EXTRAORDINARY HALL EFFECT IN THE MAGNETIC SEMICONDUCTOR Sn$_{1-x}$Mn$_x$Te

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We have studied the extraordinary Hall effect (EHE) in the magnetic semiconducting solid solutions Sn$_{1-x}$Mn$_x$Te over the ranges of carrier concentrations : $3 \times 10^{20} < p < 8 \times 10^{20}$ cm$^{-3}$, and Mn concentrations : $2.5 < x < 7.5$ at.%. We have calculated the skew scattering contribution to the EHE arising from both spin independent and spin dependent potentials ; we have also estimated the current renormalization contribution. Good agreement has been found between the calculated values of extraordinary Hall coefficient and the experimental ones over the whole range of parameters studied.

1. INTRODUCTION.

The EHE, i.e. that part of the Hall effect which in a magnetic conductor depends on magnetization rather than on magnetic induction, is a typically spin dependent transport phenomenon. Luttinger [1] has shown that the EHE arises from the interband matrix elements of the spin-orbit coupling. The study of this effect which would be vanishingly small for free electrons requires a knowledge of the actual band structure. A detailed analysis of the EHE [1,2] allows one to separate different contributions the relative importance of which varies with carrier concentration and scattering mechanisms. Finally theoretical [3], and experimental [4] results have pointed out that, in a semiconductor, the EHE may be defined with a small number of band parameters namely the ratios $\alpha = \varepsilon_F / \varepsilon_g$ and $\beta = \Delta / \varepsilon_g$ ($\varepsilon_F$ Fermi energy, $\varepsilon_g$ energy gap, $\Delta$ spin-orbit energy). It is obviously of interest to study the EHE in a magnetic semiconductor where the band parameters and the scattering parameters are fairly well known.

Sn$_{1-x}$Mn$_x$Te solid solutions are small gap, highly degenerate, p type semiconductors with a rather large spin-orbit coupling energy ($\varepsilon_g = 0.27$ eV, $p \sim 10^{20}$ - $10^{21}$ cm$^{-3}$, $\Delta = 0.55$ eV). Indirect exchange through carriers couples the magnetic moments carried by the Mn ions and leads to a ferromagnetic ordering at low temperatures and to spin polarization of the carriers ; for the studied range of carrier concentrations $p$, the Curie temperature $T_C$ ($^\circ$K) $\sim 1.4 \times$ (at.%) depends only slightly on $p$. Monocrystalline samples have been grown in which the Mn concentration and the carrier concentration are varied indepedently, and the EHE is easily
detectable [5]. Sn$_{1-x}$Mn$_x$Te then constitutes a very suitable material for the study of the EHE. Upon varying (i) the magnetic parameters, (ii) the Fermi energy and (iii) the scattering parameters, detailed comparisons between experiment and theory are possible. The band structure is rather intricate; however, a simple nonparabolic band scheme allows one to account for the electronic properties (effective masses, mobility).

2. ESTIMATION OF THE EHE.

Let us consider first the skew scattering contribution to the EHE. It arises from the fact that, when the spin-orbit coupling is properly included in the wave functions, the transition probability $W_{kk'}$, associated with a scattering event contains a term which is antisymmetric with respect to $k$ and $k'$ [3]. Our band scheme will be the one of InSb with the parameters $\varepsilon_g$ and $\Delta$ appropriate to the matrix SnTe, the multivalleys character being taken into account.

In Sn$_{1-x}$Mn$_x$Te, at low temperatures, three different mechanisms take part in the scattering processes namely: (i) scattering by native impurities (Sn vacancies). They are specified by their potential $-U_I$. We will assume their concentration $N_I$ to be equal to holes one. (ii) scattering by the spin independent part $-U_M$ of the Mn impurities potential. $N_M$ is their concentration. (iii) scattering by the s-d like interaction between the carrier's spin $S$ and spin $\mathbf{S}$ of Mn ions: $-J S \cdot \mathbf{S}$. For the sake of simplicity, we assume these potentials to be constant within the unit cell volume $\Omega$ and vanishing outside.

Once the wave functions are known, one may calculate (to second Born approximation) that part of the transition probability which is responsible for the skew scattering [3]. A straightforward extension of this calculation allows one to include the three scattering contributions into the Hall resistivity expression $\rho_{H}^{sk}$, using Boltzmann equation. We have retained only the lowest order terms:

$$
\rho_{H}^{sk} = \frac{m_c m_d}{4(6\pi^2)^{1/3} e^2 \hbar^5 p^{1/3}} \left[ \frac{8/5(2/2bc - b^2)[N_I(U_I)^3 + N_M(U_M)^3] J\Omega}{2e_F} \right] \times \frac{M}{g_B^*} (1)
$$

where $m_c$ and $m_d$ are the conductivity and density of states masses, $M$ the magnetization per unit volume and the factors: