Temperature dependence of the resistivity of thin tungsten plates in a strong magnetic field

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(Submitted 4 April 1978)
Zh. Eksp. Teor. Fiz. 75, 1356–1361 (October 1978)

The magnetoresistance of thin single-crystal tungsten plates was investigated in a wide range of magnetic fields (5–60 kOe) and temperatures (4.2–100°K). The behavior of the surface conductivity σ_s due to the static skin effect was investigated as a function of H, T, and state of the surface of the sample. It was found that the specularity parameter p did not vary significantly with temperature in the range 4.2–15°K.

PACS numbers: 73.25. + i

INTRODUCTION

The static skin effect and the associated surface conductivity have a strong influence on the transport properties of thin conductors. According to Peschanskiĭ and Azbel',[1] the surface conductivity σ_s of plates of compensated metals subjected to a strong magnetic field H depends on the orientation of the vector H and it is determined by the nature of electron reflection from the boundary of the metal. For H lying in the plane of the sample (but perpendicular to the current j), the component of the conductivity due to the glancing electron trajectories is limited—in the extreme cases of purely specular ($p = 1$) or purely diffuse ($p = 0$) reflection—either by the mean free path l or by a characteristic length equal to the Larmor precession radius r. Consequently, the surface conductivity for a diffusely reflecting boundary is l/r times less than for a specular one and it does not depend on T via l (T is the temperature of the investigated crystal plate). In the intermediate and most important from the experimental point of view case $0 < p < 1$ the temperature dependence $\sigma_s(T)$ becomes weaker on increase of the field H and in the high-field limit, when the condition $1 - p \gg r/l$ is obeyed, this dependence disappears completely. Finally, if we bear in mind a possible temperature dependence as well as the contribution of the bulk conductivity of the crystal to the total value for a thin sample, we find that the resultant resistivity is then a complex function of T, H, p, and d, where d is the thickness of the plate.

The present paper reports an experimental investigation of the above features of the magnetoresistance of thin single-crystal tungsten plates, determined in a wide range of temperatures and magnetic fields for different states of the surface. Earlier investigations have shown that the reflection of conduction electrons from the tungsten surface depends strongly on the state of the crystal boundary and can sometimes be predominantly specular. Investigations of the static skin effect[2] and of the electron focusing (carried out by us in cooperation with V. S. Tosoĭ and I. I. Razgonov) have shown that, in particular, electron reflection from a cleaned (110) surface kept in high vacuum is largely specular (the specularity parameter is estimated to be $p = 0.6-0.8$) and changes to diffuse reflection when the surface is covered by a film of a different substance. The electron focusing method has also established that predominantly specular nature of reflection is also realized in those cases when the (110) tungsten surface is subjected solely to electrolytic polishing.[3] We have no information capable of explaining the reasons for this behavior but we may point out that the apparent conflict between the results reported in Ref. 2 and those given by Tsoĭ and Razgonov[3] is most likely due to the simple fact that etching produces a dense oxide film which acts as a protective coating. The cases when such a coating do not disturb the translational symmetry (which is essential[4,5] for specular reflection) and hardly affects the specular nature of reflection are known and have been investigated earlier[6] in the specific cases of Cu on the (110) face of W.

The very existence of high specularity and the ability to control it in a significant range has made it possible to investigate the temperature dependence of the specularity coefficient p.

EXPERIMENTAL METHOD

Measurements were carried out in a cryostat in which temperature could be varied in a continuous manner from 4.2 to 300°K. The temperature in the working chamber of the cryostat was measured with a differential gold–Chromel thermocouple and maintained at the set value (to within ±0.1°K) by an electronic servo circuit. Magnetic fields up to 70 kOe were provided by a superconducting solenoid. In all cases the magnetic field was oriented parallel to the surface of the sample and in such a way that $H \perp j$, where j was the direction of the measuring current.

Our samples were rectangular plates of linear dimensions 6×1.5 mm and 50–120 μ thick; they were cut from a single-crystal ingot of high-purity tungsten characterized by the ratio $\rho(300°K)/\rho(4.2°K) \sim 10^5$. The surfaces of the plates coincided with the (110) crystallographic plane and the measuring current flowed in the $\langle 100 \rangle$ direction. The surface was oriented to within 30′. The surfaces were ground and then polished electrochemically in an alkaline solution until a mirror-like luster was achieved. Measurements were carried out in high vacuum (10^{-11} Torr). The construction of the vacuum glass vessels, the method for supporting a sample, and the surface cleaning procedure were all described earlier.[2,6] The state of the boundary of a

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crystal changed as a result of cleaning or deposition of a monomolecular impurity film which was precipitated from the residual gases in the vacuum system. Some of the measurements were carried out "in air" on samples subjected only to electrical polishing in an alkali.

The thermal contact between the outer medium and a sample (in vacuum measurements) was made by heat conduction through molybdenum crossbars, which were parts of the vacuum system. Comparative measurements carried out before and after sealing of the vacuum chamber and pumping out indicated that the likely difference between temperatures as a result of poorer thermal contact was unimportant and its value was few tenths of a degree.

The resistance was measured by a compensation method. The recording instrument was an R-348 potentiometer.

RESULTS AND DISCUSSION

Figure 1 shows a series of typical experimental curves representing the dependences $\rho_H(T)$ obtained for the thinnest tungsten sample ($d = 0.052$ mm) under various conditions. In this case the magnetic field and the surface impurity concentration were varied. The results indicated that the removal of an adsorbed impurity from the surface of the crystal altered considerably the value of ρ_H and the dependence $\rho_H(T)$ at lowest temperatures. The resistivity increased with temperature ["anomalous" dependence $\rho_H(T)$ in the range $T < 15$°K], but the rise became weaker on increase of the field; this was followed by a typical (for a bulk metal) reduction in the resistivity to a minimum and a further rise of $\rho_H(T)$. Moreover, the deep resistivity minima, characteristic of all the curves, shifted considerably toward higher values of T on increase of the magnetic field.

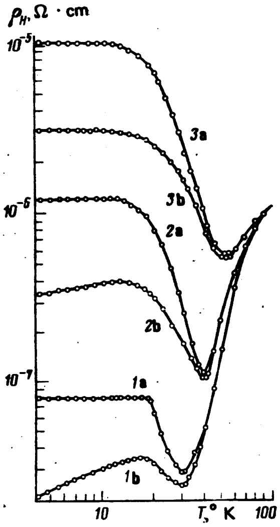

FIG. 1. Temperature dependences of the magnetoresistance of a thin ($d = 0.052$ mm) tungsten plate recorded in magnetic fields H of various intensities and for different states of the surface. The curves with the index a were obtained for samples whose surface was contaminated by a film of adsorbed impurities; the curves with the index b correspond to a sample cleaned in high vacuum. 1) $H = 5$ kOe; 2) $H = 20$ kOe; 3) $H = 60$ kOe.

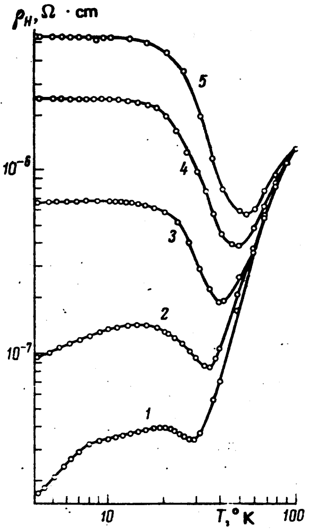

FIG. 2. Temperature dependence of the magnetoresistance of a thin ($d = 0.115$ mm) tungsten plate recorded in air on application of various magnetic fields H(kOe): 1) 5; 2) 10; 3) 20; 4) 40; 5) 60.

Figure 2 shows the dependences $\rho_H(T)$ for a plate whose surface was treated only in an alkaline solution and measurements were carried out in air. As for a plate with an atomically clean surface, the dependence $\rho_H(T)$ was anomalous at low temperatures in relatively weak fields. In fields of 40–60 kOe the $\rho_H(T)$ curve was flat up to 20°K. The positions of the minima of the curves in Figs. 1 and 2 were identical for the same magnetic fields.

Figure 3 gives the dependences of the resistivity (curves 1 and 2) of a thin tungsten plate ($d = 0.083$ mm) on the temperature T in zero magnetic field. The resistivity of a sample with a "clean" surface was found to be approximately half that of a sample with a "contaminated" surface at $T = 4.2$°K, but this difference gradually decreased on heating to 20°K.

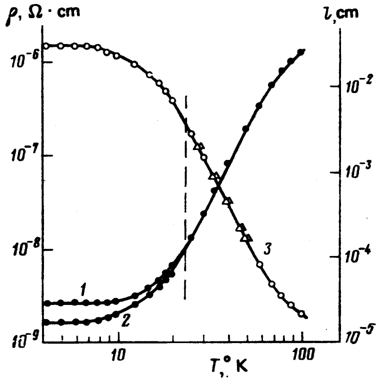

FIG. 3. Temperature dependences of the resistivity of a thin ($d = 0.082$ mm) tungsten plate in $H = 0$: 1) surface coated with an assorbed film; 2) surface cleaned in high vacuum; 3) temperature dependence of the mean free path of electrons $l(T)$. When the evacuated vessel was opened and the sample exposed to air for 2h, the temperature dependence of the resistivity changed to that represented by curve 2.

The results obtained were reversible and were easily reproduced during the subsequent cleaning or contamination cycles.

We shall interpret the results by considering first the mean free path l of electrons as a function of T. At relatively high temperatures ($T > 25°K$) we shall assume that $l(T) = A/\rho(T)$, where $\rho(T)$ is the resistivity in zero magnetic field, and we shall estimate the coefficient of proportionality from the positions of the minima of curves 1 and 2. It is known that the minimum of the dependence $\rho_H(T)$ in $H = \text{const}$ divides magnetic fields into effectively low ($r > l$) or high ($r < l$); at the minimum itself, we have $r = l$. The results of our estimates of l are represented by curve 3 in Fig. 3. The triangles are the values of l obtained from Figs. 1 and 2 on the assumption that $r = 10\ \mu$ in a field $H = 10$ kOe.

At low temperatures ($T < 25°K$) where the scattering on the boundaries is important, we can unfortunately give only the lower limit of $l(T)$ obtained from the dependence $\rho(T)$ for an atomically clean surface of the sample. The scattering by the boundaries of the plate prevents us from determining the true value of l and its temperature dependence in this important range of T. However, we shall mention that estimates of l at $T = 4.2°K$ give values of the order of 1 mm, which is clearly greater than the plate thickness (this applies in the region to the left of the dashed line in Fig. 3). The very existence of the dependence of ρ on the state of the surface at low values of T is also indirect evidence that $l > d$.

We shall analyze the size dependences of the magnetoresistance using a model of the static skin effect. According to Peschanskiĭ and Azbel',[1] the expression for the magnetic correction to the conductivity of a thin sample in a aparallel magnetic field (H ⊥ n, where n is the normal to the surface of the plate) is:

$$\sigma = \sigma_0 \frac{\gamma}{q+\gamma} \frac{r}{d} + \sigma_0 \gamma^2, \tag{1}$$

where σ_0 is the conductivity in the absence of a magnetic field; $\gamma = r/l$; $q = 1 - p$. The first term on the right-hand side of Eq. (1) represents the surface conductivity σ_s. It follows from Eq. (1) that in the limit of a thin sample ($d < l$) the surface conductivity in a high magnetic field ($\gamma \ll q$) shunts completely the bulk conductivity (second term) and the total conductivity of the plate is independent of l (and, consequently, of T via l).

We shall now consider the experimental results. For the upper pair of curves in Fig. 1, measured in a magnetic field $H = 60$ kOe at $T = 4.2°K$, the inequalities $d < l$ and $\gamma \ll q$ are satisfied well and the magnetoresistance of a plate is indeed independent of T in the range $T < 15°K$. At higher temperatures the surface conductivity makes a smaller contribution and the dependence $\rho_H(T)$ shows a fall of ρ_H, which is typical of bulk metal. On the other hand, in relatively weak magnetic fields of $H = 5$ kOe (the lower pair of the curves) the criterion $\gamma \ll q$ is satisfied less accurately and the dependence $\rho_H(T)$ obtained for plates with atomically clean surfaces (and, consequently, lower values of q) exhibit an anomalous rise. Physically, this rise is due to the fact that for high values of r and correspondingly large electron drift lengths along glancing surface trajectories it is highly probable that electrons are scattered by phonons in the bulk of the metal. Thus, the anomalous behavior of $\rho_H(T)$ supports a high degree of specularity of the crystal boundary. The results obtained for a polished surface (Fig. 2) are in agreement with this hypothesis.

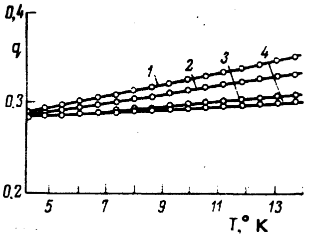

FIG. 4. Temperature dependences of the values of $q = \rho_2(T)/\rho_1(T)$ calculated for various magnetic fields H(kOe): 1) 10; 2) 20; 3) 40; 4) 60.

Formally, the rise of $\rho_H(T)$ in the range $T < 15°K$ can also be due to the dependence of q on T. However, we shall show that this dependence is weak and plays no significant role. Since no data are available to us on the detailed nature of the dependence $l(T)$, we shall find $q(T)$ for a plate with an atomically clean surface simply from $q = \rho_2(T)/\rho_1(T)$, where $\rho_1(T)$ and $\rho_2(T)$ are the magnetoresistance of a plate before and after cleaning the surface in a field $H = \text{const}$. This approximate expression follows from Eq. (1); it ignores the contribution of the bulk conductivity and is thus valid in a limited range of temperatures when $l > d$ and $\gamma \ll 1$. At a given temperature the accuracy of this expression improves on increase in the magnetic field intensity. For simplicity, we shall also assume that the surface of a contaminated plate scatters electrons in a purely diffuse manner, i.e., we shall assume that $q = 1$.

The results of estimates of $q(T)$ for various values of H are plotted in Fig. 4. As expected, the values of q calculated for various fields H are in good agreement only at low values of T and begin to diverge considerably at higher temperatures. It should be stressed that in a field $H = 60$ kOe the calculated values of q are practically independent of temperature. We may assume that a further increase in the field may reduce the slope of the dependences $q(T)$ still further. Thus, the diffuseness coefficient is $q \approx 0.3$ or the specularity coefficient is $p \approx 0.7$ and it does not vary greatly with temperature in the range 4.2–15°K.

This conclusion is in agreement with the results reported by other authors. For example, the calculations of Baskin and Éntin[7] and also those of Ustinov[8] indicate that the equilibrium thermal vibrations on the surface of a metal are small and they cannot alter significantly q at low temperatures. Prange[9] analyzed the experimental data obtained by the Koch group[10] on the temperature dependence of the damping of magnetic surface states[11] and reached the same conclusion. According to Prange,[9] the change in the surface impedance as a function of a weak magnetic field in the range 2–25°K is due to the scattering of resonance electrons by bulk phonons; surface phonons localized near the boundary within a layer ~100Å thick make a negligible contribution. It should be pointed out that Gaĭdukov and Kadletsova[12] carried out a comparative analysis of the temperature dependences of the resistivity of thin whiskers and bulk samples of zinc and cadmium and found a strong temperature dependence $q(T)$ in the range $T < 15$°K. It is possible that Gaĭdukov and Kadletsova[12] ignored the dependence of the coefficient q on the angle of incidence of electrons on the surface, which is extremely important in the limiting case of a thin sample ($d \ll l$) and, consequently, in the case of glancing incidence on imperfect surfaces.[13]

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Translated by A. Tybulewicz