Kinetics of conduction electrons in multidomain ferromagnetic structures

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The kinetics of conduction electrons in ferromagnetic conductors with a periodic domain structure is considered. It is shown that the specific distribution of the magnetic induction leads to resonance absorption of an electromagnetic field at a frequency which depends on the domain structure period $\omega_{res} = \pi v_F/d$ (v_F is the charge carrier Fermi velocity and $2d$ is the domain structure period). The shape of the resonance absorption line is found.

1. FORMULATION OF PROBLEM. CHOICE OF MODEL

As is well known, a multidomain ferromagnet is characterized by spatial periodicity of the magnetic induction. This special form of the inhomogeneity of the magnetic induction causes the dynamics of conduction electrons to have interesting features[1]. A new parameter with dimension of length, namely the period 2d of the domain structure (d is the dimension of the domain) comes into play in the problem of electron motion in a magnetic field. Depending on the relation between this parameter and the cyclotron radius $R = cP_\perp/eB$ (c is the speed of light, e is the electron charge, $\mathbf{P}_\perp$ is the projection of the electron momentum on a plane perpendicular to B), we can distinguish between three electron groups whose trajectories differ qualitatively from one another. The kinetic properties of the electron system differ in this case strongly from the effects in a homogeneous magnetic field and depend on the period of the domain structure.

In the analysis that follows, we replace the exact distribution of the magnetic induction by the model distribution (Fig. 1)

$$B(x) = B_z(x) = B_0 \operatorname{sign} \sin(\pi x/d). \tag{1.1}$$

The z axis is directed along the easy axis of the magnet, and the x axis is perpendicular to the phase-separation plane. In this model, no account is taken of the distortion of the domain structure near the surface of the sample, nor is the influence of the domain boundaries on the influence of the conduction electrons taken into account. The surface distortion of the magnetic structure influences strongly the kinetic effects in the case when the perturbation of the electron subsystem takes place in a narrow surface layer of the sample (of width ~d). In the case when the characteristic depth of the perturbation of the electron system greatly exceeds the dimension of the domain, the distortion of the magnetic structure is a surface effect and can be neglected. The influence of the domain walls on the motion of the conduction electrons reduces in the main to the following.

1) The trajectories are bent within the limits of the domain wall. For this effect to be negligible it is necessary to have

$$\delta_0/v_x \ll \Omega_0^{-1}, \quad \Omega_0 = eB_0/mc, \tag{1.2}$$

where δ_0 is the width of the domain wall, v_x is the electron velocity in the x direction, and Ω_0 is the cyclotron frequency.

2) If the temperature of the sample is much lower than the Curie temperature, then the Landau-Lifshitz solution[2] holds in the domain wall, and the magnetic moment changes only in direction. In this case, forces connected with the "disorientation" of the electron spin and of the vector of the magnetic induction B come into play. However, the exchange interaction of the conduction electrons with the lattice atom, under the condition

$$\hbar v_x/I\delta_0 \ll 1 \tag{1.3}$$

ensures that the spin "follows" adiabatically the direction of the magnetic induction during the course of the electron motion[3] ($I \cong 0.1$ eV is the exchange integral).

3) The electrons are scattered by spin waves propagating in the domain wall. However, as shown by Turov and Voloshinskiĭ[4], the effectiveness of this scattering decreases with temperature T like $T^{3/2}$, and at sufficiently low temperatures this effect can be neglected.

The inequality (1.2) ceases to be satisfied for a very small group of electrons with small v_x, the contribution of which to the kinetic effect is negligible. The condition (1.3) is satisfied for the electron groups that will be considered from now on.

2. RESONANT ABSORPTION OF HIGH-FREQUENCY FIELD

One of the simplest kinetic effects illustrating clearly the features of the system under consideration is absorption of a high-frequency electromagnetic field (frequency ω) under conditions of the normal skin effect. The most interesting is the case when

$$d \ll l \ll \delta_{sk}, \tag{2.1}$$

where l is the mean free path and δ_{sk} is the depth of the skin layer.

The left-hand inequality, as will be seen from what follows, ensures a sufficiently sharp resonance absorption. The right-hand inequality corresponds to the normal skin effect and is satisfied for conductors with sufficiently low carrier density or for doped semiconductors.

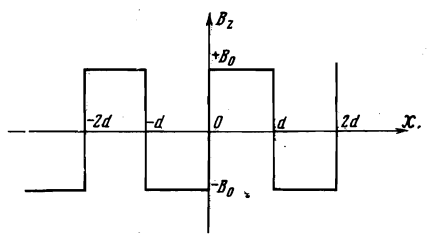

FIG. 1. Coordinate dependence of the magnetic induction.

The kinetic equation for the nonequilibrium increment f to the electron distribution function, linearized with respect to the external field, is

$$(\nu - i\omega)f + v_x \partial f/\partial x + \Omega(x)\partial f/\partial\varphi = -e\mathbf{E}\mathbf{v}\,\partial f_0/\partial\varepsilon, \qquad (2.2)$$

$$f(\varphi + 2\pi) = f(\varphi), \quad f(x + 2d) = f(x). \qquad (2.3)$$

Here ν is the frequency of the collisions with the scatterers, E is the amplitude of the external monochromatic field of frequency ω, φ is the angle in momentum space, $\tan\varphi = v_y/v_x$, f_0 is the equilibrium electron distribution function, and

$$\Omega(x) = eB(x)/mc = \Omega_0 \operatorname{sign}[\sin(\pi x/d)]. \qquad (2.4)$$

The boundary conditions (2.3) with respect to the coordinate x reflect the periodicity of the distribution of the magnetic induction in the conductor.

The motion of the electron in the field (1.1) is along a circular arc so long as the electron is within the confines of one domain. When the domain wall is crossed, the curvature of the trajectory reverses sign. It is convenient to classify the electron trajectories in terms of the rotation-center coordinate x reckoned from the nearest domain boundary (on the left):

$$X = x - dE(x/d) - R\sin\varphi, \qquad (2.5)$$

where x is the coordinate of the electron, φ determines the direction of the velocity at the point x, and E(x/d) is an integer defined in such a way that

$$0 \leqslant x/d - E(x/d) < 1.$$

Depending on the type of trajectory, the electron motion can be broken up into three groups.

The first group (Fig. 2) is made up of electrons that rotate in circles in the xy plane and do not touch the domain walls. For these electrons we have

$$-R < X < d - R. \qquad (2.6)$$

The second group (Fig. 3) is made up of electrons with either

$$0 < X < R,\ d - R, \qquad (2.7)$$

or

$$R,\ d - R < X < d. \qquad (2.8)$$

These electrons execute infinite motion along the domain wall, whereas their motion in the direction of the periodicity of the magnetic structure (the x axis) is finite.

The third and most interesting electron group (Fig. 4) is defined by the condition

$$d - R < X < R. \qquad (2.9)$$

These electrons execute infinite motion along the x axis and "feel" the periodicity of the domain structure. The electron velocity is periodic (with period 2d) as a function of the coordinate x on the trajectory of motion, as the result of which the electrons of the third group make a special resonant contribution to the absorption of the high-frequency field.

After solving equation (2.2) with conditions (2.3), we can calculate the electric conductivity tensor $\sigma_{ik}(\omega, x)$. The contributions of the three electron groups differ qualitatively from one another. In the case of quadratic dispersion, the expression for $\sigma_{ik}(\omega, x)$ is

$$\sigma_{ik}(\omega, x) = \sigma_{ik}^{(1)}(\omega) + \sigma_{ik}^{(2)}(\omega, x) + \sigma_{ik}^{(3)}(\omega, x), \qquad (2.10)$$

where $\sigma_{ik}^{(m)}$ is the contribution made to the electric conductivity by the m-th group of electrons:

$$\sigma_{ik}^{(1)} = \sigma_{ik}^{0}\Phi_{ik}^{(1)}, \quad \sigma_{ik}^{(2)} = \sigma_{ik}^{0}[\Phi_{ik}^{(2)} + \Phi_{ik}^{(3)}], \quad \sigma_{ik}^{(3)} = \sigma_{ik}^{0}[\Phi_{ik}^{(4)} + \Phi_{ik}^{(5)}], \qquad (2.11)$$

$$\Phi_{ik}^{(l)} = A_{ik}^{-1}\Omega_0^{-1}\int_{L_l} d^3p\left(-\frac{\partial f_0}{\partial\varepsilon}\right)v_i\int_{-\infty}^{0} ds\, V_k^{(l)}(s, x, p)\exp\left[\frac{\nu - i\omega}{\Omega_0}s\right], \qquad (2.12)$$

$$V_x^{(l)} = v_\perp\cos\varphi^{(l)}(s), \quad V_y^{(l)} = v_\perp\sin\varphi^{(l)}(s), \quad V_z^{(l)} = v_z, \qquad (2.13)$$

$$\varphi^{(l)}(s) = \begin{cases} s & \text{if } l = 1 \\ \varphi_{(+)}^{(l)} - \dfrac{2}{\pi}\varphi_{(-)}^{(l)}\arcsin\left[\cos\dfrac{\pi}{2}\dfrac{s - s^{(l)}(x)}{\varphi_{(-)}^{(l)}}\right], \end{cases} \qquad (2.14)$$

$$s^{(l)}(x) = \begin{cases} \varphi_2^{(l)} - \varphi & \text{for } \Omega(x)/\Omega_0 > 0 \\ \varphi - \varphi_2^{(l)} & \text{for } \Omega(x)/\Omega_0 < 0 \end{cases}; \qquad (2.15)$$

$$\varphi_{(\pm)}^{(l)} = {}^1/_2[\varphi_1^{(l)} \pm \varphi_2^{(l)}], \qquad (2.16)$$

$$\begin{aligned} &\varphi_1^{(2)} = \pi - \alpha_{(-)}, \quad \varphi_1^{(3)} = \varphi_1^{(4)} = \alpha_{(+)}, \quad \varphi_1^{(5)} = \pi - \alpha_{(+)}, \\ &\varphi_2^{(2)} = \varphi_2^{(4)} = \alpha_{(-)}, \quad \varphi_2^{(3)} = \pi - \alpha_{(+)}, \quad \varphi_2^{(5)} = \pi - \alpha_{(-)}, \end{aligned} \qquad (2.17)$$

$$\alpha_{(\pm)} = \arcsin\left\{\sin\varphi + \frac{d}{\pi R}\left[\arcsin\left(\cos\frac{\pi x}{d}\right) \pm \frac{\pi}{2}\right]\right\}. \qquad (2.18)$$

The tensor A_{ik} is obtained from the normalization condition

$$\sum_{l=1}^{5}\Phi_{ik}^{(l)} = 1, \quad \omega = 0,$$

where σ_{ik}^0 is the static electric-conductivity tensor. The symbol L_e in the integral of (2.12) means that integration in the formula is limited by the following conditions: (2.6) for L_1, (2.7) for L_2, (2.8) for L_3, (2.9) and $-\pi/2 \leq \varphi \leq \pi/2$ for L_4, and (2.9) and $\pi/2 \leq \varphi \leq 3\pi/2$ for L_5.

An analysis of (2.11)–(2.18) shows that the contribution of the electrons of the first group $\sigma_{ik}^{(1)}$ describes the usual diamagnetic resonance in the absorption of the electromagnetic field, since near the resonant frequency $\omega_{res} = \Omega_0$ we obtain for the high-frequency power absorbed by the first group of electrons

$$Q_1 = \frac{1}{2}\sum_{i,k}E_iE_k\operatorname{Re}\sigma_{ik}^{(1)} \cong \frac{\nu}{\nu^2 + (\omega - \Omega_0)^2}\sum_{i,k}\gamma_{ik}E_iE_k,$$
$$\gamma_{ik} = \sigma_{ik}^0 A_{ik}^{-1}\int_{L_1} d^3p\left(-\frac{\partial f_0}{\partial\varepsilon}\right)v_iv_k. \qquad (2.19)$$

The kinetic properties of the electrons of the second group recall the properties of surface electrons in metals. The local power $Q_2(x)$ absorbed by this group has a resonant character, but the resonance frequency depends on the coordinate x of the observation point. Therefore, after averaging $Q_2(x)$ over the period of the domain structure, the resonant singularity becomes smoother. Strictly speaking, the treatment of this group of electrons within the framework of the chosen model is not fully justified, since it includes glancing electrons for which the condition (1.2) are not satisfied, and it is necessary to provide details of the domain-wall structure. A rigorous analysis of this group of electrons is contained in the paper by Mints[5].

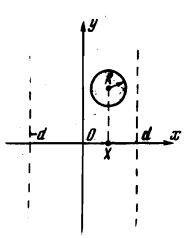

FIG. 2

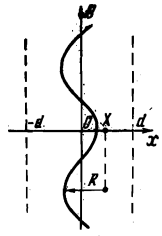

FIG. 3

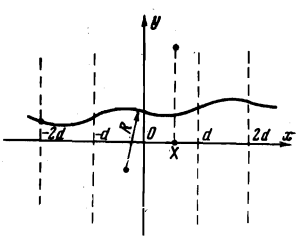

FIG. 4

FIG. 2. Trajectories of electrons that do not cross domain walls.

FIG. 3. Typical trajectory of electrons that execute infinite motion only along the domain wall.

FIG. 4. Trajectory of electron motion that is infinite in the periodicity direction.

Greatest interest attaches to the contribution of the electrons of the third group. Analysis of expressions (2.11)–(2.18) shows that only the component $\sigma_{xx}^{(3)}$ has a singularity after averaging over the period of the domain structure. This singularity occurs only at temperatures much lower than the degeneracy temperature. At higher temperatures, the singularity due to the integration with respect to energy in (2.12) vanishes. The final result assumes the simplest form when

$$v_F / \Omega_0 d \gg 1. \tag{2.20}$$

In this limit, the resonant contribution to the absorption is given by

$$Q_3(\omega) = {}^1/_2 (\mathrm{Re}\,\sigma_{xx}^{(3)}) E_x^2; \tag{2.21}$$

$$\mathrm{Re}\,\sigma_{xx}^{(3)} \cong \sigma_0 \frac{2e_F}{A_{xx}} \iint dp_z\, d\varphi \frac{\nu}{\nu^2 + (\omega - \omega_0)^2}, \qquad \omega_0 = \pi \frac{v_F}{d} \frac{p_\perp}{p} \cos\varphi, \tag{2.22}$$

$$\sigma_0 = \sigma_{xx}^0 \frac{2}{d^2} \int_0^d \int_0^d dx\, dx' \frac{V_x^{(4)}(x, x', \varphi = 0, p_z = 0)}{v_F} \cos\frac{\pi x}{d} \cos\frac{\pi x'}{d}, \tag{2.23}$$

$$x' = v_F s / \Omega_0 + x. \tag{2.24}$$

It is seen from (2.23) that the resonance frequency ω_0 as a function of p_Z and φ has a maximum at the point φ, $p_Z = 0$. In this case as shown by Kaner et al.[6], the shape of the resonance-absorption line is asymmetrical and is given by

$$Q_3(\omega) \cong KE_x^2 \left(1 + \frac{2}{\pi} \mathrm{arctg} \frac{\omega_{res} - \omega}{\nu}\right), \tag{2.25}$$

$$K = \frac{4}{\pi} \left(\frac{\Omega_0 d}{v_F}\right)^2 \frac{p_F^2 d}{A_{xx}} \varphi_{xx}^0, \tag{2.26}$$

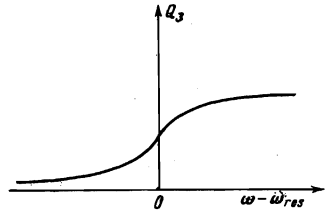

FIG. 5. Shape of resonance-absorption curve.

where the resonance frequency ω_{res} is given by

$$\omega_{res} = \pi v_F / d. \tag{2.27}$$

As seen from (2.25), the amplitude of the resonance absorption depends strongly on the orientation of the polarization vector of the absorbed wave relative to the domain structure, and the resonance frequency is simply connected with the dimension of the domain. A plot of the resonance curve is shown in Fig. 5.

The considered effect is an illustration of the singularity of the kinetics of the electrons in multidomain structures. A similar resonance effect should take place also in the absorption of sound.

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[1] A. S. Rozhavskiĭ and R. I. Shekhter, Sol. State Comm. 12, 603 (1973).
[2] L. D. Landau and E. M. Lifshitz, Phys. Zs. Sowjet 8, 153 (1935).
[3] Yu. I. Balkareĭ and L. N. Bulaevskiĭ, Fiz. Tverd. Tela 14, 2407 (1972) [Sov. Phys.-Solid State 14, 2081 (1973)].
[4] E. A. Turov and N. A. Voloshinskiĭ, Trudy 10-ĭ Mezhdunarodnoĭ konferentsii po fizike nizkikh temperatur, (Proc. 10-th Internat. Conf. on Low Temperature Physics), LT-10, Vol. 4, A16, 105 VINITI, 1967.
[5] R. G. Mints, ZhETF Pis. Red. 9, 629 (1969) [Sov. Phys.-JETP Lett. 9, 387 (1969)].
[6] É. A. Kaner, O. I. Lyubimov, I. E. Aronov, and R. I. Shekhter, Fiz. Tekh. Poluprov. 4, 57 (1970) [Sov. Phys.-Semicond. 4, 43 (1970)].

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