Tunnel current as detector of EPR of impurity spins in a junction

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The effect of an RF field on the anomalies of the tunnel conductivity of junctions with magnetic impurities contained in an oxide layer and situated in a constant magnetic field is considered. The alternating field increases the conductivity near a zero value of the voltage applied to the junction. The change of conductivity can reach values equal to the characteristic anomalies observed in the absence of an RF field. The effect is at resonance with the frequency of the alternating field and depends substantially on the degree of the EPR saturation of the impurities. The possibility of using tunnel junctions to detect EPR signals is discussed.

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1. The presence of magnetic impurities in a thin dielectric layer between two normal metals affects substantially the current-voltage characteristics of such a tunnel junction (see, e.g., Ref. 1). Near-zero applied voltage ($V=0$) the junction conductivity $G(V)$ has a logarithmic peak. In a constant magnetic field, the picture of the anomaly of $G(V)$ changes radically: the peak at $V=0$ decreases in amplitude (to as little as zero) and two side peaks symmetrical about $V=0$ are produced, with the distance between them proportional to the applied magnetic field. This behavior of the conductivity is due to the lifting of the spin degeneracy in the magnetic field.

Appelbaum and Anderson[2] investigated theoretically the influence of electron scattering by localized spins on the tunnel characteristics of junctions in a constant magnetic field. They have shown that a substantial role is played in the behavior of the conductivity by the population of the Zeeman sublevels of the spins localized in the contact. This makes it possible to influence the amplitudes of the anomalies in $G(V)$ by varying these populations. The state of the Zeeman subsystem is extremely sensitive to an external resonant RF field. It is precisely this circumstance which leads to the two problems treated in the present paper. The first is the effect of an RF field on the conductivity of a tunnel junction with impurities in a constant magnetic field. The second is the feasibility, in principle, of investigating the resonant characteristics of the spins localized in the junctions by measuring the tunnel conductivity.

2. The action of the alternating field is best assessed by the tunnel-Hamiltonian method used to describe the properties of the junction in a constant magnetic field.[2] In this method, the Hamiltonian of the problem

$$H=H_0+H_1, \qquad H_0=H_0^e+H_0^s \tag{1}$$

contains, in addition to the main Hamiltonian that includes the energies H_0^s of the magnetic impurities in the oxide layers and the energies H_0^e of the conduction electrodes in both electrodes, also a small perturbation H_1 that describes the electron tunneling and reflection.

The Hamiltonian of the conduction electrons is of the form

$$H_0^e=\sum_{k\sigma}(\varepsilon_{k\sigma}^a+eV)a_{k\sigma}^+a_{k\sigma}+\sum_{k,\sigma}\varepsilon_{k\sigma}^b b_{k\sigma}^+b_{k\sigma}, \tag{2}$$

where $a_{k\sigma}$ and $b_{k\sigma}$ are the Fermi operators of the electrons in the first and second electrodes, and $\varepsilon_{k\sigma}^a$ and $\varepsilon_{k\sigma}^b$ are their energies reckoned from the Fermi level ε_F and include the Zeeman energy.

The Hamiltonian of the impurity spins situated in a constant field $\mathbf{h}_0$ and the alternating field $\mathbf{h}_1$ ($\mathbf{h}_1\perp\mathbf{h}_0$) is given by

$$H_0^s=-\omega_0\sum_j S_z^j-\omega_1\sum_j(S_+^je^{i\omega t}+S_-^je^{-i\omega t})+H_R, \tag{3}$$

where $\omega_0=\gamma h_0$, $\omega_1=\gamma h_1$, and H_R describes the spin relaxation processes.

The operator H_1, whose form is

$$H_1=\Big(T+T_a\sum_j\Big)\sum_{k,k',\sigma}a_{k\sigma}^+b_{k'\sigma}+\sum_{j,k,k',\sigma,\sigma'}(T_Ja_{k\sigma}^+b_{k'\sigma'}\boldsymbol{\sigma}_{\sigma\sigma'}\mathbf{S}^j)$$
$$+\sum_{j,k,k',\sigma,\sigma'}\Big(\frac{J_a}{2}a_{k\sigma}^+a_{k'\sigma'}+\frac{J_b}{2}b_{k\sigma}^+b_{k'\sigma'}\Big)\boldsymbol{\sigma}_{\sigma\sigma'}\mathbf{S}^j+\text{H.c.}, \tag{4}$$

describes electron tunneling without interaction with the impurities (the terms $\propto T$) and the processes accompanied by magnetic (the terms $\propto T_J$) and nonmagnetic (terms $\propto T_a$) scattering of the electrons by the impurities. The terms proportional to J_a and J_b correspond to reflection of the electrons from the oxide layer on account of the electron interaction with the impurity spins. To simplify the calculations we assume that the impurities are concentrated near the boundary of the a-electrode with the oxide layer ($J_b=0$). No account is taken in the Hamiltonian of the interaction between the impurity spins, or of the multiple scattering of the electrons, since the spin density is assumed to be small. We can therefore omit from the subsequent calculations the summation over the impurities (Σ_j) and multiply in the final expressions the terms with T_a and T_J by the number N_s of the spins on the a-side of the barrier. If the constant field is not uniform, the multiplication by N_s must be replaced by summation with appropriate weighting coefficients determined by the character of the inhomogeneity. An example of such a calculation can be found in Ref. 3. The field inhomogeneity is not taken into account hereafter, so as not to clutter up the result. We confine the analysis for the localized angular momenta to the spin $S=\frac{1}{2}$, and assume in addition that the g-factors of the spins and of the conduction electrons differ enough to make the alternating field nonresonant for the electrons.

The current through the junction is

$$I=-e\langle dN_a/dt\rangle=ie\langle[N_a,H]\rangle,\quad N_a=\sum_{k,\sigma}a_{k\sigma}^+a_{k\sigma}, \tag{5}$$

where $\langle\ldots\rangle=\mathrm{Tr}(\rho\ldots)$ and ρ is the density matrix of the entire system. Owing to the properties of the Hamiltonian (4), the terms I_2 and I_2 in the current $I=I_1+I_2$ through the junction are respectively dependent on and independent of the spin of the impurities. The alternating field influences the current via its influence on the impurity spins, whose contribution to the current

$$I_2=-2eT_J\sum_{k,k',\sigma,\sigma'}\mathrm{Im}\langle a_{k\sigma}^+b_{k'\sigma'}\sigma_{\sigma\sigma'}\mathbf{S}\rangle \tag{6}$$

will be calculated below. The contribution

$$I_1=-2e(T+T_a)\sum_{k,k',\sigma}\mathrm{Im}\langle a_{k\sigma}^+b_{k'\sigma}\rangle \tag{7}$$

remains unchanged when the alternating field is turned on and coincides with the analogous term of the expression obtained in Ref. 2 for the current.

3. It is expedient to calculate the mean values in (6) in the so-called "double rotating coordinate system" (DRCS) in the space of the spin variables of the impurity[4]:

$$\langle a_{k\sigma}^+b_{k'\sigma'}S_\alpha\rangle=\mathrm{Sp}\{\tilde\rho(t)a_{k\sigma}^+b_{k'\sigma'}\tilde S_\alpha(t)\}. \tag{8}$$

The conversion to the DRCS is via the transformation

$$\tilde S_\alpha(t)(\tilde\rho(t))=\hat N(t)\hat L\hat R(t)S_\alpha(\rho)\hat R^{-1}(t)\hat L^{-1}\hat N^{-1}(t), \tag{9}$$

where $\hat R(t)=\exp(-i\omega S_z t)$ is the operator of the transition to the coordinate system (RCS) that rotates about the z axis at the frequency ω of the alternating field; $\hat L=\exp(-i\vartheta S_y)$ is the operator of the rotation of the z axis of the RCS to align it with the direction of the effective magnetic field $\mathbf{h}_e=(\Delta^2+\omega_1^2)^{1/2}/\gamma\equiv\omega_e/\gamma$, which lies in the zx plane of the RCS at an angle $\vartheta=\tan^{-1}(\omega_1/\Delta)$, $\Delta=\omega-\omega_0$, with the z axis; $\hat N(t)=\exp(-i\omega_e S_z t)$ is the operator of the transition to a coordinate system that rotates with frequency ω_e around $\mathbf{h}_e$.[4] The use of the DRCS is convenient because the impurity Hamiltonian takes in it the simplest form

$$\tilde H_0^s(t)=\tilde H_R(t),$$

while in the evolution operator of the entire system

$$U(t_i,t_j)=\exp\{iH_0^e(t_i-t_j)\}T\exp\left\{i\int_{t_j}^{t_i}\tilde H_R(t_i)dt_i\right\} \tag{10}$$

we can, by virtue of the smallness of the operator H_R relative to the Zeeman energy of the spin and to the energy H_0^e we can use a perturbation theory in $\tilde H_R(t)$, i.e., in the entire impurity Hamiltonian in the DRCS. We shall use hereafter in the evolution operators the zeroth approximation in $H_R(t)$, since the resultant corrections are small $(\sim(H_R/H_0^s)^2)$. The relaxation processes are thus taken into account by us only in the time evolution of the spin-system density matrix, where their role is essential.

Solving the equation of motion for the density matrix of the system in the DRCS accurate to second order in $\tilde H_1(t)$ we have for the mean value of the arbitrary operator Q

$$\langle Q\rangle=\mathrm{Sp}\{\tilde Q(t)\tilde\rho_0(t)\}-i\int_{-\infty}^{t}dt_1\mathrm{Sp}\{\tilde Q(t)U^+(t,t_1)[\tilde H_1(t_1),\tilde\rho_0(t_1)]U(t,t_1)\}$$
$$-\int_{-\infty}^{t}dt_1\int_{-\infty}^{t_1}dt_2\mathrm{Sp}\{\tilde Q(t)U^+(t,t_1)[\tilde H_1(t_1),U^+(t_1,t_2)[\tilde H_1(t_2),\tilde\rho_0(t_2)]U(t_1,t_2)]\times U(t,t_1)\}, \tag{11}$$

where in accord with the foregoing

$$U(t_i,t_j)=\exp\{iH_0^e(t_i-t_j)\}, \tag{12}$$

$\tilde\rho_0(t)=\rho_0^e\tilde\rho_0^s(t)$, where ρ_0^e is the equilibrium density matrix of the conduction electrons, and $\rho_0^s(t)$ is the density matrix, corresponding to $\tilde H_0^s(t)$, of the impurity spins in the alternating spin. The form of the matrix $\tilde\rho_0(t)$ permits separate averaging over the spin and Fermi operators. The correlators for the electron system are obtained from the equations of motion, and the expressions obtained for them enter in the formula for the current in such a way that their dependence on the electron-spin orientation can be neglected.

4. Retaining in the expressions for I_2 the term that contribute to the conductance $G=\partial I/\partial V$, we obtain the corrections of first and second order in the perturbation H_1:

$$I_2^{(1)}=-4K\,\mathrm{Re}\int_{-\infty}^{\infty}d\varepsilon_k\int_{-\infty}^{\infty}d\varepsilon_{k'}f(\varepsilon_{k'})\int_{-\infty}^{t}dt_1\exp[i(eV+\varepsilon_k-\varepsilon_{k'})(t-t_1)]$$
$$\times[f(\varepsilon_k)(A_1(t,t_1)-A_1(t_1,t))+A_1(t_1,t)], \tag{13}$$
$$A_1(t_i,t_j)=\mathrm{Sp}\{\tilde\rho_0^s(t_i)\tilde{\mathbf S}(t_i)\tilde{\mathbf S}(t_j)\},$$

where $K=eT_J^2\rho_a(\varepsilon_F)\rho_b(\varepsilon_F)N_s$, $\rho_{a,b}(\varepsilon_F)$ are the state densities in the metals a and b, and $f(x)$ is the Fermi function, while

$$I_2^{(2)}=-4KJ_a\,\mathrm{Re}\int_{-\infty}^{\infty}d\varepsilon_k\int_{-\infty}^{\infty}d\varepsilon_l\int_{-\infty}^{\infty}d\varepsilon_{k'}f(\varepsilon_{k'})\int_{-\infty}^{t}dt_1\int_{-\infty}^{t_1}dt_2\exp[i(eV+\varepsilon_k-\varepsilon_{k'})(t-t_1)]$$
$$\times\{\exp[i(\varepsilon_k-\varepsilon_l)(t_1-t_2)][f(\varepsilon_l)B_1+f(\varepsilon_k)B_2-f(\varepsilon_l)f(\varepsilon_k)(B_1+B_2)]$$
$$+\exp[i(eV+\varepsilon_l-\varepsilon_{k'})(t_1-t_2)][f(\varepsilon_l)B_3-f(\varepsilon_k)B_1+f(\varepsilon_l)f(\varepsilon_k)(B_1+B_2)]\},$$

where the time dependent functions B_1, B_2, and B_3 are defined as follows:

$$B_1=A_2(t_2,t_1,t)+A_2(t_2,t,t_1),\quad B_2=A_2(t,t_1,t_2)+A_2(t_1,t,t_2),$$
$$B_3=A_2(t_2,t_1,t)-A_2(t_1,t,t_2);\ A_2(t_i,t_j,t_k)=\mathrm{Sp}\{\tilde\rho_0^s(t_2)\tilde{\mathbf S}(t_i)[\tilde{\mathbf S}(t_j)\tilde{\mathbf S}(t_k)]\}. \tag{14}$$

To calculate the quantities A_1 and A_2 in (13) and (14) we use the well-known expression for the density matrix in the RCS.[5] To this end, we subject A_1 and A_2 to the following identity transformation:

$$\mathrm{Sp}\{\tilde\rho_0^s(t_2)\tilde S_\alpha(t_i)\tilde S_\beta(t_j)\tilde S_\gamma(t_k)\}$$
$$\equiv\mathrm{Sp}\{\hat N(t_2)\hat L\rho^s_{0\,\mathrm{RCS}}(t_2)\hat L^{-1}\hat N^{-1}(t_2)\tilde S_\alpha(t_i)\tilde S_\beta(t_j)\tilde S_\gamma(t_k)\}$$
$$\equiv\mathrm{Sp}\{\rho^s_{0\,\mathrm{RCS}}(t_2)\hat L^{-1}\hat N^{-1}(t_2)\tilde S_\alpha(t_i)\tilde S_\beta(t_j)\tilde S_\gamma(t_k)\hat N(t_2)\hat L\}. \tag{15}$$

In the case of the spin-phonon relaxation mechanism, neglecting the spin-spin interaction for a spin $S=\frac{1}{2}$ in the stationary regime, the matrix elements $\rho^s_{0\mathrm{rcs}}$ are independent of time and are given by

$$\rho_{11}-\rho_{22}=\mathrm{th}\frac{\omega_0}{2\Theta}\left(\frac{1+\Delta^2\tau_2^2}{1+\Delta^2\tau_2^2+\omega_1^2\tau_1\tau_2}\right),\quad\rho_{11}+\rho_{22}=1,$$
$$\rho_{12}=\rho_{21}^*=-\frac{1}{2}\mathrm{th}\frac{\omega_0}{2\Theta}\left(\frac{\omega_1\tau_2}{1+\Delta^2\tau_2^2+\omega_1^2\tau_1\tau_2}\right), \tag{16}$$

where τ_1 and τ_2 are the times of the longitudinal and transverse spin relaxation, and Θ is the temperature. Substituting (16) and (15) in (13) and (14), we obtain an equation for the conductance of the junction:

$$G=G_1+G_2^{(1)}+G_2^{(2)}. \tag{17}$$

The term G_1 corresponds to the contribution I_1 to the tunnel current, and its value according to Ref. 2 is

$$G_1=4\pi e^2\rho_a(\varepsilon_F)\rho_b(\varepsilon_F)\left[T^2+N^s(T_a^2+2TT_a)\right]. \tag{18}$$

The contributions to G corresponding to $I_2^{(1)}$ and $I_2^{(2)}$ take the form

$$G_2^{(1)}=\pi eK\{3-{}^1/_2(\rho_{11}-\rho_{22})[Y(eV)+Y(-eV)]\},$$
$$Y(eV)=\sin^2\vartheta\,\mathrm{th}\,\varphi_{10}+2\cos^4\frac{\vartheta}{2}\,\mathrm{th}\,\varphi_{11}+2\sin^4\frac{\vartheta}{2}\,\mathrm{th}\,\varphi_{1-1}; \tag{19}$$

$$G_2^{(2)}=-2\pi eJ_aK[Z_0(eV)+Z_0(-eV)+Z_1(eV)+Z_1(-eV)], \tag{20}$$
$$Z_0(eV)=\cos\vartheta\left\{\cos\vartheta-(\rho_{11}-\rho_{22})\left[\cos^4\frac{\vartheta}{2}\,\mathrm{th}\,\varphi_{11}-\sin^4\frac{\vartheta}{2}\,\mathrm{th}\,\varphi_{1-1}\right]\right\}F(\varphi_{00})$$
$$+\sin^2\vartheta\left\{1-\frac{1}{2}(\rho_{11}-\rho_{22})\left[\sin^2\frac{\vartheta}{2}(\mathrm{th}\,\varphi_{10}-\mathrm{th}\,\varphi_{-11})+\cos^2\frac{\vartheta}{2}(\mathrm{th}\,\varphi_{11}-\mathrm{th}\,\varphi_{-10})\right]\right\}F(\varphi_{01}),$$
$$Z_1(eV)=\sin^2\vartheta\left\{1-\frac{1}{2}(\rho_{11}-\rho_{22})\left[\sin^2\frac{\vartheta}{2}\,\mathrm{th}\,\varphi_{1-1}+\cos^2\frac{\vartheta}{2}\,\mathrm{th}\,\varphi_{11}\right]\right\}F(\varphi_{10})$$
$$+\cos^4\frac{\vartheta}{2}\left\{2-(\rho_{11}-\rho_{22})\left[2\sin^2\frac{\vartheta}{2}\,\mathrm{th}\,\varphi_{10}+\cos\vartheta\,\mathrm{th}\,\varphi_{11}\right]\right\}F(\varphi_{11})$$
$$+\sin^4\frac{\vartheta}{2}\left\{2-(\rho_{11}-\rho_{22})\left[2\cos^2\frac{\vartheta}{2}\,\mathrm{th}\,\varphi_{10}-\cos\vartheta\,\mathrm{th}\,\varphi_{1-1}\right]\right\}F(\varphi_{1-1}),$$
$$F(\varphi_{\alpha\beta})=-\int_{-\infty}^{\infty}\frac{\partial f(x-2\Theta\varphi_{\alpha\beta})}{\partial x}g(x)\,dx,\quad g(x)=\int_{-E_0}^{E_0}\frac{f(y)\rho(y)}{y-x}dy,$$
$$\varphi_{\alpha\beta}=\frac{eV+\alpha\omega+\beta\omega_e}{2\Theta},\quad \alpha(\beta)=0,\pm1.$$

In the calculations that follow we use the approximation

$$F(\varphi_{\alpha\beta})\cong\rho(\varepsilon_F)\ln\left[\frac{2\Theta}{E_0}(0{,}675+|\varphi_{\alpha\beta}|)\right], \tag{21}$$

where E_0 is a cutoff parameter. We have left out of (19) and (20) the terms due to the off-diagonal matrix elements of the density matrix (16). Estimates for the region where the alternating field affects most the anomalies of the conductivity (the region of saturation of the magnetic resonance) show these terms to be small.

We note that at low alternating-field amplitudes ($\omega_1\to 0$) or in the case of nonresonant saturation ($|\Delta|\to\infty$) the expressions for the conductivity of the tunnel junction coincide exactly with the result of Refs. 2 for $S=\frac{1}{2}$.

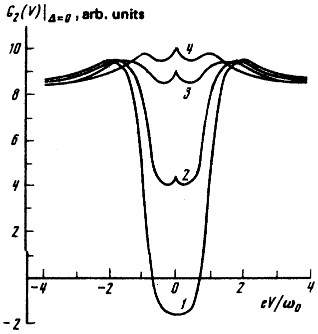

FIG. 1. Dependence of the conductance $G^2(V)|_{\Delta=0}$ on the applied voltage at various values of the saturation factor $z=\omega_1^2\tau_1\tau_2$ (Θ = 0.3 K, $\omega_0 = 3.75\times10^{10}$ Hz): 1) z = 0, 2) z = 1, 3) z = 10, 4) $z=\infty$.

5. Formulas (19) and (20) yield an expression for the conductivity of a tunnel junction with magnetic impurities in a constant and alternating magnetic fields. We shall discuss two of their results, which in our opinion are of greatest interest. The first is the dependence of the conductivity on the applied voltage at various levels of the impurity spin-resonance saturation. It is natural to expect a maximum influence of the alternating field on the behavior of the conductivity under resonance conditions ($\Delta=0$). Recognizing that $\omega_0\gg\omega$ and that for reasonable values $\omega_1\ll\Theta$, we obtain from (19) and (20)

$$G_2(V)|_{\Delta=0}=G_2^{(1)}(V)|_{\Delta=0}+G_2^{(2)}(V)|_{\Delta=0},$$
$$G_2^{(1)}(V)|_{\Delta=0}=\pi eK\left[3-\frac{1}{1+z}\,\mathrm{th}\frac{\omega_0}{2\Theta}(\mathrm{th}\,\varphi_1^0-\mathrm{th}\,\varphi_{-1}^0)\right], \tag{22}$$
$$G_2^{(2)}(V)|_{\Delta=0}=-2e\pi J_aK\left\{\left[2-\frac{1}{1+z}\,\mathrm{th}\frac{\omega_0}{2\Theta}(\mathrm{th}\,\varphi_1^0-\mathrm{th}\,\varphi_{-1}^0)\right]F(\varphi_0^0)\right.$$
$$\left.+\left[2-\frac{1}{1+z}\,\mathrm{th}\frac{\omega_0}{2\Theta}\,\mathrm{th}\,\varphi_1^0\right]F(\varphi_1^0)+\left[2+\frac{1}{1+z}\,\mathrm{th}\frac{\omega_0}{2\Theta}\,\mathrm{th}\,\varphi_{-1}^0\right]F(\varphi_{-1}^0)\right\}$$

where $\varphi_\alpha^0=(eV+\alpha\omega_0)/2\Theta$, α = 0 and ±1, and $z=\omega_1^2\tau_1\tau_2$ is the saturation factor.

The conductance component that depends on the voltage V is shown in Fig. 1. In the numerical calculations we used in (19) and (20) at the parameters E_0 = 10 MeV and $J_a\rho(\varepsilon_F)$ = 0.01, which correspond to the experimental situation.[2] It is seen from the figure that with increasing power of the RF field the conductivity increases in the vicinity of V=0. The physical reason is that the alternating field decreases the difference between the populations of the Zeeman sublevels, and this difference determines $G_2(0)$. Thus, when the RF field is turned on we obtain not the two peaks whose position is determined in the constant field by the spin splitting, but three peaks, with the amplitude strongly dependent on the magnetic-resonance saturation levels. We note that the change of the amplitude of the central peak is comparable in magnitude with the observed anomalies.

Obviously, detuning from resonance (increase of $|\Delta|$) leads to a decrease of the degree of saturation of the spin system. One can therefore expect the dependence of the conductivity on the alternating-field frequency to be resonant. The maximum influence of the resonance saturation on the conductivity occurs in the vicinity of V=0 (see Fig. 1), so that an examination of the dependence of just $G_2(0)$ on Δ is in order. Setting V in (19) and (20) equal to zero, we obtain the plot, shown in

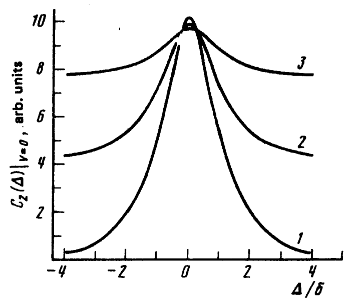

FIG. 2. Amplitude of G^2 at V = 0 as a function of Δ for different temperatures ($\omega_0 = 3.75\times10^{10}$ Hz, $h_0\sim 13$ kG; $\omega^1 = 1.25\times10^6$ Hz, $h^1\sim 1$ G; $\delta = 1.25\times10^6$ Hz; z = 10): 1) Θ = 0.5 K, 2) Θ = 1 K, 3) Θ = 2 K.

Fig. 2, of $G_2(\Delta)|_{V=0}$ on the detuning from resonance at various temperatures but at a constant saturation level $z=10$.

In the limit $\omega_0 \gg \Theta$ and $\omega_e \ll \Theta$ we get for $G_2(\Delta)|_{V=0}$ the simple expression

$$G_2(\Delta)|_{V=0} \approx \pi e K\{[1-4J_a F(\omega_0/2\Theta)] \\ +2[1-2J_a(F(0)+F(\omega_0/2\Theta))][1-(\rho_{11}-\rho_{22})]\}, \quad (23)$$

$$[1-(\rho_{11}-\rho_{22})] \approx \frac{\omega_1^2\tau_1\tau_2}{1+\omega_1^2\tau_1\tau_2+\Delta^2\tau_2^2},$$

which corresponds to the standard magnetic-resonance line shape under saturation conditions. The width δ of this line is determined by the alternating-field amplitude and by the relaxation times:

$$\delta=\omega_1(\tau_1/\tau_2)^{1/2}. \quad (24)$$

Comparison of the approximate result (23) with the conductance $G_2(\Delta)|_{V=0}$ calculated from (19) and (20) shows that the width of the real resonance curve practically coincides with (24).

Thus, an investigation of the function $G_2(\Delta)|_{V=0}$ at sufficiently low temperatures ($\tanh(\omega_0/2\Theta) \sim 1$) makes it possible in principle to study the resonance characteristics of spins localized inside a tunnel junction. The sensitivity of the method proposed for detecting the magnetic resonance may turn out to be very high. As already noted, the resonance signal is comparable with the tunnel-conductivity peaks, which are reliably observed at a rather small number of impurity moments. For example, it follows from the data of Bermon *et al.*[6] that the presence of 10^{11} iron ions in the oxide layer of an $Al-Al_2O-Al$ junction leads to a considerable amplitude of the conductivity anomalies. Under the experimental conditions of Ref. 6, the iron ions are concentrated in a narrow layer, and this makes it necessary to take into account the interaction between the impurity spins, something not done in our model. Allowance for the spin-spin interaction, however, does not alter the result qualitatively, and furthermore the number 10^{11} is apparently not the lowest one at which anomalies in the conductivity can be observed. At the same time, for typical parameters, for modern EPR installations $5\times10^{10}-10^{11}$ spins is the limit.

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Surface absorption of electromagnetic waves in metals by random boundary inhomogeneities

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Absorption of an electromagnetic wave by scattering of grazing electrons by random inhomogeneities of the surface of a metal, in a parallel magnetic field, is investigated theoretically. On the basis of diffraction theory, the effective electronic diffusivity coefficient of a slightly rough boundary is found as a function of its statistical characteristics. Additivity is established for the contributions of volume and surface collisions to the electromagnetic absorption, and the possibility is demonstrated of introducting a surface scattering frequency $\nu_a^{(s)}$ of the grazing electrons. The dependence of the surface impedance, the diffusivity coefficient, and the frequency $\nu_a^{(s)}$ on the mean height and length of the irregularities, the constant magnetic field, and the skin thickness, frequency, and polarization of the external electromagnetic field is determined and analyzed. It is shown that there exists a quite broad range of values of the parameters within which surface scattering of electrons dominates over volume scattering.

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1. INTRODUCTION

Interaction of electrons with the specimen surface exerts a substantial influence on the high-frequency properties of metals in a magnetic field **H**. As an example, we mention a number of papers[1-7] in which the role of reflection of electrons from a metal boundary in the phenomenon of cyclotron resonance was investigated. When the reflection is nearly specular, the character of the resonance changes because of the appearance in the

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