AIP | Applied Physics Letters

Anomalous rf magnetoresistance in copper at 4 K

J. T. Rogers, S. De Panfilis, A. C. Melissinos, B. E. Moskowitz, Y. K. Semertzidis, W. U. Wuensch, H. J. Halama, A. G. Prodell, W. B. Fowler, and F. A. Nezrick

Citation: Applied Physics Letters **52**, 2266 (1988); doi: 10.1063/1.99509
View online: http://dx.doi.org/10.1063/1.99509
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/52/26?ver=pdfcov
Published by the AIP Publishing

Anomalous rf magnetoresistance in copper at 4 K

J. T. Rogers, S. De Panfilis, A. C. Melissinos, B. E. Moskowitz, Y. K. Semertzidis, and W. U. Wuensch
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

H. J. Halama and A. G. Prodell
Brookhaven National Laboratory, Upton, New York 11973

W. B. Fowler and F. A. Nezrick
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

(Received 19 February 1988; accepted for publication 25 April 1988)

We have measured the effect of a magnetic field on the surface resistance of polycrystalline Cu at $f = 1.2$ GHz and at 4.4 K; under these conditions the surface resistance is well into the anomalous skin effect regime but has not reached its limiting value. We find that the transverse and longitudinal magnetoresistance are an order of magnitude smaller than the dc magnetoresistance and depend quadratically on the field. At low fields we observe a decrease in surface resistance with increasing field which can be interpreted as a size effect of the rf surface current, but is also typical of superconductors.

The resistivity of a metal is the sum of a temperature-dependent term arising from electron-phonon scattering and a temperature-independent term due to impurities and other lattice defects. At low temperatures the resistivity of Cu is dominated by these defects. Their contribution can be characterized by measuring the residual resistivity ratio defined as $\mathrm{RRR} = \rho(T = 273\ \mathrm{K})/\rho(T = 4.2\ \mathrm{K})$. Also, the resistivity of metals generally increases in a magnetic field. Longitudinal magnetoresistance, where the current is parallel to the magnetic field **B**, tends to be smaller by about an order of magnitude than transverse magnetoresistance, with the current perpendicular to **B**. At high frequencies, the currents in a conductor are confined to a thin surface layer, which possesses a surface resistance. In the present investigation we measured the surface resistance as a function of temperature and of magnetic field in a microwave cavity manufactured from Hitachi oxygen-free electronic (OFE) hard drawn copper[1] of nominal purity 99.996%.

The apparatus used for these measurements is part of a detector searching for the existence of galactic axions in the 1–3 GHz range.[2] The interest in magnetoresistance arises in connection with the superconducting super collider (SSC) design studies.[3] The SSC beam pipe is Cu plated and it is desirable to know the surface resistance of Cu at high frequencies and at low temperatures in a transverse magnetic field. These measurements show that even for a 5.8 T magnetic field the surface resistance changes by only a few percent.

Surface resistance. The surface resistance R_s was deduced from the measured electrical quality factor Q_0 of a microwave cavity. The cavity was constructed as a cylinder of 7.94 cm inner radius and 40.48 cm length. The cavity surface was honed to 3 μm flatness and electropolished with a solution of 75% phosphoric acid (85% ACS) and 25% Electro-Glo 200 concentrate.[4] This treatment produced a visually specularly reflecting surface.

The cavity Q_0 is defined by $Q_0 = \omega(W/P)$, where W is the stored energy, P the power dissipated in the cavity walls, and ω the angular frequency. The dissipated power is proportional to R_s and to the square of the tangential component of the oscillating magnetic field $\mathbf{B}_t$ integrated over the cavity surface; in kms units we have

$$P = \frac{1}{2\mu_0^2} R_s \int_s \mathbf{B}_t^* \cdot \mathbf{B}_t \, ds.$$

The stored energy is

$$W = \frac{1}{2}\epsilon_0 \int_v \mathbf{E}^* \cdot \mathbf{E} \, dv,$$

the integration being over the cavity volume. Thus it is possible to express

$$Q_0 = A/R_s, \tag{1}$$

where A is a calculable constant dependent on the cavity geometry and the mode under consideration.[5]

A swept frequency microwave generator fed power to the cavity through a very weakly coupled loop; the transmitted power was picked up by a weakly coupled loop and displayed on a network analyzer (Fig. 1). The full width of the cavity resonance at half-maximum, Δf, could be measured to an accuracy of 3%, yielding the quality factor $Q_0 = f/\Delta f$. The cavity was allowed to fill with liquid helium, with no measurable effect on Q_0.

The results obtained for R_s as a function of temperature for two different cavities for the TM_{010} mode ($f = 1.249$ GHz) and TE_{114} mode ($f = 2.426$ GHz) normalized for an

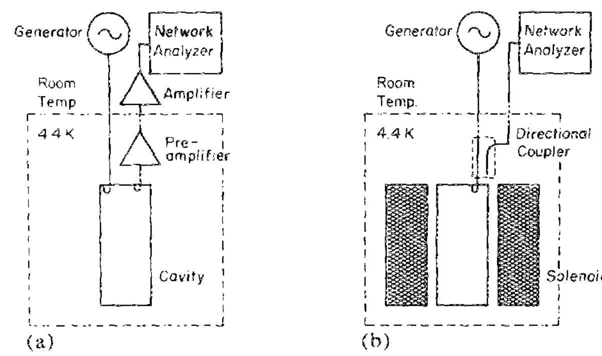

FIG. 1. Schematic diagram of the apparatus. (a) Measurement of Q value by transmission; (b) measurement of $\Delta Q/Q$ by reflection.

$\omega^{2/3}$ frequency dependence to $f = 1.249$ are shown in Fig. 2 and are in excellent agreement. We note that R_s changes only by a factor of 4 from room to liquid-helium temperature. The saturation has two causes: lattice defects and the anomalous skin effect.

Anomalous skin effect. At room temperature the surface resistance can be related to the resistivity of the material by the classical skin depth expression[6]:

$$R_s = \rho/\delta, \quad \delta = \sqrt{2\rho/\mu_0\omega}. \tag{2}$$

Using $\rho(273) = 1.55\times10^{-8}\ \Omega$ m for Cu we find that at $f = 1.249$ GHz, $R_s(273) = 8.5\times10^{-3}\ \Omega$, in good agreement with the data.

As the temperature decreases so does the resistivity, and for sufficiently low ρ the mean free path l of the conduction electrons becomes longer than the classical skin depth. In this case the classical assumption of diffusive electron flow, and therefore Eq. (2), becomes invalid, and in this anomalous skin effect limit[7] the surface resistance approaches a limiting value R_∞. The departure of the resistivity from the classical model can be characterized by the dimensionless parameter

$$\alpha = \tfrac{3}{4}\mu_0\omega(\rho l)^2\rho^{-3}. \tag{3}$$

For $\alpha \lesssim 0.02$, Eq. (2) is valid; for $\alpha \gtrsim 3$ the surface resistance is well represented by[8]

$$R_s = R_\infty(1 + 1.157\alpha^{-0.276}), \tag{4}$$

where

$$R_\infty = [\sqrt{3}\pi(\mu_0/4\pi)^2(\rho l)\omega^2]^{1/3}. \tag{5}$$

We note that (ρl) is a property of the material, independent of purity, temperature, or frequency; for Cu $(\rho l) = 6.6\times10^{-16}\ \Omega\ \mathrm{m}^2$. On the other hand, α is temperature and impurity dependent through the (ρ^{-3}) term. It follows that R_∞ is temperature and impurity independent.

The solid curve in Fig. 2 is the expected value of R_s as calculated from Eqs. (3)–(5) using the value RRR = 220 as provided by the manufacturer.[1,9] This disagrees with the data which can be best fit by the dashed curve which corresponds to RRR = 24. This difference may be due to surface conditions or lattice defects introduced when manufacturing the cavity.

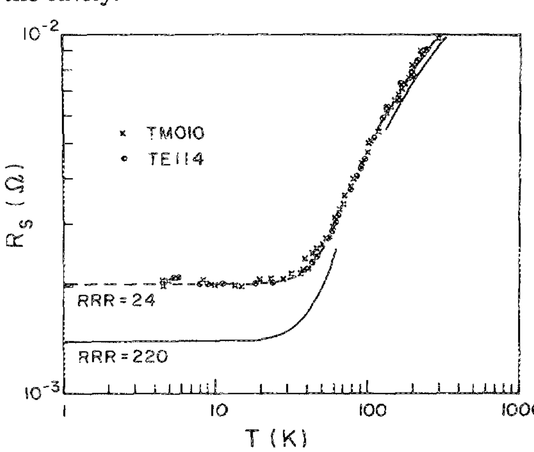

FIG. 2. Surface resistance in ohms vs temperature, normalized to $f = 1.249$ GHz. The curves are the predictions of the theory of the anomalous skin effect for two different values of RRR. The errors of the data points are of the order of the symbols used in the graph.

Magnetoresistance. To measure the magnetoresistance the cavity was placed in the bore of a superconducting solenoid,[10] immersed in liquid helium at 4.4 K. The average magnetic field at the cavity surface was raised from 0 to 5.5 T in 0.53 T increments. In this series of measurements we were more interested in changes in Q than in its absolute value. Thus we measured the power reflection coefficient Γ^2 of the undercoupled cavity with a 30 dB directional coupler.

The resonance reflection coefficient, coupling β, and external and unloaded quality factors Q_E and Q_0 are related as follows:

$$\beta = Q_0/Q_E, \quad \Gamma^2 = |(1-\beta)/(1+\beta)|^2. \tag{6}$$

For fixed Q_E the changes in these quantities are

$$\frac{\Delta Q_0}{Q_0} = \frac{\Delta\beta}{\beta} = \frac{\Delta(\Gamma^2)}{\Gamma(1-\Gamma^2)}. \tag{7}$$

For a given value of $(\Delta Q_0/Q_0)$ the change $\Delta\Gamma^2$ in the reflection coefficient is maximized for $\Gamma^2 = 1/3$. We approximated this condition for the modes tested. The coupling loop position was held fixed during the measurements.

Data for the TM_{010}, TE_{112}, and TE_{113} modes are shown in Fig. 3. The fractional change in R_s, approximately the

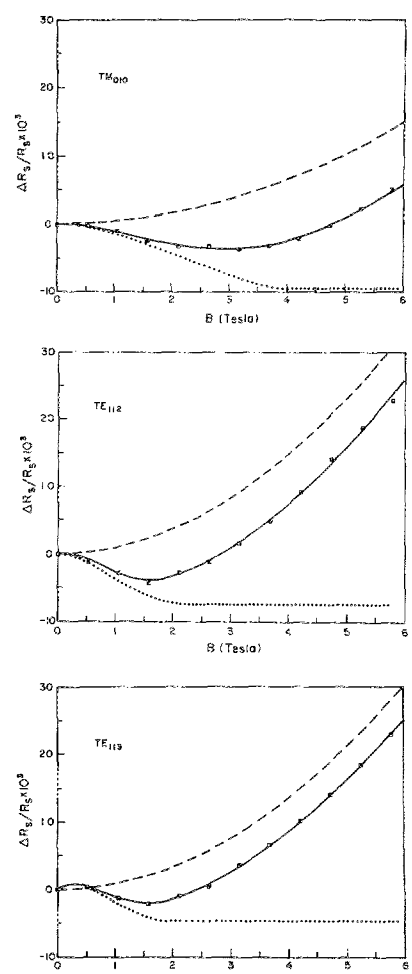

FIG. 3. Fractional change in surface resistance as a function of magnetic field. Dashed curve: quadratic fit to data for $B > 2.5$ T shifted to the origin at $B = 0$; dotted curve: residuals obtained by subtracting the quadratic effect from the data. Data are shown for three modes. The errors are typically $|\delta(\Delta R_s/R_s)| \lesssim 10^{-3}$.

negative of the fractional change in Q, is plotted as a function of B. We first note that $\Delta R_s/R_s$ for the TM_{010} is much smaller than for the TE_{112} and TE_{113} modes. This is expected because the TM_{010} current flow is predominantly parallel to the magnetic field, and longitudinal magnetoresistance is, in general, smaller than transverse magnetoresistance. The calculated fraction of resistive dissipation due to the transverse and longitudinal currents is given in Table I. Secondly, we observe that at high fields ΔR_s is proportional to B^2. This is in contrast to dc magnetoresistance which for polycrystalline Cu in this field range is nearly linear[11] in B. We note, however that dc magnetoresistance in single Cu crystals is quadratic[12] in B. The best quadratic fit to the high-field data ($B > 2.5$ T) is shown by the dashed curve in Fig. 3. We now assume that

$$\Delta R_s = \frac{I_{\parallel}^2}{I_{\parallel}^2 + I_{\perp}^2}\Delta R_{s\parallel} + \frac{I_{\perp}^2}{I_{\parallel}^2 + I_{\perp}^2}\Delta R_{s\perp} \qquad (8)$$

and from the data find[13]

$$\Delta R_{s\perp}/R_s = (1.21 \pm 0.06)\times 10^{-3} B^2,$$
$$\Delta R_{s\parallel}/R_s = (0.26 \pm 0.07)\times 10^{-3} B^2, \qquad (9)$$

where B is expressed in tesla.

In contrast to the quadratic dependence on B, as shown in Eqs. (9), the dc magnetoresistance is linear in the magnetic field. For our best fit value of RRR = 24 the bulk magnetoresistance at $B = 5.8$ T is[11,14] $\Delta\rho_{\perp}/\rho = 0.39$ and $\Delta\rho_{\parallel}/\rho \simeq 0.1$–$0.3$ depending on oxygen content. At the same field value, the measured data show a change in surface resistance of only a few percent. That the effect is so small can be attributed to the small skin depth associated with the rf surface current.[15]

Size effects. Of special interest is the behavior of $\Delta R_s/R_s$ at small magnetic fields. The data indicate a reduction in resistivity of *similar magnitude* for all three modes. By subtracting the quadratic fit from the $\Delta R_s/R_s$ data, we obtain the lower curve shown in Fig. 3; the data are summarized in Fig. 4. Similar effects are found in thin films or wires[16] when the conduction electrons are confined to smaller cyclotron orbits by the increasing magnetic field and thus suffer fewer collisions with the metal surface. The average cyclotron radius of a conduction electron is

$$r_c = k_F(\hbar c/eB) = (6.4\times 10^{-6})(1\ \mathrm{T}/B)m,$$

where we used $k_F \simeq 10^8\ \mathrm{cm}^{-1}$. This is to be compared with the mean free path, which for our best fit value of RRR = 24 is $l = 1.1\ \mu$m and with the classical skin depth at 1.2 GHz which is $\delta = 0.7\ \mu$m.

The initial decrease in conductivity appears to saturate at $B \sim 2$–3 T as seen in Fig. 4. At this field value the cyclotron radius is of the same order as the mean free path and skin

TABLE I. Properties of cavity modes.

Mode	f(GHz)	A	Q_0(4 K)	$I_{\perp}^2/(I_{\perp}^2 + I_{\parallel}^2)$
TM_{010}	1.415	378	1.13×10^5	0.16
TE_{112}	1.298	343	1.15×10^5	0.73
TE_{113}	1.523	473	1.15×10^5	0.58

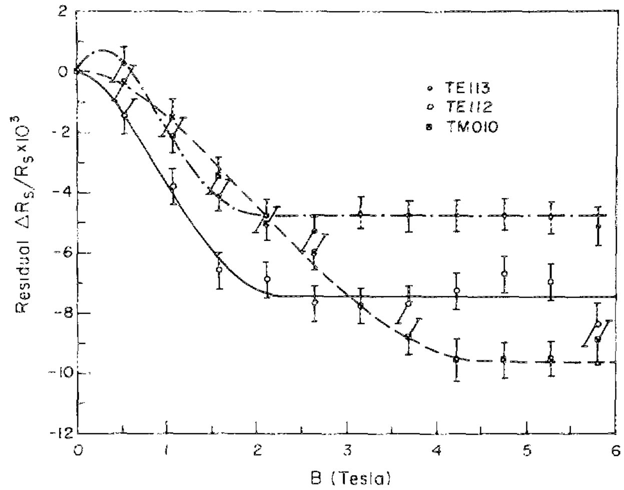

FIG. 4. Residuals for all three modes are of the same order and are attributed to a size effect.

depth. This is consistent with the assumption that the magnetic field decreases the rate of collisions with the surface and that the resultant increase in conductivity is due to the finite size of the rf conduction layer.[17] Negative rf magnetoresistance has been reported for superconducting aluminum and superconducting tin by Glosser.[18] In that case the maximum effect occurs as the critical field is approached. It would be of interest to establish whether these two similar effects have the same origin.

It is a pleasure to acknowledge the continued support of the High Energy Physics and AGS programs at Brookhaven National Laboratory. We thank Professor T. G. Castner for many valuable discussions and P. Borrelli and H. Hildebrand for important technical contributions. This work was supported by the U.S. Department of Energy.

[1]Hitachi, Ltd., alloy number C101000FE-HIT oxygen-free electronic copper.
[2]S. De Panfilis, A. C. Melissinos, B. E. Moskowitz, J. T. Rogers, Y. K. Semertzidis, W. U. Wuensch, H. J. Halama, A. G. Prodell, W. B. Fowler, and F. A. Nezrick, Phys. Rev. Lett. **59**, 839 (1987).
[3]Conceptual Design of the Superconducting Super Collider, SSC Central Design Group c/o LBL, Berkeley, CA.
[4]Proprietary copper electropolishing concentrate produced by Electro-glo Corporation, Chicago, IL.
[5]See, for instance, J. C. Slater, *Microwave Electronics* (Van Nostrand, Princeton, 1950).
[6]J. D. Jackson, *Classical Electrodynamics*, 2nd ed. (Wiley, New York, 1975), pp. 298, 339.
[7]H. Hahn and H. J. Halama, BNL Report AADD-129, January 1967 (unpublished).
[8]A. B. Pippard, Proc. R. Soc. London Ser. A **191**, 385 (1947).
[9]Our own measurement of an annealed wire sample obtained from this copper gave RRR = 180.
[10]J. A. Bamberger, G. T. Mulholland, A. G. Prodell, H. A. Worwetz, and C. N. Whetstone, Adv. Cryog. Eng. **13**, 132 (1967).
[11]Selected Cryogenic Data Notebook, Brookhaven National Laboratory Report BNL 10200-R, Vol. I, 1980.
[12]J. L. Olsen, *Electron Transport in Metals* (Interscience, New York, 1967), p. 74.
[13]The values of $\Delta R_{s\perp}/R_s$ and $\Delta R_{s\parallel}/R_s$ obtained from the TM_{010} and TE_{112} pair are in agreement with those from the TM_{010} and TE_{113} pair.
[14]R. L. Dolecek, Phys. Rev. **119**, 1501 (1960).
[15]In the extreme anomalous skin effect limit one expects R_{∞} to be independent of B.
[16]R. G. Chambers, Proc. R. Soc. London Ser. A **202**, 378 (1950); E. H. Sondheimer, Adv. Phys. **1**, 1 (1952).
[17]The observed effects for thin wires are considerably larger than those found in this investigation; see also Ref. 12.
[18]R. Glosser, Phys. Rev. **156**, 500 (1967) and references therein.