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Investigation of the applicability of the vortex model for bridge junctions of superconductors with the A-15 lattice

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The properties of V_3Si bridge junctions of variable thickness prepared by the double-scribing method are studied. The current–voltage characteristics (CVC) and the temperature dependence of the critical current are measured for such junctions, and the nature of the interaction of the vortex structure with a variable electromagnetic field is investigated. Characteristic current steps are observed on the CVC, and it is shown that the model based on the movement of a chain of Abrikosov vortices through the junction agrees well with the experimental data. Some parameters of the motion of the vortices are estimated on the basis of this model.

PACS numbers: 74.50. + r, 85.25. + k, 74.90. + n

INTRODUCTION

The present paper is devoted to the study of the properties of bridges made of high-temperature superconductors with the A-15 structure. The interest in these materials is due to their high critical parameters, which opens up areas of application inaccessible to ordinary superconductors. Furthermore, superconductors with the A-15 lattice possess a number of other anomalous properties,[1-3] and this makes them interesting objects of physical investigation. One of such properties is the smallness of the coherence length ξ_0 (~30 Å), which is connected with the smallness of the conduction-electron concentration. This should lead to a number of peculiarities in the manifestation of the Josephson effect in such systems.

In our previous investigations[4-7] we studied in detail the properties of Nb_3Sn bridge junctions. It was shown that these junctions are well described by the vortex model.[7-9] The purpose of the present investigation was to verify the generality of the vortex model for these superconductors. The investigation was carried out on bridges made of the V_3Si alloy.

The choice of V_3Si as the object of investigation is due to a number of reasons. First, this superconductor belongs to a group of vanadium high-temperature superconducting compounds whose physical characteristics differ somewhat from the characteristics of the niobium compounds. In V_3Si we have the highest value of the critical temperature T_c among the vanadium alloys. Second, as far as we know, no attempts have thus far been made to produce bridge junctions from the vanadium compounds and investigate their properties. Third, the relative closeness of the melting (and vaporization) points of vanadium and silicon allows us to use, in preparing the alloy films, the method of vaporization from one source, which ensures higher sample homogeneity in comparison with the method of vaporization of the components from different sources.

In the present paper we propose a method for fabricating V_3Si bridges, study the temperature dependence of their critical current, the shape of the current-voltage characteristics (CVC), and the nature of the interaction of such bridge junctions with electromagnetic radiation, and determine the parameters of the vortex motion in the bridges.

EXPERIMENT

V_3Si films were prepared by the method proposed in Ref. 10. In this case the evaporation of the drop prepared by preliminary fusion of vanadium and silicon was carried out by an electron beam in a 1×10^{-5}-Torr vacuum. The alloy films were deposited on heated ruby, sapphire, and quartz substrates. The optimal temperature of the substrates was 1100 °C. The rate of deposition was 100 Å/sec and the thicknesses of the prepared films were $0.2-0.8\ \mu$. For the investigation we used films with sufficiently high T_c values. In the best of them T_c attained a value of 17 K (at the beginning of the transition) for a transition width of 1 K. The V_3Si microbridges were prepared by the double-scribing method.[7,11] Bridges of width from 1 to 30 μ and length $1-2\ \mu$ were fabricated by this method.

The apparatus for, and the scheme of, the measurement of the temperature dependence of the critical current I_c and the CVC of the bridges are described in detail in Ref. 6. The experimental setup for the investigation of the interaction of the bridge junctions with an external SHF field is similar to the setup used by Anderson and Dayem.[12] The experiments were carried out in the 0.4 – 7.6-GHz frequency range. The sample was placed near a loop connected to a coaxial cable that joined the cryostat to the microwave generator. The radiated power was measured at the output end of the generator by a "Measurer of low powers" of the type MZ-1A. The experiments were performed in the temperature range $T = 13 - 20.3$ K. As the cooling agent we used hydrogen. The temperature was determined from the hydrogen-vapor pressure with the aid of a carbon thermometer.

RESULTS

1. The dependence of the strength, I_c, of the critical current on T obeys well in a wide range of temperatures the law $I_c(T) \propto (T_{cb} - T)^{\alpha}$, where T_{cb} is the critical temperature of the bridge. For high-T_c samples the quantity $\alpha \approx 2.5$. In Fig. 1 we show the temperature dependence of the critical current for one of such bridges; the solid curve corresponds to the law $I_c(T) \propto (T_{cb} - T)^{2.5}$. The quantity α correlated with the value of the T_c of the films: for films with low $T_c (\lesssim 10$ K) the value of α fell to 1 – 1.5. It should be noted that the critical current density in the V_3Si bridges used attained values $\sim 10^4$ A/cm^2 at $T = 14$ K.

2. The CVC of the V_3Si bridges had the parabolic shape observed earlier for Nb_3Sn bridges.[4] In Fig. 2 we show the CVC of a typical V_3Si bridge junction for different temperatures. We have carried out a computer analysis of a large number of CVC of different V_3Si bridge juctions with the aid of the program described in Ref. 6. It is shown that the CVC are described to within a few percent by the formula

$$I = (\bar{V}/C + I_c^2)^{1/2} + \bar{V}/R_n, \qquad (1)$$

where I is the current through the bridge, $\bar{V}$ is the mean voltage across it, R_n is the normal shunting resistance, and C is some temperature-dependent dimensional coefficient. The analysis revealed the existence of a correlation between C and I_c: as the temperature varies, C also varies roughly according to the law $C \propto 1/I_c$ (see

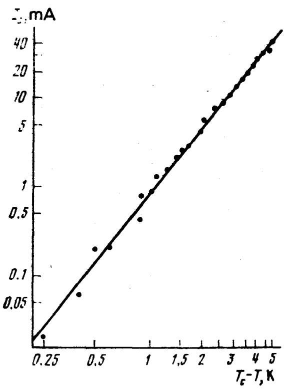

FIG. 1. Temperature dependence of the critical current of one of the V_3Si bridges. The solid curve corresponds to the law $I_c \propto (T_{cb} - T)^{2.5}$.

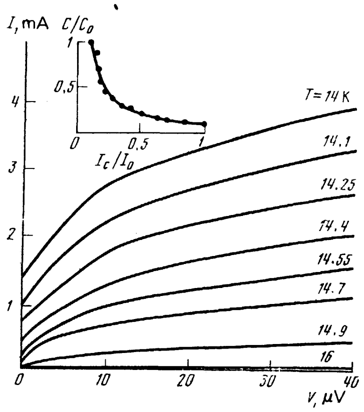

FIG. 2. Current-voltage characteristics of a V_3Si bridge junction for different temperatures. In the insert is shown the dependence of the parameter C on I_c (C_0 and I_0 are some constants). The solid line in the insert corresponds to the law $C \propto I_c^{-1}$.

the insert in Fig. 2). The higher the characteristics (the T_c value, the sharpness of the transition into the superconducting state) of the bridge, the more exactly the inverse-proportionality law between C and I_c is fullfilled.

Let us note that, in the case of the V_3Si films investigated by us, to obtain a nonzero critical current in the bridges in the region of liquid-hydrogen temperatures ($T \geqslant 13.9$ K), the bridge width had to be greater than 5 μ. When the bridge width was decreased below this limit, a sharp decrease in the T_{cb} of the bridge was observed. Usually, for the quantitative measurements we used bridges of width ranging from 5 to 20 μ. Such wide bridges possessed low differential resistances at low voltages.

3. We also performed a series of experiments in which we investigated the nature of the interaction of the vortex structure of the V_3Si bridges with electromagnetic radiation. In a microwave field the CVC of the bridges manifested a steplike structure at voltages corresponding to the Josephson relation

$$V_n = nhf/2e, \qquad (2)$$

where n is a whole number (the step number), h is the

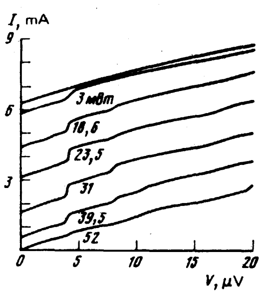

FIG. 3. The CVC of a V_3Si bridge for different SHF-radiation power levels (frequency 1.914 GHz, $T = 13.5$ K). The numbers near the curves indicate the microwave-radiation power, measured at the output end of the generator; the upper curve is the CVC of this junction in zero SHF field.

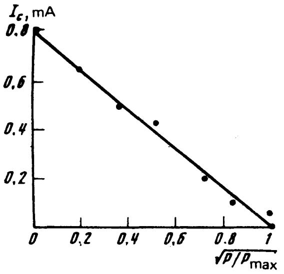

FIG. 4. Dependence of the critical current I_c on $\sqrt{P}$ for one of the V_3Si bridges; P_{max} is the peak microwave-power value.

Planck constant, e is the electron charge, and f is the frequency of the external electromagnetic field.

In Fig. 3 we present examples of the CVC of a V_3Si bridge located in a microwave-radiation field for different microwave-power levels. The radiation frequency was 1.914 GHz, the temperature of the sample 13.5 K. Six-seven steps were observed on the CVC of bridges with sufficiently high differential resistances (R_d) at $\overline{V} \approx 0$.

A study of the dependence of the critical current of the bridges and the amplitudes of the steps on the microwave-radiation power, P, showed that I_c decreases roughly linearly with increasing $\sqrt{P}$. No oscillations in I_c and the amplitudes of the steps were observed here as the power was varied (Fig. 4).

To explain the behavior of superconducting Nb_3Sn bridge junctions in a SHF field, in Ref. 7, a vortex model was constructed on the basis of a theory proposed by Likharev[8] and Aslamazov and Larkin.[9] In this model the appearance of current steps on the CVC is due to the synchronization of the moments of production of the vortices by the microwave field. In Fig. 5 we show CVC computed on the basis of this model. The parameters R_d and I_c of the curve for zero SHF field (the upper curve) correspond to the experimental CVC shown in Fig. 3. The lower curves in Fig. 5 were obtained by successively increasing the amplitude of the alternating current from zero to I_c. The CVC computed on the basis of the vortex model are found to agree (in their general shape, number of steps, step amplitudes, dependence of the microwave-radiation power, etc.) with the experimental curves obtained for V_3Si bridge junctions. The slight difference in step steepness between the experimental and theoretical curves is due to the fact that the vortex model constructed in Ref. 7 does not take account of the effect of fluctuations. In our case, as in the case of microbridges with dimensions $\lesssim \xi$ (the characteristic length for the variation of the order parameter in the Ginzburg-Landau theory), allowance for the fluctuations leads to the washing out of the step structure of the theoretical CVC and an improvement in the agreement with experiment.

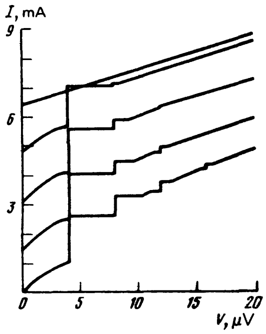

FIG. 5. Calculated—on the basis of the vortex model[7]—CVC of a bridge with the parameters R_d and I_c corresponding to the experimental CVC in Fig. 3. The top curve is for zero microwave field, while the lower curves correspond to different amplitudes (I_f) of a variable current of frequency f.

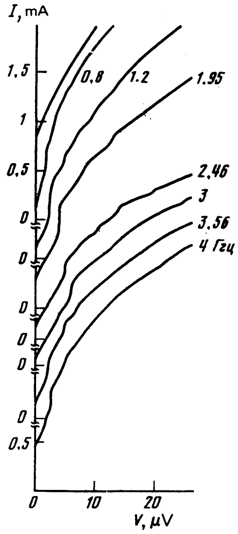

FIG. 6. CVC of a V_3Si bridge junction ($T = 14$ K) corresponding to different SHF-radiation frequencies (the numbers by the curves are the radiation frequencies). The top curve is the CVC of this junction in the absence of a microwave field.

For junctions with low differential resistances (~$10^{-3}\Omega$), it is necessary to take into consideration in the computation the nonlinearity of the CVC at low voltages as well. This refinement of the Golovashkin-Lykov model[7] was made in the first approximation. The most important result of the refinement was the appearance at the voltage $V_2 = hf/e$ of a step with amplitude

$$A = I_f^2/2(hf/Ce + I_c^2)^{1/2}, \tag{3}$$

where I_f is the amplitude of a variable current of frequency f induced by the external microwave field. Allowance for the parabolicity of the CVC improved the agreement of the theory with experiment for such junctions.

Besides the primary structure, the CVC of the V_3Si bridges manifested anomalies at the fractional voltages $V = nhf/2me$, where m is an integer (step subharmonics). The subharmonic structure was especially clearly observed when the radiation frequency was increased.

In Fig. 6 we show the CVC, obtained in a microwave field at different radiation frequencies, of one of the V_3Si junctions. It can be seen from the figure that, as the radiation frequency is increased, the step subharmonics on the CVC become more and more marked, and, starting from some frequency (for the junction to which Fig. 6 corresponds this frequency is equal to 3.5 GHz), they predominate.

For some of the junctions we observed an irregular structure, as distinguished from the regular steplike structure, which is due to the coherent motion of the vortices in the bridge. The curves were similar to the

CVC obtained by Janocko *et al.*[13] on wide Nb_3Ge bridges. The locations of the steps were determined as before by the expression (2), but some of the steps were absent. Also, strong step subharmonics with $m=2$ appeared (also irregularly). Such a picture indicates the absence of total coherence in the motion of the vortices and the fact that partial coherence can be realized under certain conditions. The CVC of some junctions in a microwave field manifested several regularly arranged singularities at the voltages $V=kV_n$, where $k=2$ or 3. Similar curves (with $k=2$) were observed earlier by us on one of the Nb_3Sn bridge junctions.[7] Such singularities are apparently connected with the appearance in the junction of two or three interacting vortex chains. In this case the indicated singularities on the CVC are observed because of the possibility of synchronization, by the external microwave field, of the motion of the vortex lattice formed.

DISCUSSION

1. The results obtained by us on V_3Si bridges agree with the results for Nb_3Sn junctions.[4-7] For the two types of junctions the temperature dependences of I_c near T_c are identical, the shape of the CVC is described with a high degree of accuracy by the same expression, (1), and a steplike structure is observed on the CVC in a microwave field. The investigations carried out showed that the behavior in a microwave field of superconducting bridges of V_3Si, as well as of Nb_3Sn, can be explained with the aid of the vortex model developed in Refs. 7–9. Taking into account the fact that materials with significantly different properties were used, and that the methods of preparation of the films and bridges were different, we must conclude that the observed properties are common to this class of superconductors and that the vortex model describes well the behavior of bridge junctions made of superconductors with the A-15 structure. The observation of a steplike structure on the CVC of V_3Si (and Nb_3Sn) bridges proves that there is produced in the bridges a coherent vortex motion sychronized by the external microwave field.

2. As is well known, in the nonstationary Josephson effect, one of the most important parameters determining the high-frequency properties of the "weak" coupling elements is the characteristic-voltage strength $V_c=I_cR_n$. In bridges made of superconductors with the A-15 structure, this quantity can, as a result of the high critical-current strengths and high film resistances in the normal state, be made very large. It is apparently because of this that the nonlinear effects (which are due to the variation of the number of vortices in the junction) in Nb_3Sn bridge junctions were observed at voltages of several tens of millivolts.[14]

Analysis of the results obtained in the study of bridge junctions made of superconductors with the A-15 structure shows that the high-frequency properties in these junctions are determined by the parameter $V_{\rm eff}=I_cR_d$. In the Nb_3Sn bridges investigated by us the quantity $V_{\rm eff}$ attained in the liquid-hydrogen-temperature range a value of 500 μV. In this case the regular current steps, determined by the relation (2), and indicating the coherence of the vortex motion in the bridges, were observed up to 150 μV.[5] In the V_3Si bridges the quantity $V_{\rm eff}$ attained a significantly lower value (~10 μV at 14 K). In these junctions the steplike CVC structure was observed only up to frequencies ~5 GHZ.

The coherent effects in bridge junctions of superconductors with the A-15 structure can be observed only under conditions when the motion of the Abrikosov vortices is an ordered one. V_3Si and Nb_3Sn bridges prepared by the method of double scribing are bridges of variable thickness (of the $S-S'-S$ type). An advantageous peculiarity of variable-thickness bridges is the fact that, because of the smaller bridge thickness, as compared to the "shore" thickness, all the processes connected with the vortex motion are localized in the region of the microbridge.[8] This eases the problem of establishing a coherent vortex motion, since in this case the vortices, repelled by their own mirror images in the shores, tend to move in one short row.

The force of the interaction between two parallel vortices in the case when $\xi\ll\lambda$, where λ is the depth of penetration of the magnetic field into the superconductor, is determined by the expressions[15]

$$F=(\Phi_0/2\pi\lambda)^2/2x,\quad \xi<x\ll\lambda, \tag{4}$$

$$F=(2\pi/\lambda x)^{1/2}(\Phi_0/4\pi\lambda)^2e^{-x/\lambda},\quad x\gg\lambda. \tag{5}$$

Here Φ_0 is the magnetic-flux quantum and x is the vortex spacing. For superconductors in the "dirty" limit (when $l\ll\xi_0$), to which correspond films with the A-15 structure,

$$\lambda=0{,}615\,\lambda_L(\xi_0/l)^{1/2}[T_c/(T_c-T)]^{1/2}, \tag{6}$$

where λ_L is the London penetration depth and l is the mean free path of the electrons. Usually, at our working temperatures the widths of the Nb_3Sn and V_3Si bridges under investigation were greater than the magnetic field's penetration depth, which in its turn exceeded the bridge lengths. On the basis of this we can estimate the interaction of a vortex with its mirror image in the shores from the formula (4), and the interaction with the neighboring vortices in the short row from the formula (5).

As can be seen from the formula (6), as l decreases, the quantity λ increases, decreasing according to the law λ^{-2} the gradient, lining up the vortices in a short row, of the force of repulsion of the vortices from their mirror images. At the same time, the repulsive force, (5), acting between the vortices in the short row increases. The joint action of these factors leads to a situation in which the destruction of the coherent nature of the processes in the bridge as a result of the breakup of the single-column motion of the vortices at small l occurs at lower voltages.

A comparison of the experimental data obtained on V_3Si and Nb_3Sn bridge junctions supports the above-presented arguments. The width of the transition into the superconducting state of the V_3Si films was roughly five times greater than the width of the transition of the Nb_3Sn films, i.e., the quantity l should be significantly smaller and λ appreciably greater in V_3Si bridges than in Nb_3Sn. Furthermore, the value of T_c for V_3Si is lower than the value for Nb_3Sn. This leads to a situation in which the regular step structure, determined by the Josephson relation (2), on the CVC of Nb_3Sn bridges could be obtained in experiment in a wider range of frequencies than for V_3Si. This range can be broadened when the properties of the films are improved.

3. A lower frequency limit for the observation of coherent effects has also been found for V_3Si bridges. The minimum external-radiation frequency at which the CVC of bridge junctions exhibit a steplike structure is determined by the magnitude of the noise broadening. It is shown in Ref. 16 that for a tunnel junction the width of the Josephson-radiation line in the case when $eV \ll kT$ is given by

$$\Delta f = 4\pi k_B T R_d^2 / \Phi_0^2 R, \tag{7}$$

where k_B is the Boltzmann constant and $R = \bar{V}/I$. This width is due to the thermal noises in the junction. The frequency $f_n = \Delta f$ is the natural lower limit at which current steps begin to appear on the CVC. For the contacts whose CVC are shown in Fig. 6, we find from (7) that $f_n \approx 0.1$ GHZ.

Experimentally, the current steps were observed in this bridge at the temperature of the pump hydrogen starting from the frequency $f = 0.5$ GHz. This discrepancy is undoubtedly connected with the existence in wide type-II superconductor bridges of additional noise sources, which are connected with the possibility of the vortices being pinned to the inhomogeneities of the superconductors. These noises can be decreased by improving the quality of the bridges and films. The lower frequency limit also increases as a result of external inductions. Notice that the probability of a vortex being caught by an inhomogeneity in a bridge junction decreases with increasing strength of the interaction between the vortices and with increasing number of vortices in a chain. This can be attained by increasing the bridge width.

4. The parabolic nature of the CVC observed experimentally in V_3Si and Nb_3Sn bridges was predicted theoretically for wide bridges in Refs. 8 and 9. Such a dependence is connected with the fact that at sufficiently high currents $I \gg I_c$ the number of vortices in a junction and the velocity of their motion are proportional to the strength of the current flowing through the junction. In this case the mean voltage across the junction, which is determined by the number of Abrikosov vortices streaming through the junction per unit time, turns out to be a quadratic function of the current. In our opinion, there exist in bridges made of superconductors with the A-15 structure favorable conditions for the verification of the conclusions arrived at in the theory developed in Refs. 8 and 9 about the quadratic shape of the CVC.

Furthermore, the theory predicts the existence of a fine CVC structure connected with the variation of the number of vortices located in the region of the junction. As shown in Ref. 9, the kinks on the CVC should appear at voltages that are multiples of the characteristic voltage

$$V_0 \approx (4/\pi) R_d I_c (2\xi/W)^{1/2}, \tag{8}$$

where W is the width of the bridge junction. Substituting into (8) the parameters of the bridge junction whose CVC are shown in Fig. 2, and setting $\xi = 30$ Å, we find that $V_0 \approx 0.1\ \mu V$. Since even the magnitude of the thermal broadening, determined by the relation (7), is greater than this voltage, no kinks are observed on the CVC of V_3Si bridge junctions.

5. Using the results of Refs. 8 and 9, we can estimate the values of certain physical quantities connected with the motion of the vortices in our bridges.

The time a pair of vortices takes to move through a junction is given by $t = h/2eV_0 \sim 1 \times 10^{-8}$ sec. The coefficient of viscosity for the vortex motion

$$\eta = 8hI_c t / \pi^2 e W^2 \sim 4 \cdot 10^{-14} \text{ g/sec.}$$

The investigations carried out showed that the vortex model used to describe the properties of wide superconducting bridges turns out to be fruitful when used to account for the shape of the CVC of the bridges and the nature of the interaction with an external electromagnetic field. The properties of bridge junctions made of superconductors with the A-15 structure are well described within the framework of such a model. Because of the small coherence length and the relatively large penetration depth, λ, of the field, the conditions under which the bridge dimensions, while remaining comparable to λ, many times exceed ξ can be fairly easily realized in such materials. The advantageous geometry of the bridge junction (of the $S-S'-S$ type) allows us to observe the coherent effects, connected with the single-column motion of the Abrikosov vortices, in a wide voltage, and a wide external-radiation-frequency, range.

Some of the results of this paper, e.g., the estimate of the effect of the variation of the mean free path on the upper frequency limit, are general for fairly wide and long–in comparison with ξ–junctions made of any type-II superconductors. Further development of the model and the estimation and realization of the ultimate potentialities of "weak" coupling elements made of high-temperature superconducting materials would be of interest.

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Multiple Sondheimer oscillations in tungsten plates with atomically pure surfaces

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Multiple Sondheimer oscillations (with periods $\Delta H_s = \Delta H_1/s$, $s = 2, 3, 4$) of the magnetoresistance of tungsten plates in a magnetic field H‖[100] perpendicular to the surfaces are investigated theoretically and experimentally. These oscillations are due to the multiple passage, through the sample thickness, of the electron reflected from the boundaries. The amplitude of the multiple harmonics depends on the electron scattering in the volume and on the character of its reflection from the metal surface. A Fourier analysis of the Sondheimer-signal spectrum and the results of the theoretical analysis, expressed in the form of simple relations, make it possible to determine the mean free path and the specularity coefficients on an atomically pure crystal surface and on a surface sputtered to saturation. The Sondheimer effect is due to the carrier of section A of the hole octahedron of the tungsten Fermi surface.

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1. INTRODUCTION

1. Interest in condensed-state physics phenomena that occur near the surface of a conducting solid or on the surface iteslf has increased recently. Since very pure materials have now become available, and new methods of purifying and obtaining controllable changes in the surface state have been developed, definite progress was made towards the solution of this problem (see, e.g. Ref. 1). This has been helped to a considerable degree by the use of methods of static and radio-frequency size effects. The point is that macroscopic properties of thin samples with dimensions smaller than the electron mean free path l are determined mainly by the scattering of the electrons from the surface. This means that the experimentally measured characteristics (dc resistance, surface impedance, etc.) contain much information on the surface mechanisms of scattering electrons, on the state of the crystal near the boundary, and so on.

2. Consider, for example, a plane-parallel plate of thickness d, placed in a magnetic field H perpendicular to the surface. In a strong magnetic field, when the cyclotron frequency Ω is much higher than the frequency ν of the collisions of the electrons with the scatterers in the volume,

$$\gamma = \nu/\Omega \ll 1, \tag{1.1}$$

the diagonal components of the tensor of the transverse conductivity of the metal are of the order of $\sigma_0\gamma^2$. Here $\sigma_0 \approx ne^2/m\nu$ is the conductivity of the bulk sample in the absence of a magnetic field; $n, -e$, and m are respectively the concentration, charge, and effective mass of the conduction electrons.

The conductivity of a plate with thickness $d \lesssim l$ can differ significantly from $\sigma_0\gamma^2$ in the case of nonspecular reflection of the electrons from the surface. The reason is that in the plate the role of l is assumed by the effective mean free path

$$l_{\text{eff}}^{-1} = l^{-1} + (2d)^{-1}[(1-\rho_0)+(1-\rho_d)].$$

The collisions of the electrons with the boundary are taken into account here phenomenologically, with the aid of a macroscopic characteristic of the metal surface—the specularity coefficient ρ, $0 \leqslant \rho \leqslant 1$. The second term in l_{eff}^{-1} is the reciprocal mean free path, in which the electron experiences diffuse scattering from the upper side of the plate with probability $1-\rho_0$ and from the lower side with probability $1-\rho_d$. Therefore the conductivity component that depends monotonically on H is given by

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