Giant positive magnetoresistance of magnetic conductors

V. A. Kashin and É. L. Nagaev

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A giant positive magnetoresistance can occur in defect-containing magnetic conductors as a result of carrier scattering by the magnetic moments produced in the field around the defects.

As is well known, a typical phenomenon in magnetic conductors is giant negative magnetoresistance. It is due to the fact that at finite temperatures the magnetic field raises the degree of magnetic order and decreases by the same token the scattering of the carriers by its fluctuations. It was recently established, however, that if the carrier density in the antiferromagnetic semiconductors EuTe and EuSe is increased to $\sim 10^{19}$ cm^{-3}, their magnetoresistance $\Delta\rho(H)$ reverses sign in the paramagnetic region in weak and moderate fields, becoming again negative only in the strongest fields.[1] The positive magnetoresistance is larger by two orders of magnitude than in nonmagnetic conductors. Since EuSe is ferromagnetic already at $n \sim 10^{18}$ cm^{-3},[2] it can be concluded that this effect is inherent only in magnetic conductors having a large number of defects and having no spontaneous moment, regardless of the character of their ordering at $T=0$.

It will be shown in this paper that giant positive magnetoresistance can be due to the formation, in the field around the defects, of magnetic moments that scatter the conduction electrons very strongly. The analysis is limited to the case most favorable for the manifestation of this effect, namely strongly doped antiferromagnetic semiconductors at $T=0$. The positive magnetoresistance in them can exceed that observed in[1] by two orders of magnitude. (The corresponding experiments cannot be carried out on EuTe in which ferromagnetic microscopic regions with increased con-

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duction-electron concentrations are produced as $T \to 0$.)[3]

Indirect exchange via the conduction electrons tends to establish ferromagnetic ordering. However, when the carrier density n is increased in an antiferromagnetic semiconductor, spontaneous magnetization appears only after a certain value n_A is reached. Nonetheless, the tendency of the electrons to establish ferromagnetic order becomes manifest also at $n < n_A$ if the crystal is placed in a magnetic field, since they increase the magnetization induced by this field. Recognizing that the random distribution of the ionized donors causes the conduction-electron density to be unevenly distributed over the crystal, it follows that the magnetization of the crystal is also uneven. It is maximal in the vicinity of the donors, where the electron density is maximal, and is minimal far from them. Thus, the field leads to the appearance of a new mechanism of carrier scattering, namely scattering by the spatial fluctuations of the magnetization.

On the other hand, the field, by causing spin polarization of the electrons, increases their kinetic energy, and this weakens their scattering by the electrostatic potential of the defects.[4] This effect is significant even in relatively weak fields, owing to the strong exchange interaction of the electrons with the moment induced by this field in the crystal. This interaction is equivalent to action exerted on the electron spins by an effective crystal field that exceeds the external field producing it by a factor $\sim AS/T_N$, i.e., by 10^2—10^3 times (A is the s-d exchange integral, S is the spin of the magnetic atom, and T_N is the Neel temperature of the impurity-free crystal). The scattering by the magnetization fluctuation is significant only at values of n close enough to n_A, whereas the electron spin polarization occurs at arbitrary n. The magnetoresistance is therefore always negative at small n, and this is not connected with the increase of the magnetic order. On the other hand, it becomes positive when n_A is approached, if the field is less than the sublattice-flipping field H_F. If it is larger, then the fluctuations of the magnetization vanish at $T = 0$, and as $H \to \infty$ the magnetoresistance is negative for all n.

To verify the feasibility of positive magnetoresistance, it suffices to consider the case of fields $H > H_p = H_F\mu/AS$, at which the conduction electrons are fully polarized along the spin (in typical conditions, the Fermi energy μ is less than the s-d exchange energy AS). The field ϕ_q of the defect causes the appearance of an effective field $\tilde{\phi}_q$ acting on the electron

$$\tilde{\phi}_{\mathbf{q}} = [1/\epsilon(\mathbf{q})]\phi_{\mathbf{q}} - \frac{AS}{2} m_{\mathbf{q}}, \quad m_{\mathbf{q}} = \frac{AS}{2T_N} n_{\mathbf{q}} a^3, \tag{1}$$

where $n_{\mathbf{q}}$ is the electron-density fluctuation induced by the field

$$n_{\mathbf{q}} = -\frac{q^2}{4\pi e^2}\left[1 - \frac{\epsilon_0}{\epsilon(\mathbf{q})}\right]\phi_{\mathbf{q}}. \tag{2}$$

The connection between the Fourier components of the relative magnetization $m_{\mathbf{q}}$ and of the electron density $n_{\mathbf{q}}$ was established in[4] for the case of a semiconductor with a conduction band much wider than AS (a is the lattice constant and ϵ_0 is the dielectric constant of the impurity-free crystal).

The dielectric constant $\epsilon(\mathbf{q})$ is calculated by varying the quasiclassical expression for the system energy

$$E = \frac{3}{5}\mu \int \frac{n^{5/3}(\mathbf{r})}{n^{2/3}} d\mathbf{r} + \frac{e^2}{2\epsilon_0} \int \frac{[n(\mathbf{r}) - n][n(\mathbf{r}') - n]}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r}\, d\mathbf{r}' - \frac{1}{4a^3 T_N} \int \left[\frac{AS}{2} n(\mathbf{r}) a^3 + HS\right]^2 d\mathbf{r} + \frac{1}{\epsilon_0} \int \phi(\mathbf{r}) n(\mathbf{r}) d\mathbf{r} \tag{3}$$

with respect to the electron density $n(\mathbf{r})$ ($\mu = (6\pi^2 n)^{2/3}/2m$, the field H is in energy units, n is the average density, and $T_N = |J|S$, where J is the exchange integral between the magnetic atoms). As a result, a relation is established between $n_{\mathbf{q}}$ and $\phi_{\mathbf{q}}$, and the use of (2) yields

$$\frac{\epsilon(\mathbf{q})}{\epsilon_0} = 1 + \frac{\lambda^2}{q^2}, \quad \lambda^2 = \lambda_0^2 \left[1 - \left(\frac{n}{4n_A}\right)^{1/3}\right]^{-1}, \quad \lambda_0^2 = \frac{6\pi e^2 n}{\epsilon_0 \mu}$$
$$n_A a^3 = (3\pi^2)^2 \left(\frac{8}{3} \frac{T_N}{A^2 S^2 m a^2}\right)^3. \tag{4}$$

Using (1), (2), and (4) in the Born approximation we obtain for the magnetoresistance with logarithmic accuracy

$$\frac{\rho(H) - \rho(0)}{\rho(0)} = 2^{-1}\left[1 - \left(\frac{n}{4n_A}\right)^{1/3}\right]^{-2} - 1 \tag{5}$$

As seen from (5), at $H > H_p$ the magnetoresistance reaches saturation as a function of the field. At $n \ll n_A$ it is negative (the field decreases ρ to one-half its value).[4] Starting with the value $n_c = 4(1 - 2^{-1/3})^3 n_A \approx 0.1 n_A$, the magnetoresistance becomes positive, and when n approaches n_A the magnetoresistance reaches a value 2.7 times larger than $\rho(0)$. At $T = 0$ and when the field increases to H_F, the magnetoresistance becomes negative jumpwise ($\rho(H)/\rho(0) \approx 1/2$ for all n).

In fields $H \ll H_p$, the behavior of the magnetoresistance turns out to be more complicated, since the carrier scattering from the less-filled band becomes weaker because of the appearance of magnetization (the second term of (1) enters with positive sign). As a result, the magnetoresistance at $H \ll H_p$ is negative in the density interval $[0.77 n_A, n_A)$, and becomes positive only in stronger fields. It reverses sign again at $H > H_F$. At the remaining densities, the sign of the magnetoresistance at $H < H_F$ should not depend on H. According to (4) at $AS = 0.5$ eV, $T_N = 25\,^\circ$K, $a = 3 \times 10^{-8}$ cm, $m = 10^{-27}$ g, $n_A = 3.2 \times 10^{20}$ cm^{-3}.

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