Surface Impedance of Normal Conducting Films Deposited on Superconducting Substrates*

HANS MEISSNER and ROBERT V. FANELLI
Stevens Institute of Technology, Hoboken, New Jersey

I. INTRODUCTION

Direct current measurements of the contact resistance of superconducting wires plated with normal metals,[1] as well as tunneling measurements of the energy gap in normal films evaporated onto superconducting films,[2] indicate the presence of an energy gap in a normal conductor adjoining a superconductor. Several authors[3–6] have proposed theoretical explanations, all of which lead to a finite energy gap in the adjoining normal conductor. In contrast to this we have found that the microwave absorption at 9 kMc/sec in gold and copper films electroplated onto tin substrates does not extrapolate to zero at absolute zero for films thicker than about 500 Å. We then proceeded to measure the penetration depth in gold-plated single crystals of tin using the method developed by Schawlow and Devlin.[7] By also measuring the resonance curves of the LC circuit used in this method we were able to obtain the change in the absolute value of the superconducting penetration depth with gold thickness. It was found that the penetration depth (counted from the outer surface of the gold) increases for films thicker than 870 Å by about the same amount by which the gold thickness is increased.

II. SURFACE RESISTANCE AT 9 kMc/sec (R. V. FANELLI)

The surface resistance of gold- or copper-plated tin was measured at 9 kMc/sec using the method of Fawcett.[8] The experimental arrangement is shown in the insert of Fig. 1. The absorption is measured calorimetrically by replacing the microwave power with heat developed in a little heater. The amount of heat is adjusted until the temperature rise of the end plate is duplicated. A second end plate, made from copper, serves to monitor the power level in the cavity. This method eliminates any ambiguity in the zero point of the absorption. The sample, a cast tin plate consisting of a few large crystals, was electrolytically polished, plated with the desired thickness, installed, and immediately cooled to liquid-nitrogen temperature. After the run, the normal metal film was electrolytically dissolved in KCN solution. The plate was then repolished and plated for the next run.

Figure 1 shows a few representative curves of the surface resistance R of the sample relative to R_{Cu}, the surface resistance of the copper reference plate plotted as a function of the temperature. It can be seen that even the heavily plated samples show a sharp decrease of the absorption at the critical temperature. The curves extrapolate to a finite resistance for gold films as thin as 500 Å.

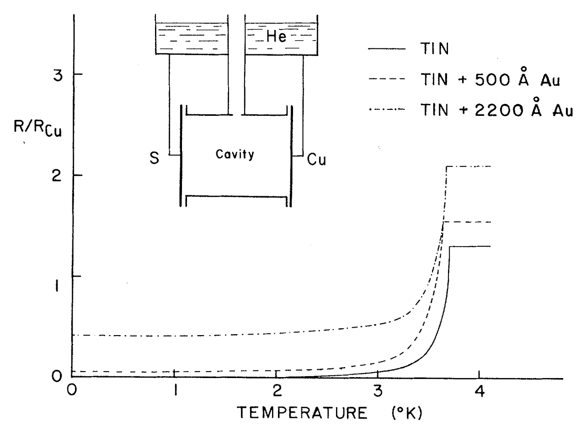

FIG. 1. Surface resistance R of the sample plate S relative to that of the copper reference plate Cu as a function of temperature.

Figure 2 shows the dependence of R_n/R_{Cu}, the resistance in the normal state, and of R_0/R_{Cu}, the resistance at absolute zero, on the thickness of the gold film. Both curves are roughly parallel and R_0/R_{Cu} goes to zero at a gold thickness of about 200 Å.

The following working model was developed for

* Work supported by the U.S. Office of Naval Research and the U.S. Department of Defense.

[1] H. Meissner, Phys. Rev. Letters **2**, 458 (1959); Phys. Rev. **117**, 672 (1960).
[2] P. H. Smith, S. Shapiro, J. L. Miles, and J. Nicol, Phys. Rev. Letters **6**, 686 (1961).
[3] L. N. Cooper, Phys. Rev. Letters **6**, 89 (1961).
[4] D. H. Douglass, Jr., Phys. Rev. Letters **9**, 155 (1962).
[5] P. G. De Gennes and E. Guyon, Phys. Letters **3**, 168 (1963).
[6] N. R. Werthamer (to be published). The authors are greatly indebted to Dr. Werthamer for a preprint of this paper.
[7] A. L. Schawlow and G. E. Devlin, Phys. Rev. **113**, 120 (1959).
[8] E. Fawcett, Proc. Roy. Soc. (London) **A232**, 519 (1955).

the interpretation of the data: It was assumed that the normal metal always exhibits a normal skin effect and that the tin has a complex surface impedance $Z_{Sn} = R_{Sn} - jX_{Sn}$. The application of the complex Poynting vector theorem then gives for the real part of the Poynting vector S:

$$\mathrm{Re}\,(S) = \tfrac{1}{2} H_0^2\{R_{Sn} + [(X_{Sn}^2 - R_{Sn}^2)/R_g]\tau + 2X_{Sn}\tau^2 + \tfrac{4}{3} R_g\tau^3\}\,, \quad (1)$$

where H_0 is the magnetic field at the outer surface of the gold, R_g is the surface resistance of the gold, and $\tau = t/\delta_g$, the ratio of gold thickness to skin depth in

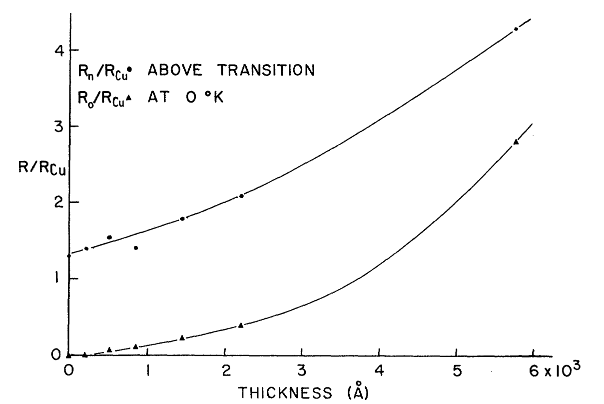

FIG. 2. Normal resistance R_n/R_{cu} and resistance at 0°K, R_0/R_{cu} as a function of gold thickness.

the gold. Terms with τ^3 and $(R_{Sn}/R_g)\tau^2$ have been neglected, but terms with $(R_g/R_{Sn})\tau^3$ have been kept in this calculation.

If the tin is normal, we assume the extreme anomalous limit, that is $X_{Sn} = \sqrt{3}\, R_{Sn}$. Equation (1) then gives for the normal surface resistance of the sample R_n:

$$R_n = R_{Sn} + 2(R_{Sn}^2/R_g)\tau + 2\sqrt{3}\, R_{Sn}\tau^2 + \tfrac{4}{3} R_g\tau^3\,. \quad (2)$$

Normalizing to the surface resistance of the copper plate and subtracting the resistance of the bare tin plate gives:

$$\frac{R_n}{R_{Cu}} - \frac{R_{Sn}}{R_{Cu}} = \frac{1}{\delta_g^2}\left[2\,\frac{R_{Sn}^2}{R_{Cu}^2}\,\delta_{Cu}t + 2\sqrt{3}\,\frac{R_{Sn}}{R_{Cu}}\,t^2 + \frac{4}{3}\,\frac{1}{\delta_{Cu}}\,t^3\right], \quad (3)$$

where δ_{Cu} is the skin depth in the copper (anomalous skin effect).

If the tin is superconducting at $T = 0$°K we have to use in Eq. (1) $X_{Sn} = \mu_0\omega\lambda$ and $R_{Sn} = 0$. Assuming that the gold is still fully normal gives for R_0, the resistance of the sample at absolute zero:

$$\frac{R_0}{R_{Cu}} = \frac{1}{\delta_g^2}\left[4\,\frac{\lambda^2}{\delta_{Cu}}\,t + 4\,\frac{\lambda}{\delta_{Cu}}\,t^2 + \frac{4}{3}\,\frac{1}{\delta_{Cu}}\,t^3\right]. \quad (4)$$

We have evaluated δ_g from the measurements of the normal resistance, using Eq. (3) and inserted this value into Eq. (4) obtaining the expected absorption at $T = 0$ if the gold were fully normal. Using $\lambda = 570$ Å for the penetration depth in the tin the values tabulated in Table I were obtained.

III. SUPERCONDUCTING PENETRATION DEPTH AT 1.2 Mc/sec

The method of Schawlow and Devlin[7] that was used for these measurements involves an inductance which tightly surrounds the sample in the shape of a cylindrical rod of 3.4-mm o.d. and 80-mm length. The coil is connected to a capacitor C of 15 000 pF. The capacitor was made from OFHC copper foil and mica. It was enclosed in a vacuum-tight can with copper terminals embedded in Stycast 2850 GT epoxy.[9] Even so it was found that there were shifts in the frequency with the density of the liquid helium, leading to a distortion of the penetration depth vs temperature curves below the λ point. Whether the capacitor was still slightly leaking or whether the effect results from stray capacitances could not yet be established.

The sample received the same treatment as the tin end plates. The absolute values of the penetration depth can be obtained by measuring the resonance curves just above the transition temperature and at some low temperature. By using the complex Poynting vector theorem one can show that the difference between the resonant frequencies f_n (in the normal state) and f_s (in the superconducting state) is given by:

[9] The authors are indebted to T. Seidel for drawing their attention to this epoxy compound.

TABLE I. Values of R_0/R_{Cu} calculated from the normal resistance and actually observed values.

Metal	Au						Cu			
Thickness, Å	190	500	840	1440	2200	5760	526	797	1060	1970
$R_0/R_{Cu,calc.}$	0.023	0.072	0.042	0.204	0.391	2.05	0.035	0.084	0.140	0.298
$R_0/R_{Cu,obs.}$	0.00	0.051	0.117	0.224	0.398	2.87	0.00	0.021	0.131	0.420

$$2\frac{f_s - f_n}{f_n} = \frac{\Delta L}{L} = K\left[\frac{X}{\mu_0\omega} - \lambda_0\right] \tag{5}$$

with

$$X = \sqrt{3}R_{\mathrm{sn}}\left[1 + 2\left(\frac{R_g}{\sqrt{3}R_{\mathrm{sn}}} - \frac{R_{\mathrm{Sn}}}{R_g}\right)\tau\right], \tag{6}$$

where L is the self-inductance of the coil with sample, K is a calibration constant involving the diameter of the sample and the frequencies of the coil with sample and the empty coil. In the derivation it has been assumed that the tin exhibits an extremely anomalous skin effect and that the gold has the normal skin effect when the tin is normal.

The change in the absorption between the two temperatures is given by

$$1/Q_n - 1/Q_s = KR/\mu_0\omega \tag{7}$$

with

$$R = R_{\mathrm{Sn}}[1 + (R_{\mathrm{Sn}}/R_g)\tau]. \tag{8}$$

The values of R_g are taken from the microwave data,

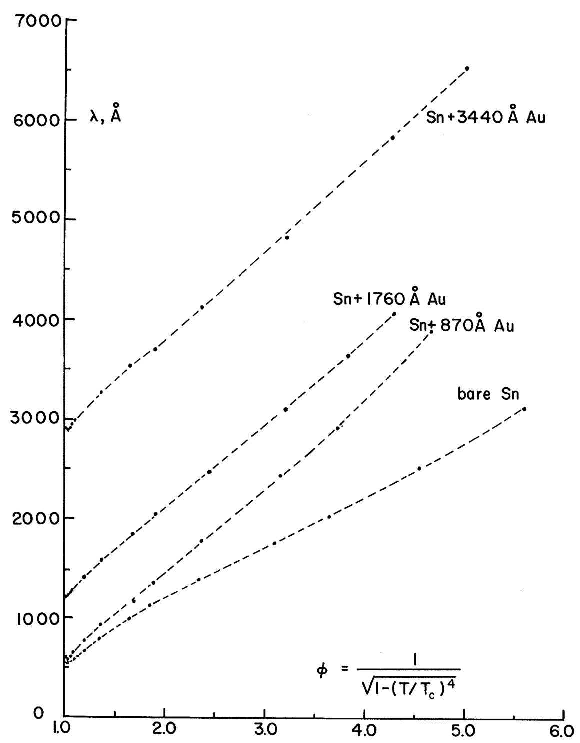

FIG. 3. Superconducting penetration depth λ as a function of ϕ.

corrected for our frequency. While $(R_{\mathrm{Sn}}/R_g)\tau$ is negligibly small, $(R_g/\sqrt{3}R_{\mathrm{Sn}})\tau$ amounts to a few 10^{-2} and has to be taken into account. Equations (5) and (6) can then be solved for λ_0. The method assumes that there are no other frequency shifts or changes in Q between the two resonance curves. Actually this is not quite true. For instance the series resistance of capacitor foil and leads will change with frequency, as will the absorption in the mica. Since the capacitor was put into operation only very recently not enough data have been accumulated in order to determine these corrections.

TABLE II. λ_0 and $d\lambda/d\phi$ for gold plated tin samples. All values are in Å.

gold thickness t	$\lambda_0(t) - \lambda_0(870)$	$t - 870$	$d\lambda/d\phi$
0	...	...	522
870	0	0	942
1760	631	890	840
3440	2305	2570	883

Since the same sample and circuit was used for all of the recent measurements, we expect that these shifts should always be the same and that we still should be able to evaluate changes in λ_0 from one gold thickness to the other. Unfortunately, we had to exclude the bare tin sample because the measurements gave a slightly smaller value of R [see Eq. (8)] than for the plated ones. This can be caused by the plated samples not being in the extreme anomalous limit. This changes the factor $\sqrt{3}$ in Eq. (6) to a slightly smaller value. The value of this shift could not be ascertained yet and therefore we are not able to compare the bare sample with the plated samples.

In Fig. 3 the penetration depth λ is plotted as a function of $\phi = [1 - (T/T_c)^4]^{-\frac{1}{2}}$ for samples with various gold thicknesses. We have arbitrarily assigned to the bare sample a value of $\lambda_0 = 570$ Å and to the sample plated with 870 Å gold a value of $\lambda_0 = 600$ Å.

The slopes of the curves for the plated samples are all larger than those of the curve for the bare sample. This was not observed in the earlier measurements reported at the last Washington meeting.[10] The different behavior is attributed to the very short time for which the new samples have been exposed to room temperature in the recent runs. This allowed for less diffusion and, according to experience with multiple films[11] leads to the gold being "more normal" than for diffused samples.

Table II lists the gold thicknesses, the change in λ_0, and the slope $d\lambda/d\phi$ for the various samples.

[10] H. Meissner, Bull. Am. Phys. Soc. 8, 307 (1963), paper E2.
[11] R. Duffy (private communication).

IV. CONCLUSIONS

Both of the experiments described above indicate that gold or copper films of a thickness larger than 500 Å adjoining tin behave as if they are almost completely normal. Only a refined theory can decide whether this result is still in agreement with present ideas, or whether modifications, for instance the assumption of a strong anisotropy of the energy gap in the normal film, are required.

ACKNOWLEDGMENTS

The authors gratefully acknowledge interesting discussions and help with computations by Dr. Harold Salwen.

Discussion 30

M. A. JENSEN, *University of California:* Can you predict possibly the value of $N(0)V$ or the transition temperature of pure gold using this technique? I think Hilsch did something like this with copper and some other superconductor.

H. MEISSNER, *Stevens Institute of Technology:* We have not perfected this particular technique up to that point.

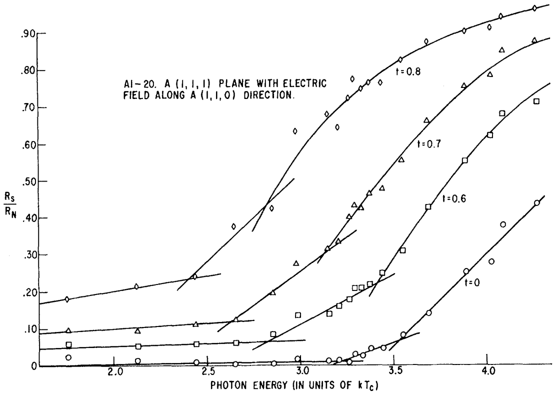

FIG. 6. Frequency dependence of the microwave absorption for a single crystal at various temperatures. The two knees in each curve suggest two energy gaps observable at this orientation and polarization.

GARFUNKEL: I'd like to report some preliminary results of an experiment that I've been doing in collaboration with William A. Thompson and Manfred A. Biondi on the determination of energy gap anisotropy in aluminum by microwave absorption. A single crystal face of aluminum was irradiated with polarized microwaves and the absorption measured calorimetrically for various temperatures and frequencies. Aluminum is a face centered cubic crystal. First we see (Fig. 6) the measured absorption, plotted as surface resistance ratio vs photon energy. This is for a [111] plane with the electric field polarized along the [110] direction. The different curves are for different temperatures, the lowest being an extrapolation to $T = 0$. For photon energies up to about 3.2 kT_c there is no absorption, then an increase to about 3.5 kT_c where an even faster increase begins, making another knee in the curve. The two knees of the curve are very suggestive of two energy gaps. As we go to higher temperature the gaps move to smaller values as one expects. The values of these two gaps as a function of temperature are given (Fig. 7). They each have more or less the right temperature dependence. Remember that these curves are for a single polarization on a single orientation. Along with the data for the [111] plane (the lower curve), are given data for a [110] plane. The two curves [Fig. 8] have the same general features except that the gaps do not coincide—the knees occur at different frequencies. Comparison between these two curves gives us the anisotropy. The smallest gap is 3.09 kT_c for the [110] plane and 3.20 kT_c for the [111] plane. This corresponds to an anisotropy of about 3% between these two planes. We have also done some very preliminary measurements on a [100] plane and from these results we infer that the anisotropy is not any larger. On the other hand, the two gaps that are suggested by the two knees observed in each of these directions differ by about 10%. In looking for an explanation of these observations, one thinks of the two pieces of Fermi surface in aluminum each contributing a different superconducting energy gap, and each having some anisotropy.

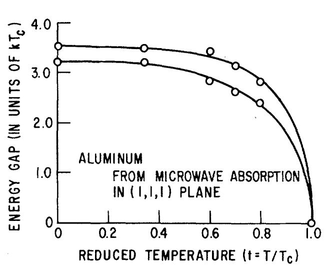

FIG. 7. Temperature dependence of the two observed energy gaps for a single sample orientation and microwave polarization.

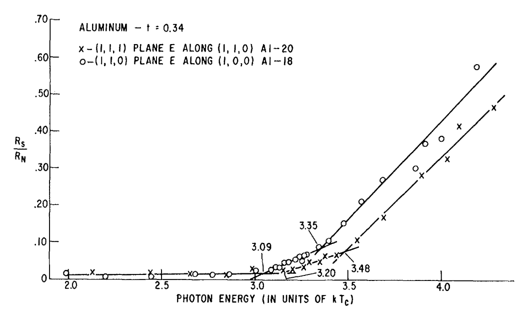

FIG. 8. Frequency dependence of the microwave absorption for two crystal orientations showing the anisotropy of the energy gap.