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LETTER TO THE EDITOR

Anisotropic dependence of the residual electrical resistivity on the current direction in aluminium single crystals

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Abstract. The detailed dependence of the residual electrical resistivity on the current direction has been measured at 4.2 K in high-purity aluminium single crystals. All the specimens with the same main surface $(1\bar{1}0)$ were cut from one single-crystal rod with the residual resistance ratio of about 50 000. The bulk residual resistivity ρ_b was obtained from the measured resistivity ρ_0 according to the Fuchs–Sondheimer theory with parameters suitable for high-purity aluminium. Large anisotropy of ρ_b with a fine structure has been found with respect to the current direction: a difference between the largest and the smallest values of ρ_b reaches 80% of the latter. This anisotropy of ρ_b shows a strong correlation with the structure of the Fermi surface.

Highly pure aluminium has been developed in our laboratory by the zone refining method [1]. Its residual resistance ratio RRR $(= R(300\,\mathrm{K})/R(4.2\,\mathrm{K}))$ has reached about 100 000. In such a pure metal, the mean free path of conduction electrons becomes 2–3 mm at low temperatures, and then unexpected properties would emerge especially in electronic transport phenomena.

Recently, we have reported that the bulk residual resistivity ρ_b at 4.2 K is anisotropic with respect to the current direction or the electric field direction in aluminium single crystals (RRR $\sim$ 50 000) with the {110} surface [2, 3]. The bulk residual resistivity increased in the order of ⟨110⟩, ⟨111⟩ and ⟨001⟩ current directions: the values along ⟨001⟩ and ⟨111⟩ are 50% and 20% larger than that along ⟨110⟩, respectively. This anisotropy of ρ_b disappeared in sufficiently thin specimens due to the increased surface scattering, showing that impurities, defects and microstructure are not the cause of the anisotropy. We have also reported that the temperature-dependent part of the resistivity, $\rho^{ph}(T)$, shows the same anisotropy as that of ρ_b at temperatures below 25 K [3]. At higher temperatures, this anisotropy of $\rho^{ph}(T)$ was eradicated by the increased electron–phonon scattering.

The anisotropic behaviour of ρ_b described above suggests some correlation with the structure of the Fermi surface. For example, the value of ρ_b along ⟨001⟩ is larger than the others, and in that direction the second-zone Fermi surface is nearest to the Brillouin zone boundary. Therefore, we performed more detailed experiments on the current direction dependence of the residual resistivity ρ_0 at 4.2 K.

Single-crystal specimens were cut with a spark erosion machine. They were prepared from close parts of one aluminium single-crystal rod produced by zone refining. The RRR of this rod was about 50 000 in bulk value. The main surface of all the specimens was set parallel to $(1\bar{1}0)$ in order to keep the surface scattering of conduction electrons identical. The surface normal and the axis orientation of the specimens were accurate within $\pm 1°$. These specimens were chemically etched with aqua regia before and after spot welding

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four zone-refined aluminium wires 0.3 mm in diameter as the electrodes for the DC four-probe measurement. Then, they were annealed at 300 °C in air for 3 h and cooled down to room temperature in an electric furnace. These specimens were carefully placed on a holder without strain. A DC current through the specimens was set at 0.5–1 A so as not to produce Joule heat or magnetoresistance due to a self-induced magnetic field. The voltage drop was measured with a superconducting chopper amplifier with the optimum resolution of 2 pV [4].

In the present experiment, the thickness of the specimens was confined to limited values between 0.3 and 0.6 mm in the light of the previous results [3]: (1) the anisotropy of the resistivity disappears in a thinner specimen due to the increased surface scattering of conduction electrons and (2) the influence of side surfaces having the different crystallographic orientation from the main surface increases in a thicker specimen. However, a thicker specimen with the [001] axis direction was included since the side surface has the same orientation {110} as the main surface.

Table 1. The size of specimens, the raw resistivity ρ_0 measured at 4.2 K, the size-corrected bulk resistivity ρ_b and the axis orientation θ defined as the angle between the crystallographic orientation [001] and the specimen axis along which an electric current flows: d is the thickness, w the width, l_P the distance between potential electrodes and L the total length of the specimen. The surface orientation of all the specimens is cut parallel to $(1\bar{1}0)$.

θ (°)	d (mm)	w (mm)	l_P (mm)	L (mm)	ρ_0 (pΩ m)	ρ_b (pΩ m)
0	0.457	3.062±0.003	12.13±0.01	24.2	1.636	0.716
0	0.980	3.268±0.001	6.78±0.02	14.3	1.208	0.705
0	0.331	2.857±0.011	15.19±0.01	23.4	1.88[a]	0.69
6	0.445	2.97 ±0.01	6.72±0.01	16.9	1.716	0.767
11	0.403	3.02 ±0.01	5.17±0.01	12.6	1.850	0.819
15	0.465	2.98 ±0.01	4.44±0.01	10.5	1.768	0.845
19	0.486	2.99 ±0.01	2.78±0.02	7.4	1.609	0.729
22	0.462	2.98 ±0.01	6.47±0.02	14.4	1.722	0.799
27	0.402	3.04 ±0.01	6.73±0.01	14.7	1.660	0.651
39	0.410	3.00 ±0.01	4.67±0.01	11.5	1.548	0.568
55	0.558	3.049±0.004	12.69±0.01	31.1	1.312	0.544
55	0.469	2.983±0.005	20.04±0.01	31.5	1.44[a]	0.56
55	0.406	3.03 ±0.01	5.06±0.01	12.4	1.530	0.548
73	0.389	3.00 ±0.01	5.88±0.01	14.4	1.518	0.511
83	0.420	2.99 ±0.01	6.52±0.01	17.1	1.478	0.525
90	0.421	3.049±0.002	8.38±0.01	14.5	1.402	0.467
90	0.428	2.954±0.003	8.06±0.01	15.3	1.401	0.473
90	0.388	3.04 ±0.01	6.60±0.02	15.0	1.483	0.482

[a] Values obtained with the direct current comparator potentiometer (Guildline, Model 9930) with a sensitivity of ±0.5 nV.

The size of the specimens and the residual resistivity ρ_0 measured at 4.2 K are listed in table 1. The resistivity ρ_0 was determined from the relation $\rho_0 = [\rho(300\,\mathrm{K})/R(300\,\mathrm{K})]R(4.2\,\mathrm{K})$. Here, $R(300\,\mathrm{K})$ and $R(4.2\,\mathrm{K})$ are resistances of the specimens measured at 300 K and 4.2 K, respectively. The resistivity at 300 K, $\rho(300\,\mathrm{K})$, has been obtained for zone-refined aluminium as 27.33 nΩ m [5]. The thickness d of the specimens was determined from the relation $d = [\rho(300\,\mathrm{K})/R(300\,\mathrm{K})](l_P/w)$, where l_P is the distance between potential electrodes and w the width of the specimens. The axis orientation of the specimens is expressed by an angle θ between the crystallographic orientation [001] and the axis direction in the $(1\bar{1}0)$ plane.

In order to obtain the bulk residual resistivity ρ_b from the measured resistivity ρ_0, we used the Fuchs–Sondheimer theory [6] using the specularity parameter $p = 0$ and the product of bulk resistivity and bulk mean free path $\rho_b \ell_b = 0.82\,\mathrm{f\Omega\,m^2}$ [7, 8]. We have previously shown that with these parameters the Fuchs–Sondheimer theory gives a good estimation of ρ_b for aluminium specimens with the {110} surface such as those treated in the present experiment when the influence of the side surface is negligible [3]. The value of ρ_b of each specimen is listed in table 1.

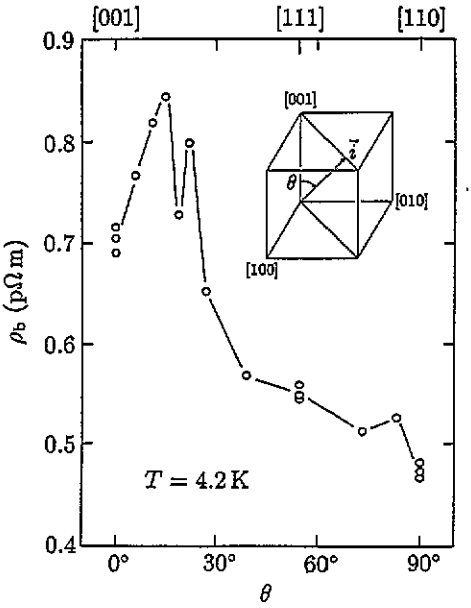

Figure 1. The bulk resistivity ρ_b at 4.2 K as a function of the angle θ between [001] and the specimen axis along which an electric current flows. The solid line is drawn to guide the eye. The inset explains the angle θ.

Figure 1 shows the bulk resistivity ρ_b as a function of the angle θ. The θ dependence of ρ_b is not monotonic, but shows a large structure around $\theta = 20°$ and a small one around $\theta = 85°$. As θ increases, ρ_b increases still more from the value at $\theta = 0°$, where the specimen axis is parallel with [001]. The value of ρ_b at $\theta = 15°$ is 80% larger than that at $\theta = 90°$ corresponding to the [110] specimens. With further increasing θ, the bulk resistivity ρ_b shows a dip around $\theta = 20°$, and then it decreases monotonically until θ reaches 90° except a small increase around $\theta = 85°$.

The behaviour of the θ dependence of ρ_b suggests some correlation with the detailed structure of the Fermi surface of aluminium. In order to see this correlation in figure 2, we plot the θ dependence of ρ_b on the polar coordinate fixed on the $(1\bar{1}0)$ cross section of the Fermi surface that includes the Γ point. We calculated this cross section according to the 4-OPW method using the pseudopotentials obtained by Joss and Monnier [9]. Strong correlation is clearly found between the anisotropy of the bulk resistivity ρ_b and the structure of the Fermi surface. The value of ρ_b increases at θ nearly in the direction that the Fermi sphere crosses the Brillouin zone boundary. Around the [111] direction ($\theta = 54.7°$) where a conduction electron is almost free electron like, the variation of ρ_b is weak. It is further noted that ρ_b is not enhanced in the direction towards the corners of Fermi surface in the second zone where the Fermi velocity of an electron is smaller than that in other regions away from the zone boundaries [10]. The experimental value of ρ_b is smallest in the [110] direction.

The results as shown in figure 2 suggest that the scattering probability of conduction electrons highly increases when the electric field is applied around the direction that the

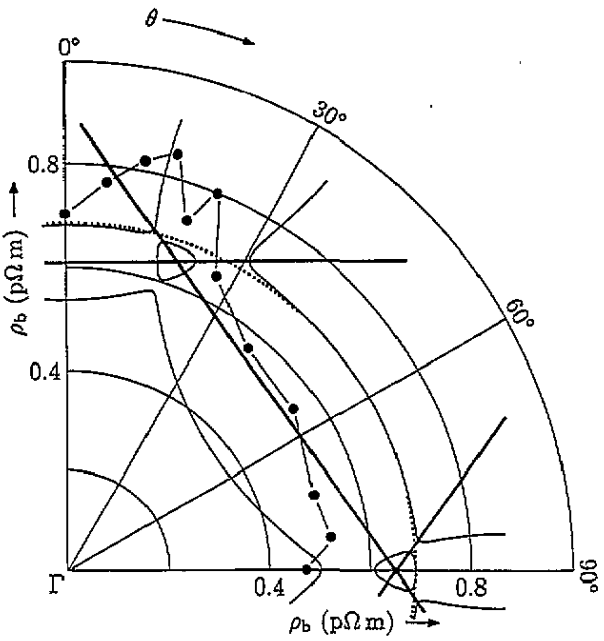

Figure 2. Polar plot of ρ_b fixed on the central $(1\bar{1}0)$ cross-section of the Fermi surface of aluminium. For clarity, the average value is plotted for the [001], [111] and [110] specimens. The thick lines show the Brillouin zone boundaries and the dotted curve represents the Fermi sphere.

Fermi sphere crosses the Brillouin zone boundary, especially in the direction to the U point on the zone boundary. The Fermi surface of aluminium is closest to the zone boundary perpendicular to [001] and involves the X, W and U points. Near the W point, the Fermi surface in the second zone contacts with that in the third zone in the 4-OPW calculation. When the electric field is applied, the electron distribution is shifted along the electric field, resulting in deviation from the equilibrium state. This deviation will depend on the direction of the electric field due to the anisotropic structure of the Fermi surface of aluminium. Therefore, we suggest that this anisotropic deviation of the electron distribution enhances the scattering probability and induces the strong anisotropy of the bulk resistivity.

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