of energy subbands in the CdTe quantum wells. The ground subband, labeled n=1, moves to higher energy as L2 is reduced as a consequence of carrier confinement. Vertical lines, in Figure 1, indicate the transition energies calculated by solving the Schrödinger's equation in a quantum well with a finite depth and assuming a zero valence band offset. The well depth was determined from the fundamental absorption edge, Eg, in the CdTe/MnTe layers, which was measured in the high energy region of the transmission spectra. The Mn concentrations in the two superlattice configurations were also deduced from the Eg value.

The calculated results predicting respectively two and six transition energies in #1 and #2 samples are in good agreement with the experiments. Increasing discrepancies, however, tend to appear for subbands with higher energy indices. This may be due to both the simplicity of the theoretical model and the experimental uncertainty in the well thickness. In addition, in the limit of our experiments the transmission spectra do not exhibit sharp peaks related to excitonic transitions, instead, they are rather broad. As proposed in Ref. 9, a small splitting of the heavy and light holes in the CdTe layers can be responsible for such broadening.

Optical transmission was also measured in the presence of magnetic fields up to 50kOe in the Faraday geometry. Figures 2 and 3 compare the zero and high field spectra of #1 and #2 superlattice configurations. The high field spectra retain the step-like characteristics, and the transition energies below the absorption edge of CdTe remain unchanged. Near the absorption edge, however, the spectra are significantly modified; for example, subband transitions labeled n=2 and n=6 in #1 and #2 samples respectively are no longer observed. The vanishing of these subbands is a consequence of the large exchange interaction in the CdTe/MnTe diluted magnetic semiconductor layers. Due to this interaction, strong splittings in the conduction and valence bands occur leading to a decrease of the optical gap. These splittings are believed to be also responsible for the weak oscillatory behavior beyond the n=5 transition in the #2 sample in Figure 3.

The reduction in the optical gap can be written\(^1\)

\[
E_g(H) - E_g(H=0) = x\alpha N_o + \beta N_o <S_2>/2
\]

where \(E_g(H=0) = 1.61.57 x\) in eV, x is the Mn molar fraction, and \(N_o\) and \(\beta N_o\) are the exchange integrals for the conduction and valence bands which have been evaluated in the bulk material by Ga and \(\alpha,\beta\)\(^1\). These authors obtain \(\alpha N_o = 230\) meV and \(\beta N_o = 800\) meV. \(<S_2>\) is the Mn\(^2+\) mean spin value in the field direction and can be directly evaluated from magnetization measurements. It is usually written as\(^2\):

\[
<S_2> = S_M S_M (5/2, g_s, g_B k (T+T_0))
\]
with $S_M$ the Mn$^{2+}$ spin saturation value and $g_{Mn^2+}$ the modified Brillouin function, $g$ is the Lande factor, $\mu_B$ the Bohr magneton, $T$ the temperature, and $T_0$ an effective temperature which reflects the antiferromagnetic type of interaction among the Mn$^{2+}$ ions. For the same reasons, $S_M$ is smaller than the $5/2$ Mn$^{2+}$ spin value. $T_0$ and $S_M$ parameters have also been reported in Ref. 17.

According to Eq. 1, at 1.6K and in a 50kOe magnetic field, the optical gap in Cd$_{1-x}$Mn$_x$Te decreases by about 45meV and 52meV in #1 and #2 samples respectively, the hole quantization in the Cd$_{1-x}$Mn$_x$Te layers has been neglected in this calculation. Thus, in the presence of magnetic fields, it may be possible that $E_g(H)$ becomes smaller than the transition energies associated with the highest subbands. These transitions, consequently, overlap the continuum of absorption in the Cd$_{1-x}$Mn$_x$Te material. For instance, in #2 sample, the calculated transition energy associated with the n=5 subband is 1.768eV, i.e. higher now than the value of $E_g(H=50kOe)=1.752eV$. Similarly, the n=2 subband transition in #1 sample is 1.693eV, whereas $E_g(H=50kOe)=1.665eV$.

![Fig. 2: Optical transmission spectrum at 1.6K of 80Å thick CdTe layers between Cd$_{1-x}$Mn$_x$Te barriers in a 50kOe magnetic field.](image)

![Fig. 3: Optical transmission spectrum at 1.6K of 250Å thick CdTe layers between Cd$_{1-x}$Mn$_x$Te barriers in a 50kOe magnetic field.](image)

So far we have neglected the Zeeman splittings and the Landau levels of the energy subbands. These effects are very small for the conditions of our experiment. The energy shift $\omega_{g/2}$ due to the Landau levels is about 2meV by assuming the same effective mass of electrons as that in CdTe, i.e. $m_{eh}^*=0.1m_0$, and the classical Zeeman splitting $g\mu_B$ is about 0.5meV for each subband. Corrections, due to the exchange interaction in the Cd$_{1-x}$Mn$_x$Te layers which result in different well depths for spin up and down subbands of the CdTe layers, modify this number. Thus, the total Zeeman splitting is larger than $g\mu_B$ and depends on the index $n$ of the subband, larger for higher $n$ values. Simple calculations show that the splitting resulting from the exchange interaction is about 1meV for the n=1 subband in #1 sample. In #2 sample, the splitting of the n=5 subband is 2meV but less than 1meV for the n=1 subband. As expected, all of these effects are small and leave the optical transmission essentially unchanged below the gap. We should mention that there is no evidence of spatially indirect transitions between the valence band of Cd$_{1-x}$Mn$_x$Te and the conduction band of CdTe. Luminescence measurements also do not exhibit such transitions but only a small shift to lower energy in the presence of magnetic field.

In summary, optical transmission in CdTe/Cd$_{1-x}$Mn$_x$Te superlattices has been measured. A number of subband transitions have been observed and they are consistent with a zero or rather small valence band offset. In the presence of magnetic field, optical transmission is strongly modified near the absorption edge of the Cd$_{1-x}$Mn$_x$Te layers. This demonstrates the large influence of the carrier-local moment exchange interaction on the magento optical properties of dilute magnetic semiconductor superlattices.

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