of the eight almost equivalent nearest-neighbor nuclei U^{3+}.

A particularly strong effect occurs at frequencies in the vicinity of ν_F, namely 13.90, 14.67, and 14.74 MHz for $\vec{H} \parallel [100]$(ν_F = 14.14 MHz), and 6.65, 6.96, 8.00, and 8.10 MHz for $\vec{H} \parallel [001]$ (ν_F = 7.54 MHz), which is apparently due to the nuclei of the second coordination sphere. It is curious that in this case practically the entire DS vanishes. No satisfactory explanation of this fact has been obtained so far.

The results give grounds for hoping that the method of a radio-frequency effect on the DS spectrum (RFDS) can be successfully used to investigate the hyperfine interaction of a magnetic center with the surrounding nuclei. The RFDS possesses in this case the simplicity of the DS procedure, and the measurement accuracy is not worse than that of ENDOR.

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INHOMOGENEOUS FERRO-ANTIFERROMAGNETIC STATE OF MAGNETIC CONDUCTORS

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It will be shown in this paper that inhomogeneous states of magnetic conductors are possible when their volume breaks up into alternating ferromagnetic and antiferromagnetic domains. This, in particular, may be the ground state of a strongly doped antiferromagnetic semiconductor, which will be used as the example in this analysis.

We consider a semiconductor with impurity concentration $\sim 10^{19} - 10^{21}$ cm^{-3}, in which the electrons of the impurity atoms are collectivized, and therefore effect indirect exchange between the localized d- or f-spins. The Fermi energy μ of the carriers (s electrons in terms of the s-d model) is smaller than or comparable with AS (A is the s-d exchange integral and S is the spin of the magnetic atom). The indirect exchange can therefore not be described here with the aid of a Heisenberg Hamiltonian. The competition between the direct Heisenberg exchange and the indirect non-Heisenberg exchange between the d-spins, the former of which strives to establish an antiferromagnetic state and the latter a ferromagnetic state, results in the existence of a carrier density interval $n_L < n < n_R$, in which neither the ferromagnetic nor the antiferromagnetic order is stable [1, 2].

It was shown in [1, 2] that the energy of a noncollinear antiferromagnetic state with nonzero magnetic moment of the type proposed in [3] is lower in this interval than the energy of the collinear states. In turn, however, a homogeneous noncollinear state may turn out to be stable against breakup into domains with carrier densities $n < n_L$ and $n > n_R$, with collinear antiferromagnetic and ferromagnetic ordering established in the former and the latter respectively. The tendency to instability is obvious even from the fact that in typical cases the total energy of the d-d and s-d exchange decreases with increasing n like n^2 [2]. Therefore, if a layer with carrier density is broken up into two layers with densities $n + \Delta n$ and $n - \Delta n$, respectively, then the exchange energy is

decreased by a factor $1 + (\Delta n/n)^2$.

On the other hand, the onset of an inhomogeneous carrier distribution is hindered by the Coulomb interaction. The latter decreases sharply with decreasing domain dimension. But then the kinetic energy of the carriers increases. The equilibrium domain dimensions at T = 0 are obtained from the condition that the total energy of the system be a minimum. In essence, the formation of ferromagnetic domains with increased carrier density in degenerate antiferromagnetic semiconductors is an effect of the same nature as the formation of ferromagnetic microscopic regions around the conduction electrons in nondegenerate antiferromagnetic semiconductors [4].

The energy of the inhomogeneous state is calculated by a variational method. It is assumed that the crystal breaks up into layers of increased carrier density with nonzero moment M per atom, alternating with layers having no carriers whatever and having no moment. The former have a thickness L and the latter a thickness Lx. Thus, the carrier density n in the enriched layer is connected with the average carrier density n_0 by the relation $n = n_0(1 + x)$. Further, the distortion of the electronic wave functions by the electric fields produced by the non-uniform carrier distribution in the crystal is disregarded. It is also assumed that the spins of all the carriers in the enriched layer are equally oriented (to this end it is necessary to satisfy the inequality $\mu(n) < |A|M$).

The total energy per unit volume of the crystal (i.e., of $L^{-1}(1 + x)^{-1}$ pairs of layers) is made up of the electron kinetic energy E_c, the energy E_M of exchange of the magnetic atoms with one another and with the conduction electrons, and the Coulomb-interaction energy E_{el}. When the first of these energies is calculated, the spatial quantization of the electron energies is taken into account in the first order in $(Ln^{1/3})^{-1}$ by using for the electron-level density an expression that differs from the one corresponding to free electrons with effective mass m by a factor $[1 - (\pi\hbar/4L\sqrt{2mE})]$ [5]. This yields

$$E_c = \frac{3}{5}\mu_0(n_0)n_0\left\{(1+x)^{2/3} + \frac{5}{18}\,\frac{(1+x)^{1/3}}{n_0^{1/3}L}\right\}, \tag{1}$$

where $\mu_0(n)$ is the Fermi energy of the free electrons with concentration n. The exchange energy E_M is given, in the case of broad conduction bands ($z\hbar^2/ma^2 >> |A|S/2 \equiv \alpha$) by [2]

$$E_M = -\frac{\beta}{2a^3} - \left[\eta(1+x)\theta(x_R - x) + \eta\,\frac{(1+x_R)^2 + an_0(x - x_R)}{1+x}\,\theta(x - x_R)\right] \tag{2}$$

$$\eta = \frac{a^2n_0^2a^3}{4\beta} \qquad \beta \equiv z|I|S^2,$$

where z is the coordination number, a the lattice constant, and I the integral of direct exchange between the nearest neighbors. The quantity x_R is connected by the relation $n_R = n_0(1 + x_R)$ with the density $n_R = 2\beta/a^3\alpha$, starting with which the ferromagnetic ordering becomes stable [2]. The step function $\theta(x)$ is equal to unity when $x \geq 0$ and to zero when $x < 0$.

The Coulomb energy E_{el} is given in the principal approximation in $(Ln^{1/3})^{-1}$ by

$$E_{el} = \frac{\pi e^2 n_0^2}{6\epsilon}L^2x^2, \tag{3}$$

where ϵ is the dielectric constant of the crystal.

Minimization of the energy $E = E_c + E_M + E_{el}$ [Eqs. (1) - (3)] with respect to the parameters L and x leads to the following results: The inhomogeneous state can be energywise favored only at concentrations n_0 exceeding n_m,

$$n_m \sim \left[\frac{e^2}{\epsilon a}\mu_0^2(a^{-3})\right]^{3/4} \beta^{9/4} a^{-9/2} a^{-3}. \qquad (4)$$

at $\alpha = 1$ eV, $\beta = 10^{-2}$ eV, $m = 10^{-27}$ g and $\epsilon = 10$ we obtain from (4) $n_m \sim 10^{19}$ cm^{-3}. A saturated ferromagnetic state is established in layers enriched with carriers. Their thickness is connected with the carrier density in them by the relation

$$L = a\left[\frac{\mu_0(a^{-3})}{2\pi}\frac{\epsilon a}{e^2}\right]^{1/3}(x a n^{1/3})^{-2/3}(1+x)^{1/9}. \qquad (5)$$

According to (5), $L \sim n_0^{-1/3}$ under typical conditions.

Comparison of expression (4) for n_m with the expression obtained in [2] for n_L shows that n_m can be either larger or smaller than n_L. In the former case there exists a concentration interval in which the noncollinear antiferromagnetic structure is stable. In the latter case such a structure is completely impossible, and the stratification of the layer begins already in the region of stability of the antiferromagnetism against homogeneous deformation of the magnetic structure. Owing to the random distribution of the impurity, local ferromagnetic ordering can exist in regions with increased impurity density also when $n_0 < n_m$.

Experiments on strongly doped antiferromagnetic semiconductors [6, 7] yield results that can be interpreted both in terms of noncollinear antiferromagnetism and in terms of the inhomogeneous ferromagnetic-antiferromagnetic state. Further study of this question is needed.

We note finally that at finite temperatures it is possible to have in strongly doped ferromagnetic semiconductors stratification into regions with increased and decreased values of the momentum. This is due to a fact established in [8], that replacement of the homogeneous electron distribution by an inhomogeneous one lowers the free energy of the system of d-spins. Just as in the case of an antiferromagnet, the Coulomb forces hinder the formation of the inhomogeneous electron distribution.

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