Manifestation of the spin glass phase in the anisotropy of the magnetoresistance of p-$Hg_{1-x}Mn_xTe$

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The decrease of the anisotropy of the magnetoresistance of the semimagnetic semiconductor p-$Hg_{1-x}Mn_xTe$, observed upon decrease of temperature or increase of the Mn concentration, is due to an increase in the intensity of the local exchange fields which are associated with acceptors "frozen-in" in the spin glass phase.

Magnetoresistance of cubic, semimagnetic, p-type semiconductors (SMS) is characterized in the region of jump and impurity conductivities by a number of peculiarities associated with the redistribution of the energy spectrum, both of the ceiling of the valence band Γ and the levels of the acceptors with effective molecular field $G_h=N_0\beta x\langle S\rangle$. This field is due to the exchange interaction (β is the corresponding constant) of the band current carriers (or carriers localized on the acceptors) with the spins $\mathbf{S}$ (polarized by a magnetic field $\mathbf{H}$) of the magnetic Mn ions,[1] whose concentration is equal to N_0x. In particular, the giant negative magnetoresistance effect, which has been studied in detail in a number of papers, is due to the so-called "boil-over" effect,[2] i.e., a decrease of the binding energy E_A of the acceptor levels in the field G_h. In weak fields $G_h \ll E_A$ the effect is explained by the difference in the effective g-factors of the free holes (g_h^*) and the holes bound to the acceptors (g_A^*) (g^* takes into account the contribution of the exchange field in the spin-induced splitting). In fields $G_h \gg E_A$ the binding energy E_A attains its minimum value which is determined by the mass of the light holes, not the heavy holes, as in the case[3] $G_h=0$. Concomitant with the growth of G_h, the wave functions of the acceptors acquire an axial anisotropy: the states with angular momentum projection $p_A=+3/2$, corresponding to the lower spin sublevel are elongated in the direction transverse to the field G_h. The given effect has been observed in the region of hopping conductivity[4] in a study of the anisotropy of the magnetoresistance $\eta^{\exp}=\rho_{\parallel}/\rho_{\perp}>1$ in p-$Hg_{1-x}Mn_xTe$ ($x\leqslant 0.1$). Here it may be noted that the magnetoresistance increases monotonically with increasing of the magnetization $\mathbf{M}\propto\mathbf{G}_h$ of the samples. Variation of $\mathbf{M}$ was achieved in Ref. 4 by varying the magnetic field $\mathbf{H}$, the temperature T, and the compensation of the semimagnetic semiconductor x. However, the measurements of η we have obtained for $x\geqslant 0.12$ lead to a qualitatively different result.

Figure 1 shows the dependences of the magnetoresistance anisotropy parameter on the magnetic field for two p-type samples with $x=0.09$ and $x=0.165$. For the sample with $x=0.09$ (Fig. 1a) it can be seen that there is an overall increase in $\eta^{\exp}$ when the temperature is lowered, caused by the resulting increase in the magnetization, in agreement with Ref. 4. For the sample with $x=0.165$, however (Fig. 1b), the

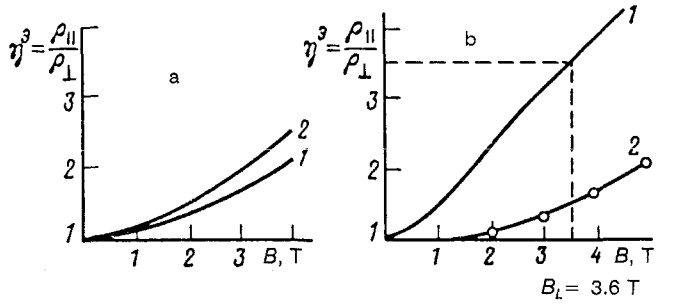

FIG. 1. Dependences of the magnetoresistance anisotropy parameter ($\eta^{exp}=\rho_{\parallel}/\rho_{\perp}$) for two samples of p-$Hg_{1-x}Mn_xTe$: p-$Hg_{0.91}Mn_{0.09}Te$ and p-$Hg_{0.835}Mn_{0.165}Te$. Curves *1* and *2* correspond to temperatures of 4.2 and 1.7 K, respectively. ○—Calculated values.

magnetoresistance anisotropy decreases markedly when the temperature is lowered, in spite of the fact that the temperature dependence of the magnetization, expected for $x>0.15$ from measurements[5] in the interval $T=2-4.2$ K, is virtually nonexistent. In the interval of fields from 0 to 1.5 T at $T=1.6$ K, in general, no magnetoresistance anisotropy is observed, while at 4.2 K, the value of η^{exp} attains a noticeable value already for $H>0.3$ T. Similar measurements were carried out for a sample with $x=0.19$, in which no magnetoresistance was generally observed in fields up to 4.5 T at 1.6 K.

Thus, the measurements show that η is not only a function of the magnetization, but also depends on the temperature and concentration of the Mn ions.

The noted differences in the behavior of $\eta^{exp}=\eta(H)$ at different temperatures may be associated with the transition of the semimagnetic semiconductor to the spin glass phase, in which samples with $x\geqslant 0.12$, according to Ref. 6, should exist at $T\leqslant 2$ K. Since the magnetic moments of the ions are frozen in the spin glass phase, the same is true of the local exchange fields G_l, which determine both the magnitude of the spin-induced splitting and the directions of the anisotropy axes for each acceptor center. Thus, in spite of the finite value of the randomly oriented G_l, for $H=0$ the crystal as a whole remains isotropic, as in the paramagnetic phase. In a magnetic field the local fields G_l, and the corresponding local magnetic moments $\mathbf{M}_l\propto\mathbf{G}_l$, change their orientation with respect to $\mathbf{H}$. This process, however, in the spin glass phase does not take place as fast as in the paramagnetic phase, because of competition between the external field and the internal fields, the latter of which tend to randomize G_l.

In accordance with the foregoing discussion, we propose the following model: 1. We approximate the acceptor wave function by an anisotropic single-exponential function with radius a of the state aligned with the field $\mathbf{G}_l$ and radius b of the state transverse to it; $\Psi(\mathbf{r})\propto\exp(-\sqrt{(x'^2+y'^2)/b^2+z'^2/a^2})$, where the z' axis of the local coordinate system is chosen to be aligned with $\mathbf{G}_l$. Assuming $b>a$, we note that both the ratio of b to a and their magnitudes depend on $|\mathbf{G}_l|$. To simplify the calculations, we assume that in the spin glass phase the ratio b/a does not vary as a result

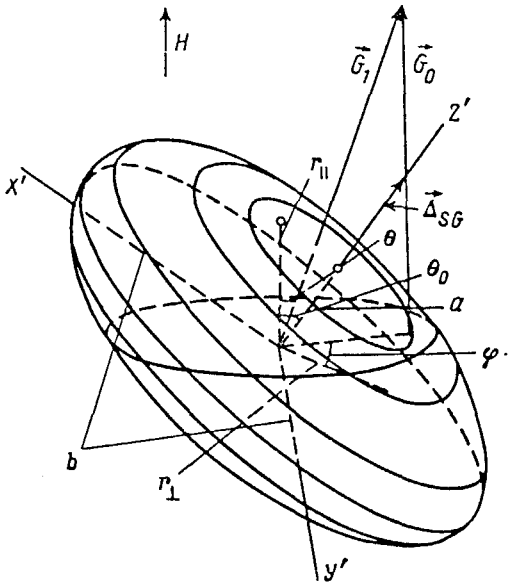

FIG. 2. Schematic diagram of the surface defined by the equation $\Psi(\mathbf{r})=const$. The coordinate system and the angles are the same as in Eqs. (1) and (2).

of the effect of the external magnetic fields, used in our experiment, thus $b/a=$const.
2. We ignore fluctuations in the magnitudes of the local fields $\vec{\Delta}_{sg}$, but take into account their random orientation.
3. We take into account the role of the external magnetic field by means of an additive correction term: $\mathbf{G}_0=\mathbf{G}_h+g\mu_B\mathbf{H}$, identical for all of the local fields $\vec{\Delta}_{sg}$. As a result, a local effective field $\mathbf{G}_l=\vec{\Delta}_{sg}+\mathbf{G}_0$ acts upon each acceptor center.
4. Since in an ensemble of identically oriented anisotropic impurity centers the magnitude of the longitudinal magnetoresistance, calculated in Ref. 7, is $\rho_{\|} \propto 1/a^2$, and since the transverse magnetoresistance is $\rho_\perp \propto 1/b^2$, we seek the desired dependence $\eta=\rho_{\|}/\rho_\perp$ in the form $\eta^T\langle r_\perp^2\rangle/\langle r_{\|}^2\rangle$, where $\langle ...\rangle$ denotes the average over the directions of the local fields $\mathbf{G}_l$, and $r_{\|}$ and $r_\perp$ are the length scales of the acceptor wave function along and transverse to the direction of the external field $\mathbf{H}\|\mathbf{G}_0$ (Fig. 2).

Taking into account the above assumptions, we obtain the following relationships between $r_{\|}$ and $r_\perp$:

$$r_{\|}^2=\frac{a^2b^2}{b^2\cos^2\theta+a^2\sin^2\theta};\quad r_\perp^2=\frac{a^2b^2}{b^2\sin^2\theta\cos^2\varphi+a^2(\cos^2\theta\cos^2\varphi+\sin^2\varphi)}. \tag{1}$$

Here θ and φ are the polar and azimuthal angles of G_l, which are related to the corresponding angles θ_0 and φ_0 for Δ_{sg} by the relations

$$\varphi=\varphi_0;\quad \theta=\theta_0-\delta\theta;\quad \sin^2\delta\theta=\frac{G_0^2\sin^2\theta_0}{\Delta_{sg}^2+G_0^2+2\Delta_{sg}G_0\cos\theta_0}. \tag{2}$$

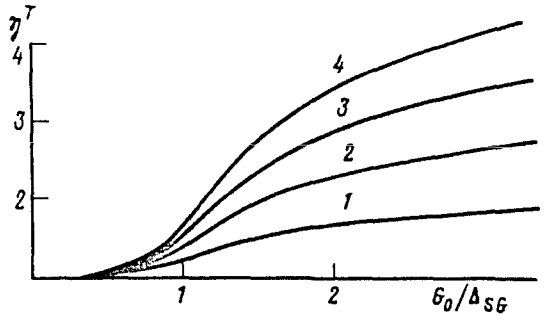

FIG. 3. Calculated dependences of the anisotropy parameter $\eta^T = \langle r_\perp^2 \rangle / \langle r_\parallel^2 \rangle$ on the effective exchange field. Curves *1–4* correspond to ratios of the squares of the semiaxes of the ellipsoid (Fig. 2), $b^2/a^2 = 2$, 3, 4, and 5, respectively.

Substituting (2) into (1) and averaging over θ_0 and φ_0, we find $\eta^T = \langle r_\perp^2 \rangle / \langle r_\parallel^2 \rangle$ for various values of b^2/a^2 and G_0/Δ_{sg} (Fig. 3). The qualitative similarity between the calculated curves and those measured for $x = 0.165$ (Fig. 1b) is evident. Quantitative agreement is achieved if we approximate $\mathbf{G}_0 = G_0(H)$ by a linear dependence (according to the measurements of $M = M(H)$ in Ref. 5, such an approximation is valid for $H < 4T$) and for Δ_{sg} we take $G_0(H_0)$, where $H_0 = 3.6$ *T* and $b^2/a^2 = 3.5$.

As an independent check of the chosen model, because the measurements of the anisotropy parameter $\eta_p^{\exp} = \eta_p^{\exp}(H)$, which were carried out for the same sample, but which at $T = 4.2$ K correspond to the paramagnetic phase (Fig. 1b). Since $G_l(H) = G_0(H)$ (which corresponds to $\vec{\Delta}_{sg} = 0$) in the paramagnetic phase in intermediate fields, the found value $b^2/a^2 = 3.5$ should be compared with the anisotropy $\eta_p^{\exp}$ observed in the paramagnetic phase at 4.2 K in the field H_1, which leads to the result $G_0 = G_0(H_0)_{T=1.7\text{ K}}$. To determine the field H_1 from the equation $G_0(H_1)_{T=4.2\text{ K}} = G_0(H_0)_{T=1.7\text{ K}}$, it is sufficient to know the dependences of the magnetization $M = M(H_1)$ for the two indicated temperatures. Such measurements were carried out in Ref. 5, but for a set of samples with $x = 0.1$, $x = 0.12$, and $x = 0.14$. By extrapolating these dependences to the value $x = 0.165$, we find that the magnetization of the semimagnetic semiconductor coincides for the two indicated temperatures with error not greater than 5% in the field region from 1 to 5 T. This means that with the indicated accuracy $H_1 = H_0 = 3.6$ T. From the measurement results for 4.2 K shown in Fig. 1 it is clear that the value of the anisotropy parameter $\eta_p^{\exp} = 3.5$ corresponds to a field of 3.6 T.

Thus, our study of the magnetoresistance anisotropy shows that randomly oriented, strong exchange fields act upon the acceptor states in a semimagnetic semiconductor at low temperatures if its concentration of magnetic component is high enough. Their mean value, calculated for the composition $x = 0.165$ using the values $N_0\beta = 0.72$ eV and $\langle S_x \rangle = 0.236$ ($T \leqslant 4$ K, $H = 3.6$ T) is $\Delta_{sg} \approx 28$ meV. As the *Mn* concentration is increased, the expected value of Δ_{sg} grows even larger, while the magnetic susceptibility of the semimagnetic semiconductor falls considerably, which is explained by

the nearly complete absence of magnetoresistance anisotropy in the sample with $x=0.19$ in fields up to 4.5 T.

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