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MAXIMUM RESISTIVITY OF FERROMAGNETIC CONDUCTORS, DUE TO CARRIER SCATTERING BY GIANT MOMENTS OF MAGNETIC CLUSTERS

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As is well known from the experiment, in most cases ferromagnetic conductors have a maximum of resistivity ρ near the Curie point T_c. At first glance, this maximum is naturally attributed to critical scattering of the carriers by the fluctuations of the magnetic-moment density. There are, however, experimental data that show convincingly that the critical scattering in perfect ferromagnetic crystals does not lead to a maximum of ρ, but only to a singularity of $d\rho/dT$, of the same type as in the specific heat. On the other hand, the maximum of ρ near T_c is the result of distortion of the crystal lattice [1], i.e., of the smearing of the phase transition. Nonetheless, there is no simple connection between the degree of smearing of the transition and the maximum of the resistivity. For example, according to the data of [2], the height of the peak of the relative resistivity drops sharply with increasing defect content, starting with a certain value of the latter; in addition, the maximum may be located far enough from T_c [3]. Thus, the trivial explanation of the nature of the maximum of ρ as a function of T in the region $T \sim T_c$ is patently inadequate.

The purpose of the present article is to show that in ferromagnetic conductors with defects the temperature minimum of mobility can be attributed to the formation in them of microscopic regions with giant magnetic moments that scatter the carriers anomalously strongly. With further rise of temperature, such giant moments vanish and the carrier mobility increases. The existence of such clusters is due to the uneven distribution of the electron density in the crystal with defects.

Let us consider, for example, a ferromagnetic semiconductor. The electrons of the partly filled d (or f) shells are localized in this conductor each on its own atom, and take no part in the charge transport. Only the electrons of the outer shells (s electrons in the s-d model terminology [4]) can transport charge. If the crystal contains donor impurities, the s electrons can be not only in states of the conduction bands, but also in localized states whose orbit radius R can greatly exceed the lattice constant a. The s electrons on the donor levels effect indirect exchange between the localized d spins in the vicinity of the defect, increasing the ferromagnetic coupling between them [5, 6]. Therefore the local ferromagnetic ordering in the vicinity of the defect is disturbed at higher temperatures than on the average in the crystal, i.e., a cluster with an anomalously large moment K is produced in the vicinity of the defect.

The relaxation time for the scattering of the conduction s electrons by the fluctuations of the d spins in a nondegenerate impurity-containing semiconductor is calculated by constructing the single-electron Green's function. The Hamiltonian used in the calculation differs from the usual s-d model Hamiltonian [4] in that the part describing the interaction between the d spins

takes into account the indirect exchange between them via the electrons of the donor levels (the corresponding procedure is described in [6]). It is assumed with respect to the parameters of the Hamiltonian that the width of the conduction band W is large in comparison with the energy AS, where A is the s-d exchange integral and S is the spin of the magnetic atom.

The analysis is confined to temperatures higher than T_c, when the correlations between the moments of the atoms making up the same cluster are appreciable. On the other hand, the correlations between the directions of the moments of different clusters, as well as the spins of the atoms not contained in the clusters, can be neglected. It is assumed that $2S \gg 1$. This makes it possible to regard the scattering of the electrons by the clusters as elastic. As a result we find that the reciprocal relaxation time $\tau^{-1}(\mathcal{E})$ can be represented as a sum of two terms, $\tau_p^{-1}(\mathcal{E})$ and $\tau_c^{-1}(\mathcal{E})$. The first describes the usual temperature-independent paramagnetic scattering of the s electrons by the d spins, when each spin scatters independently of the other. (According to the condition $AS/W \ll 1$, the Born approximation is sufficient for this term.) The second term describes the correlated scattering by the spins of the atoms contained in the cluster. Since the ratio AK/W is generally speaking not small, the Born approximation may turn out to be insufficient for the calculation of this term. If the magnetization K is close to the maximum, if the wavelength of the electron is large in comparison with the radius of the cluster, we obtain for $\tau_c^{-1}(\mathcal{E})$:

$$\tau_c^{-1}(\mathcal{E}) = \frac{2\pi}{\hbar} g(\mathcal{E}) n_d \frac{A^2}{4} \frac{\overline{K^2} + (\overline{K^2})^2 |F|^2}{|1 - \overline{K^2}F^2|^2}$$

$$F = \frac{A}{2N} \sum \frac{1}{E - \mathcal{E}_k - i\eta} \quad (\eta \to 0) \qquad K^2 = \sum_{g \neq f}' (S_g S_f) \tag{1}$$

where n_d is the relative defect concentration, $g(\mathcal{E})$ is the density of the electron level, $\mathcal{E}_k$ is the energy of an electron with quasimomentum k, and the bar denotes temperature averaging over the states of the spins. The prime at the summation sign in the expression for K^2 means that the summation is confined to atoms belonging to the same cluster.

The energy denominator in (1) reflects the possibility of the existence of a bound state with a cluster whose energy is given by

$$1 + FK = 0 \quad \text{or} \quad 1 - FK = 0 \tag{2}$$

depending on the sign of A. At small n_d, the bound states of the electrons with clusters have little effect on the crystal mobility. As seen from (1), if the cluster magnetization is close to the limiting value, even when the conditions for the applicability of the Born approximation is satisfied for the scattering by the cluster, $K^2F^2 \ll 1$, the scattering by the cluster is proportional to the square of the number of atoms in the cluster. At a donor state radius (2 - 3)a, the number of atoms in the cluster is $z \sim 30 - 100$, i.e., the correlated scattering by the clusters exceeds their concentration by 3 - 4 orders. The condition for maximum magnetization of such a cluster at $T \sim T_c$ are satisfied, for example, at a typical value $AS \sim 1$ eV, if $T \sim (AS/z) \sim 10^{-3}$ eV. If the quantity K^2F^2 cannot be regarded as small, then the scattering intensity is even larger than in the Born approximation. It is particularly large under resonance conditions, when the real part of (2) vanishes inside the conduction

band. With increasing temperature we have $K \to 0$, and the effects of anomalous scattering vanish. They may not exist also at $T \to 0$, when the concept of the cluster moment becomes meaningless. Thus, the scattering by clusters can indeed lead to a sharp drop in the mobility near $T \sim T_c$.

Such clusters can appear in strongly doped ferromagnetic semiconductors in which the electrons are collectivized. Owing to the nonuniform distribution of the impurities over the crystal, the conduction-electron density is also unevenly distributed, and the ferromagnetic coupling in the regions with increased electron density is stronger than on the average throughout the crystal. With increasing impurity density, the relative fluctuations of the electron density decrease, and accordingly the scattering by the moments of the clusters decreases. With increasing n_d, a situation becomes possible wherein doped semiconductors change from the semimetallic to the insulating state with increasing temperature [7]. The reason for the transition is that in the insulating state the degree of inhomogeneity in the distribution of the electron density decreases exponentially. Thus, the temperature peak of the resistivity in the region $T \sim T_c$ becomes gigantically large under the indicated conditions.

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