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Determination of the Specular Reflection Coefficient of Conduction Electrons in Zn Whiskers at $T = 4.2°K$

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The influence was studied of the transverse dimensions of Zn single crystals in the form of whiskers and thin platelets on their specific resistance at $T = 4.2°K$. *The thickness of the specimens measured ranged from 10 μm to 0.2 μm. With a decreasing thickness of the specimens the specific resistance increased considerably. Under the assumption that for a pure diffuse reflection of electrons on the specimen boundary the product* $(\rho_\infty \cdot d_\infty)$ *in a bulk specimen is equal to* $1.8 \times 10^{-11}\ \Omega cm^2$ *for a crystallographic orientation corresponding to whiskers, and* $2.2 \times 10^{-11}\ \Omega cm^2$ *for a crystallographic orientation corresponding to platelets, a specular reflection coefficient* p *approximately equal to* $p = 0.6$ *was calculated for both whiskers and platelets.*

1. INTRODUCTION

An increase of the ratio λ_∞/d (λ_∞—the mean free path of an electron in a bulk conductor, d—the smallest transverse dimension of the specimen) leads to the growth of the influence of electron-scattering processes on the specimen boundaries on kinetic phenomena in metals. At the same time static size effects—variations of the electric, magnetic, and galvanomagnetic properties of metals—appear.

Assuming $\lambda_\infty \gg d$, the size effects appear in a pure form. The quantity d consequently plays the basic role during scattering and thus becomes the effective mean free path of the electrons.

One of the demonstrations of the size effects is the growth of the specific resistance in thin specimens. The above effect is weaker when a partial specular reflection occurs on the specimen boundaries. When a pure specular reflection takes place, the specimen behaves like a bulk crystal, since for a specular reflection the component of the electron velocity in the direction of the flux remains conserved. This, however, need not hold[1] for materials with a nonspherical Fermi surface. Consequently in such cases the influence of the dimensions is apparent even for a pure specular reflection.

The condition $\lambda_\infty \gg d$ can be satisfied only at helium temperatures for thin and extremely pure specimens. From this viewpoint whiskers, i.e., thin metal single crystals grown by special methods are appropriate for size effect studies.

Whiskers are superperfect single crystals the boundary surfaces of which are nearly perfect reflectors of optical rays. Therefore it is very interesting to study the behavior of the above surfaces with respect to the conduction electrons. The purpose of the present paper was to determine the specular reflection coefficient for Zn whiskers. Preliminary experimental results were previously published.[2]

2. EXPERIMENTAL

2.1. Specimens

The zinc whiskers were grown from vapor by the method described by Coleman.[3] The initial zinc had a residual resistance ratio $\rho_{295°K}/\rho_{4.2°K} = 10{,}000$ (specimen thickness about 1 mm). Among the whiskers grown there was a sufficient number (approximately one hundred in one ampule) of such the length of which was from 1 to 3 mm. The specimens grew predominantly as whiskers; in each ampule there were several single crystals in the form of thin platelets. The thickness of the specimens measured ranged from 0.2 μm to 10 μm. Zachrova[4] determined by x-ray analysis the axes of platelet growth and whisker growth as $[2\bar{1}\bar{1}0]$ and $[2\bar{1}\bar{1}3]$, respectively. However, Skove and Stillwell[5] give $[10\bar{1}0]$ for platelets and $[11\bar{2}1]$ for whiskers. The orientation of the specimens can also be determined indirectly from the anisotropy of the resistance in a magnetic field. From such measurements we were able to conclude that the platelets grow both in the $[2\bar{1}\bar{1}0]$ and the $[10\bar{1}0]$ directions. The whisker growth axes lie in the $(1\bar{1}00)$ plane and the angle between the whisker growth axis and the [0001] axis is approximately 60° and 40°, which corresponds to the axes $[11\bar{2}1]$ and $[\bar{1}\bar{1}22]$.

2.2. Whisker Mounting

Whisker mounting is the most complicated and most responsible part of the experiment. The basic requirements for the correct mounting of the whiskers are that the electrical contacts must have a low ohmic resistance and that they must be mechanically strong and heat-resisting. In addition, it is necessary for the specimens to be free of introduced by mounting defects as much as possible. We have described in detail[6] the method of "pressed contacts" used by us for the mounting of the whiskers. With respect to the above method the whisker is placed on four contacts represented by narrow copper bands covered with an indium layer and pressed to them by means of a glass platelet. This method practically always guarantees an electrical and mechanical reliability of the contacts; however, sometimes it introduces defects into the crystal lattice of the whisker in the nearest neighborhood of the contacts. The problem will be discussed later in more detail.

2.3. Determination of Specimen Thickness

The quantity d, discussed below, determines the average specimen thickness. In the case of whiskers it is the average geometric specimen thickness, i.e., $d = \sqrt{s}$, where s is the area of the cross section. The area s is calculated from the resistance measured at room temperature, from the distance of the potential contacts, and from the known specific resistance of bulk zinc $\rho_{295°\mathrm{K}} = 6 \times 10^{-6}\,\Omega\mathrm{cm}$. (The size effect at room temperature need not be taken into consideration since $\lambda_{295°\mathrm{K}} = 10^{-6}$ cm.) The accuracy of the determination of the thickness d is given by the accuracy with which it is possible to measure the distance between the potential contacts and that depends on the width of the contacts. In our case the width of the contact was approximately 30 μm and the distance between the contacts approximately 500 μm. The accuracy of the determination of d for whiskers is approximately 5%. The thickness of thin platelets was determined analogously; the thickness was calculated after the microscopical measurement of the length and the width of the platelet. The accuracy in this case is about 10%. The thinnest specimens studied were 1 μm (whiskers) and 0.2 μm (platelets).

3. RESULTS AND DISCUSSION

The ratio $\delta = \rho_{4.2°\mathrm{K}}/\rho_{295°\mathrm{K}}$ for whiskers and platelets as a function of the inverse value of their thickness d^{-1} is plotted in Fig. 1. The first noticeable fact in Fig. 1 is a considerable dispersion of experimental points. It is not probable that the above dispersion could be caused by the variation of the values λ_∞ or by the variation of the specular reflection coefficient p in different specimens, since the initial material, the conditions of the growth of the specimens, and the method of mounting were always the same. It is assumed that the dispersion of the experimental points coheres with the formation of microdefects in the specimens. These defects can originate either during the process of mounting (mainly in the neighborhood of the potential contacts) or during the cooling of the specimen to low temperatures. This assumption has been verified by the following experiment: A long whisker was divided into two parts and the δ of both parts was measured. The experiment was performed with a number of specimens. In some cases both parts had the same δ, in others the δ of both parts considerably differed. Further it has been observed that for a repeated cooling of the same specimen from room to helium temperature, the resistance of the specimen was higher than for the first cooling, which verifies the assumption of the origin of microdefects. Let us now prove that the considerable dispersion of the experimental points measured appears in similar measurements,[5,7] where different methods for the mounting of whiskers were applied, such methods that should, according to their character, introduce less defects into the specimen.

The second characteristic fact from Fig. 1 is that most of the experimental points lie close to the curve 1 for whiskers* and curve 2 for platelets. No points lie under the two curves. Consequently it is quite logical to consider these curves as

*Experimental errors are higher than the effect of the different orientation of the growth axes of the whiskers.

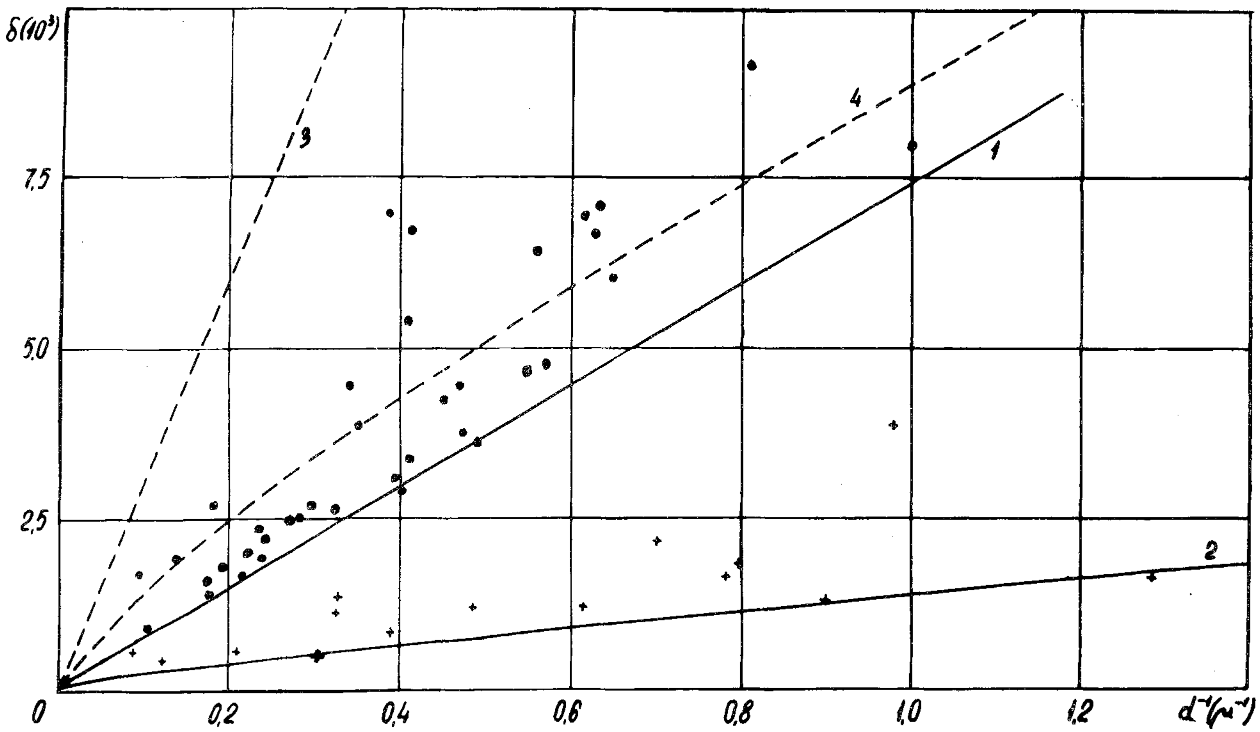

Fig. 1. Dependence of relative change of resistance of zinc whiskers and platelets $\delta = \rho_d^{4.2°K}/\rho_d^{295°K}$ on the specimen thickness d. • Experimental points for whiskers; + experimental points for platelets. Curves 1 and 2—"reference" curves for whiskers and platelets, respectively (see text). Curve 3—plotted for whiskers with respect to Eq. (1), $(\rho_\infty \cdot \lambda_\infty) = 1.8 \times 10^{-11}\ \Omega\text{cm}^2$, $p = 0$. Curve 4—plotted for platelets with respect to Eq. (2), $(\rho_\infty \cdot \lambda_\infty) = 2.2 \times 10^{-11}\ \Omega\text{cm}^2$, $p = 0$, $\lambda_\infty^{4.2°K} = 300\ \mu\text{m}$.

belonging to crystals without defects, since there exist a number of reasons leading to an increase of δ but no reason leading to its decrease. Therefore the courses of curves 1 and 2 can be considered as "correct" courses of the dependence $\rho_{4.2}(d)$ for whiskers and platelets. The curves 1, 2 are called "reference" curves and their parameters will be analyzed below.

Since $\rho_{295^\circ\mathrm{K}}$ is practically independent of the dimensions of the specimen, it can be written in the first approximation for whiskers according to Dingle[8]:

$$\delta_d = \delta_\infty \cdot \frac{\lambda_\infty}{d} \cdot \frac{1-p}{1+p} \qquad \text{provided} \qquad \lambda_\infty/d \gg 1 \tag{1}$$

where the index d is related to a thin specimen with a thickness d and the index ∞ denotes a bulk specimen ($d \gg \lambda_\infty$); p is the specular reflection coefficient ($0 \leq p \leq 1$). Equation (1) holds for specimens with a circular cross section. In the case of a square cross section Eq. (1) has to be multiplied by a coefficient 0.9.[9] In the present paper, because of considerable dispersion of the experimental points, the coefficient was neglected.

For thin platelets the relation derived by Fuchs[10] can be used:

$$\delta_d = \tfrac{4}{3}\delta_\infty \cdot \frac{1}{d} \cdot \frac{1-p}{1+p} \ln\left(\frac{\lambda_\infty}{d}\right)^{-1} \qquad \frac{\lambda_\infty}{d} \gg 1 \tag{2}$$

The nonzero slope of the reference curves in Fig. 1 points to the fact that the reflection of the electrons from the specimen boundaries is not purely specular* ($p \neq 1$).

The magnitude of p can be determined only provided the magnitude of the product $(\rho_\infty \cdot \lambda_\infty)$ that is constant for the given material is known. This product was determined for zinc by Alexandrov[11] by gradually etching off bulk crystals. Assuming that at $T = 4.2^\circ$K the reflection of electrons is purely diffuse ($p = 0$), Alexandrov obtained a value of $(\rho_\infty \cdot \lambda_\infty) = 0.9 \times 10^{-11}\,\Omega\mathrm{cm}^2$ for specimens with axes parallel to the [0001] axis and $(\rho_\infty \cdot \lambda_\infty) = 2.2 \times 10^{-11}\,\Omega\mathrm{cm}^2$ for specimens with axes perpendicular to the [0001] axis. With respect to the various orientations of the whiskers studied the average value of $1.8 \times 10^{-11}\,\Omega\mathrm{cm}^2$ was taken as the value of the product $(\rho_\infty \cdot \lambda_\infty)$. Curve 3 in Fig. 1 is plotted with respect to Eq. (1) with the above average value of $(\rho_\infty \cdot \lambda_\infty)$. The comparison of the slope of curves 1 and 3 shows that the reflection from the specimen boundaries is partially specular ($p \neq 0$) for whiskers. Calculations give a value of $p = 0.6$ for the reference curve. Let us point out that most of the points for whiskers lie in the region $0.5 < p < 0.6$. The straight line 1 also satisfies the condition $\lambda_\infty^{4.2^\circ\mathrm{K}} \geq 300\,\mu$m. (The initial zinc had $\lambda_\infty^{4.2^\circ\mathrm{K}} \geq 300\,\mu$m.) The values found for zinc by Skove and Stillwell[5] also correspond to the value $p = 0.6$. Analogously for copper whiskers it has been found[7] that $p \neq 0$ ($p = 0.6$).

The influence of the dimensions on the resistance of zinc platelets is much lower than for whiskers, as can be seen from curve 2 in Fig. 1. This curve has been

*Since the whisker axes are rational crystallographic directions the Price effect[1] does not evidence itself.

plotted with respect to Eq. (2) using parameters $\lambda_\infty^{4.2\,°K} = 300\ \mu$m and $(\rho_\infty \cdot \lambda_\infty) = 2.2 \times 10^{-11}\ \Omega\text{cm}^2$; the calculation leads to a value of $p = 0.75$. We put $\lambda_\infty^{4.2\,°K} = 300\ \mu$m since (1) the results of the measurements on whiskers give $\lambda_\infty^{4.2\,°K} \geq 300\ \mu$m, and (2) there is no reason for an assumption that there is a considerable difference in $\lambda_\infty^{4.2\,°K}$ of the initial material and the whiskers grown from it. Besides that, if it holds that $\lambda \gg d$, the influence of λ on the size effect is considerably lower for platelets than is the influence of the coefficient p. For a better illustration curve 4 is plotted in Fig. 1; curve 4 differs from curve 2 only by the fact that a diffuse reflection of electrons from the surface ($p = 0$) is assumed.

From an analysis of experimental data it follows that for the zinc specimens (whiskers and platelets) studied $\lambda_\infty^{4.2\,°K} \geq 300\ \mu$m and the coefficient of specular reflection p satisfies the inequality $0.5 < p < 0.75$. It can therefore be concluded that zinc whiskers are a very appropriate object for the study of size effects.

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