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ACCEPTORS IN SEMIMAGNETIC SEMICONDUCTORS

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Resistivity of p-$Hg_{1-x}Mn_xTe$ with $x \sim 0.15$ was measured for temperatures 4 - 50 K and magnetic fields 0 - 7 T. A strong negative magnetoresistance observed in the extrinsic and hopping conductivity ranges was interpreted as being caused by the exchange hole - Mn^{++} interaction. The binding energy of a shallow acceptor decreases and the acceptor's radius increases in the magnetic field.

I. Acceptor in Strong Magnetic Field

In non-magnetic open-gap semiconductors with the diamond or the zinc-blende structures, in the absence of an external magnetic field the ground state of a shallow acceptor is four-fold degenerate [1,2].

In semimagnetic semiconductors, like $Hg_{1-x}Mn_xTe$ or $Cd_{1-x}Mn_xTe$, the exchange interaction of the Γ_8 valence electrons with the $3d^5$ electrons of Mn^{++} -ions yields a splitting of the Γ_8 - level determined by [3,4]

$$B = \frac{1}{6} x N_o \beta \langle S_z \rangle_{av} . \qquad (1)$$

N_o is the number of unit cells in unit volume and β is the exchange integral for the Γ_8 bands. $\langle S_z \rangle_{av}$ is the average z-component of spin of the manganese ions (in units of $\hbar$). We have assumed that the other components have zero average, as is the case for the external magnetic field in z-direction.

In narrow-gap semimagnetic semiconductors (like $Hg_{1-x}Mn_xTe$ with $0.07 < x \lesssim 0.2$) the acceptor binding energy E_{A0} in the absence of an external magnetic field (i.e. for $\langle S_z \rangle_{av} = 0$, $B = 0$) is small. Therefore, in a strong magnetic field it is possible to have $\langle S_z \rangle_{av}$ high enough to yield

$$2 |B| \gg E_{A0} . \qquad (2)$$

In this narrow-gap semiconductor we are then in the ultra-quantum limit, i.e. we can construct the acceptor wave functions from the functions of the highest Landau valence subband. For $\beta > 0$, which is the case in $Hg_{1-x}Mn_xTe$, this is the heavy-hole $b_v(-1)$ subband [3,4]. In the symmetric gauge, the acceptor wave function in the ultra-quantum limit is

$$\Psi(\vec{r}) = (2\pi\lambda^2)^{-1/2} \exp[-(x^2+y^2)/4\lambda^2] F(z) \phi_4(\vec{r}), \qquad (3)$$

where the envelope function F(z) is a solution of

$$\{-\frac{1}{2}\frac{d^2}{d\xi^2} - (2\pi\lambda^2/a_{hh}^2)^{1/2}\exp(\xi^2)[1-\Phi(|\xi|)] - 2E_{AH}/\hbar\omega_{hh}\}F(\xi)=0 \ . \tag{4}$$

The dimensionless variable used here is given by $\xi=z/\sqrt{2}\lambda$, a_{hh} is the Bohr radius for heavy holes (with masses m_{hh}) $a_{hh}=\hbar^2\varepsilon/e^2m_{hh}$, ε is the static dielectric constant of the crystal, $\lambda^2=\hbar c/eH$, E_{AH} is the energy with respect to the $b_V(-1)$ -level, and ω_{hh} is the cyclotron frequency for heavy holes. $\Phi_4(\vec{r})$ is the function of the basis of Γ_8 -level, corresponding to $J_z=-3/2$. Function Φ is defined as

$$\Phi(x)=(2/\pi^{1/2})\int_0^x \exp(-t^2)dt \ . \tag{5}$$

In vacuum orin nonmagnetic semiconductors the ultra-quantum limit corresponds to the magnetic length λ much smaller than the Bohr radius. Equation (4) can then be solved numerically (see, e.g.,[5]). For an acceptor in the semimagnetic semiconductor considered here, the situation can be just the reverse: for a magnetic field which is not too strong,

$$\lambda \gg a_{hh} \ . \tag{6}$$

This follows from the fact that on the left-hand side of the ultra-quantum limit condition (2) we have the exchange splitting $2|B|$ instead of a much lower cyclotron energy.

If the condition (6) is fulfilled, one can expand, for $|\xi| \ll 1$ [6,7].

$$\exp(\xi^2)[1-\Phi(|\xi|)] \approx 1-(2/\pi^{1/2})|\xi| \ . \tag{7}$$

Equation (4) can now be solved analitically in Bessel and Hankel functions. For the ground state

$$E_{AH}=-(\pi/2)^{1/2}\ \frac{e^2}{\varepsilon\lambda}\ [1-0.73(a_{hh}/\lambda)^{1/3}] \ . \tag{8}$$

In the zeroth order in a_{hh}/λ, the ionization energy of the acceptor in the presence of a magnetic field is, therefore, <u>independent</u> of m_{hh}. Because of inequality (6) it is <u>lower</u> than the ionization energy in the absence of a magnetic field, and the acceptor transverse radius (2λ) is <u>larger</u> than in the absence of a magnetic field. This behaviour is very unusual when compared with that found in vacuum and in nonmagnetic semiconductors.

II. Experiment

We have studied single crystals of $Hg_{1-x}Mn_xTe$ in the composition range $0.12<x<0.17$. For such values of x, $Hg_{1-x}Mn_xTe$ is an open-gap semimagnetic semiconductor with energy gap 160 meV $< E_g <$ 330 meV. The crystals were obtained by a modified Bridgeman method from melt doped with indium and were annealed in mercury vapour. In the end, the samples were partially compensated p-type, with the acceptor concentration of the order of $10^{16}cm^{-3}$.

The samples had high resistance, ranging from $10^5\Omega$ to $10^8\Omega$ at liquid helium temperature in the absence of a magnetic field. The contacts were checked to be ohmic. The resistivity of the samples was measured in the temperature range 4.3 - 50 K and in magnetic fields up to 7 T, in both the longitudinal and the transverse configurations.

The dependence of the resistivity on magnetic field for a sample with $x \approx 0.155$ ($E_g \approx 270$ meV) and for two temperature values is shown in Fig. (1). At the liquid helium temperature, the resistivity is more than two orders of magnitude lower at H = 7 T than in the absence of a magnetic field. This effect was already observed [8]. It is also interesting that the longitudinal resistivity is higher than the transverse resistivity, in strong magnetic fields.

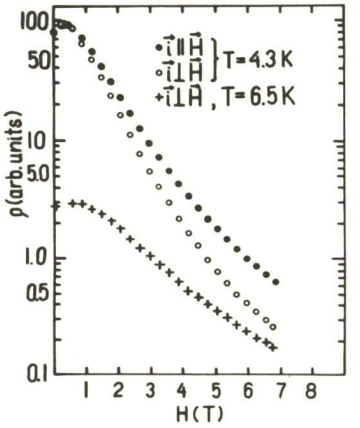

Fig.1 Resistivity versus magnetic field for a sample with $x \approx 0.155$

The dependence of the tranverse resistivity on the temperature for another sample with the same composition but of a higher resistance, is shown in Fig. (2) for H = 0, 1.5 T and 3.5 T. The slopes of the three stright parts of the curves correspond (going from high to low temperatures) to the conductivity activation energies ϵ_1, ϵ_3, and ϵ_t. For H = 0, 1.5, 3.5 T there is ϵ_1 = 8.2, 7.5, 5.6 meV, ϵ_3 = 1.8, 1.4, 0.8 meV, and ϵ_t = 5.4, 4.4, 3.5 meV, respectively.

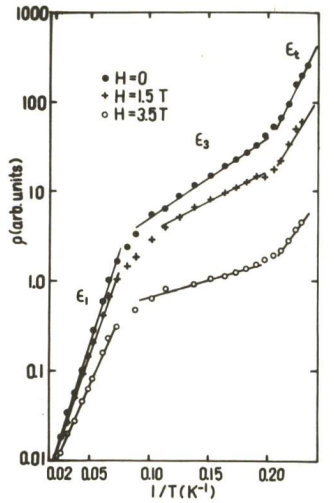

Fig.2 Transverse resistivity versus inverse temperature for a sample with $x \approx 0.155$: The activation energies corresponding to the three temperature ranges are indicated

The decrease of ϵ_1 with the magnetic field can be explained as being an effect of the exchange interaction on the acceptors, as for the partially compensated p-type samples in the extrinsic conductivity range $\epsilon_1 = E_{AH}$. The acceptor ionization energy E_{A0}, calculated by Schechter's method [1] is about 9 meV for our sample, and obtained for H=3.5 T from the formula for the ultra-quantum limit, eq. (8), is 5.5 meV, which agrees well with the experimental values of ϵ_1. It should be mentioned, however, that the ultra-quantum limit condition (2) is not well-fulfilled at 12 K and 3.5 T. 2B is less than twice higher than E_{A0} if one takes $N_0\beta \approx 1.5$ eV [3,4], and a bit lower than E_{A0} if the value $N_0\beta \approx 0.65$ eV is accepted [9,10].

The ϵ_3-range corresponds to hopping conductivity. As the radius of the acceptor ground state in the absence of a magnetic field is about 40 Å and the magnetic length λ at H=3.5 T is 137 Å, the transverse radius of the ground state in the ultra-quantum limit (2λ) is seven times larger. Therefore, the values of the overlap integrals between neighbouring acceptors are much higher, and the conductivity should be also much higher (especially in the transverse direction). The decrease of ϵ_3 in the magnetic field may be caused by the Mott transition induced by the increase of the acceptor radius.

The behaviour at the lowest temperature may be interpreted by a self-trapping of the hopping carrier on a given acceptor, due to the

ordering of manganese spins in the vicinity of this acceptor by their exchange interaction with that carrier. Such a "phase transition", consisting of the partial ordering of spins by the interaction with the acceptor hole, has already been proposed to explain the weak-field exciton splittings in $Cd_{1-x}Mn_xTe$ [11]. The effect is similar to the bound magnetic polaron formation in magnetic semiconductors, e.g. EuSe [12,13],and is weaker for larger acceptor radius. For $Hg_{1-x}Mn_xTe$ with $x \approx 0.15$, one can estimate theoretically the transition temperature to be a few K. The self-trapping effect should be weaker in strong magnetic fields, as the acceptor radius is then larger and all the manganese ions become spin-polarized. Our experimental results seem to follow these predictions.

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