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SPIN - DEPENDENT SCATTERING OF CONDUCTION ELECTRONS BY MAGNETIC IMPURITIES

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By means of magnetophotoconductivity measurements the spin dependent scattering of conduction electrons by magnetic ions was observed in semimagnetic semiconductors HgMnTe and CdMnSe. The theoretical description in HgMnTe is given.

The observation of the spin-dependent scattering (SDS) has been previously attempted in various materials [1,2] . However, an unambiguous separation of SDS from other effects has not been done yet. We succeeded in doing that in HgTe-MnTe and CdSe-MnSe semimagnetic semiconductors (SMSC). Recent extensive investigations of SMSC revealed a great importance of conduction electron - Mn^{2+} ion exchange interaction [3,4] . The idea of our experiment was to measure magnetoresistivity in a sample illuminated with microwave radiation. We used the superconductive coil and the carcinotron as millimeter waves source (110 - 130 GHz, output power about 10 mW). In high magnetic field (5T) and 4.2K one has a quantum limit conditions for $Hg_{1-x}Mn_xTe$ ($x = 0.003$) with free electron concentration $\sim 3\cdot 10^{16}\,cm^{-3}$ [5] . The Mn ions in this sample are spatially well separated and in the above conditions the spin splitting of the Mn^{2+} ground state $g\mu_B B > k_B T$ i.e. only the lowest state with $S_z=-5/2$ is occupied. So, both spin systems, electronic and that of Mn ions, are polarized (Fig. 1).

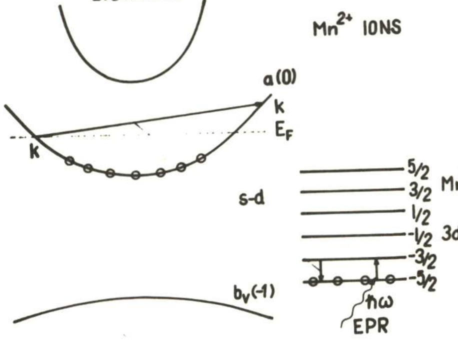

Fig.1 Energy levels of electrons and Mn^{2+} ions in HgMnTe in a high magnetic field. EPR transition and inelastic s-d scattering are schematically shown

The results of the photoconductivity vs. magnetic field measurements for $Hg_{1-x}Mn_xTe$ ($x = 0.003$) are shown in fig.2. The background signal comes from free carrier absorption which causes both the intraband photoconductivity and the bolometric effect. At the EPR a resonant increase of the resistivity was observed.

Apart from SDS there are other mechanisms which may lead to similar results. These are schematically depicted in fig.3: a) the bolometric effect (path 3-4-6 in fig.3) and b) negative photoconductivity due to fact that at EPR less photons are directly absorbed by free carriers (path 3 opens, and path 2 becomes less effective).

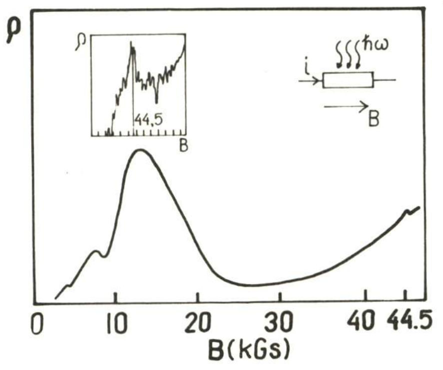

Fig.2 Longitudinal photoconductivity vs. magnetic field for $Hg_{1-x}Mn_xTe$ /x = 0.003/ at 4.2K. The incident light energy $\hbar\omega$ = 0.5meV, current through the sample i = 10μA. Resonance peak is enlarged in the insert

Since the band structure of SMSC depends strongly on $\langle S_z \rangle$ - the polarization of Mn spins, a resonant change of the Fermi level ε_F has to be considered as an explanation of our results. However, the shift of ε_F as estimated with help of SMSC band structure [3] is far too small to be observed. In order to rule out two former

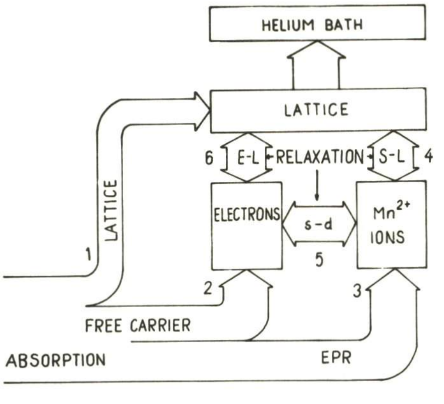

Fig.3 Energy flow chart for the microwave absorption in SMSC

possibilities the lock-in, microwave modulation ($10 - 10^3$Hz) measurements with careful analysis of the phase of the output signal were done. It turned out that the response time at the resonance is shorter than 10^{-5}s which is too short for the bolometric effect. The response time at the resonance was shorter than that of the background signal by about two orders of magnitude. This fact rules out the negative photoconductivity leaving us with SDS as the remaining explanation.

In order to bring theoretical calculations to some quantative level one has to know the electron wave functions and their dispersion relation and also the parameters of s-d Hamiltonian. All these are relatively well know for SMSC. We carried out the calculations of the conductivity limited by SDS in the quantum limit using wave functions suitable for a narrow-gap material [6] with coefficients corrected for the exchange interaction [7] . Due to the spin-orbit interaction the wave function has a mixed character with both spin-up and-down parts. This has an important consequence: even in the extreme quantum limit the inelastic process involving Mn spin "flip" is allowed. The relaxation time, describing longitudinal conductivity, is given by (strong degeneracy assumed)

$$\frac{1}{\tau_{sd}} = (8\pi\hbar^2 c\,\varepsilon_g D_o^2/eB)^{-1} n_{Mn}[A(\varepsilon_F)(\langle S^+S^-\rangle + \langle S^-S^+\rangle) + B(\varepsilon_F)(\langle S_z^2\rangle - \langle S_z\rangle^2)],$$

$$A(\varepsilon_F) = \beta^2(\varepsilon_g + \varepsilon_F)\hbar\omega_c k_F/9,$$

$$B(\varepsilon_F) = \{\alpha^2 D_o^2 \varepsilon_F^2 + \frac{1}{9}\beta^2(\varepsilon_g + \varepsilon_F)^2[(\hbar\omega_c/4)^2 + (\hbar^2 k_F^2/2m_o^*)^2] + \frac{2}{3}\alpha\beta\varepsilon_F(\varepsilon_g + \varepsilon_F) D_o\hbar^2 k_F^2/2m_o^*\}\, 2m_o^*/[(\varepsilon_g + 2\varepsilon_F)\hbar^2 k_F],$$

$$D_o = \hbar\omega_c/2 + \hbar^2 k_F^2/2m_o^* - \frac{1}{2}(g^* + \frac{1}{3} n_{Mn}\langle S_z\rangle\beta),$$

where α, β are exchange interaction constans (see [7]), k_F is the Fermi momentum and $\langle S^+S^-\rangle$, etc. are spin correlation functions (we put $\langle S^+\rangle = \langle S^-\rangle = 0$).

At the EPR a fraction c of Mn ions is disoriented i.e. $\langle S_z\rangle_{EPR} = 5/2 - 1/2\,c$ which gives: $\langle S^+S^-\rangle = 5 + 3c$, $\langle S^-S^+\rangle = 5c$, $\langle S_z^2\rangle - \langle S_z\rangle^2 = -1.5c - 0.25c^2 \approx -1.5c$ (the last equality holds for $c \ll 1$). Accordingly the resistivity increase is $\Delta\rho/\rho = -\frac{\rho_{illum}-\rho_{dark}}{\rho_{dark}} = 5c(8 - 3B/2A)$ which for x = 0.003 sample gives $\Delta\rho/\rho = 0.3c$. A precise determination of c is difficult in our case because microwaves penetrate only a skin layer of the material where they are absorbed

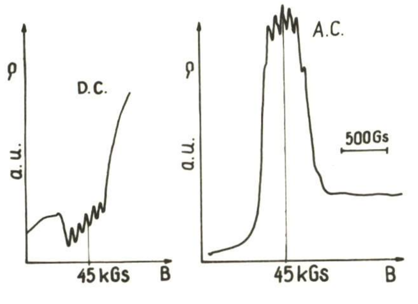

Fig.4 Longitudinal photoconductivity vs. magnetic field for $Cd_{1-x}Mn_xSe$ (x = 0.001) at 4.2K ($\hbar\omega$ = 0.5 meV): DC measurement is shown on the left hand side, AC measurement (f = 1KH$_z$) - on the right hand side

by carriers and Mn ions. An estmation based on transmission experiments [5] gives $c = 10^{-4}$. This value leads to correct sign of our effect and a resonable order of magnitude $\Delta\rho/\rho \sim 10^{-5}$ for x = 0.003 sample. Similar measurements were also done in $Cd_{1-x}Mn_xSe_1$ x = 0.001 (see Fig.4). Greater penetration depth in this case permitted observation both in low frequency (bolometric effect-fig.4a) and high frequency regime (SDS-fig.4b). The signal was so strong that clear hyperfine structure was visible. It is now difficult to make theoretical analysis of the effect in this material since the conduction mechanism is still not well established. It seems, however that a narrow impurity band responsible for the conduction and interpretation in terms of SDS will be similar to the previous case.

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