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Superconductivity of Contacts with Interposed Barriers*

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Resistance *vs* current diagrams and "Diagrams of State" have been obtained for 63 contacts between crossed wires of tin. The wires were plated with various thicknesses of the following metals: copper, silver, gold, chromium, iron, cobalt, nickel, and platinum. The contacts became superconducting, or showed a noticeable decrease of their resistance at lower temperatures if the plated films were not too thick. The limiting thicknesses were about 35×10^{-6} cm for Cu, Ag, and Au; 7.5×10^{-6} cm for Pt, 4×10^{-6} cm for Cr, and less than 2×10^{-6} cm for the ferromagnetic metals Fe, Co, and Ni. The investigation was extended to measurements of the resistance of contacts between crossed wires of copper or gold plated with various thicknesses of tin. Simultaneous measurements of the (longitudinal) resistance of the tin-plated gold or copper wires showed that these thin films of tin do not become superconducting for thicknesses below certain minimum values. These latter findings are in agreement with previous measurements at Toronto. The measurements at Toronto usually were believed to be unreliable because films of tin evaporated onto quartz substrates can be superconducting at thicknesses as small as 1.6×10^{-6} cm. It is now believed that just as superconducting electrons can drift into an adjoining normal conducting layer and make it superconducting, normal electrons can drift into an adjoining superconducting layer and prevent superconductivity.

I. INTRODUCTION

THIS investigation was started in order to obtain an understanding of the mechanism which gives rise to the superconductivity of contacts. The first part of this work has already been published[1] giving the historical background and detailed results on contacts between crossed wires of clean tin, tin plated with various thicknesses of copper, tin and indium, and tin and copper. Several short communications[2–3] have reported further progress. Since publication of the first report measurements on over 63 contacts have been collected. In order to conserve journal space only a few representative diagrams and abbreviated tables shall be presented here. All details can be found in an unpublished report which is on file at government agencies.[4]

II. EXPERIMENTAL ARRANGEMENT

The cryostat, the circuit, the mount for the contacts, and the automatic temperature control were essentially the same as described in reference 1 with only a few refinements added. The temperature was determined from the vapor pressure above the liquid helium, using the 1955_E vapor pressure scale.[5] A standard U-type manometer was used for vapor pressures above 5 mm and a simple compression manometer for vapor pressures between 2 and 5 mm.

In order to facilitate entries in tables it was tried to measure at certain "standard" temperatures (1.49, 2.30, 2.65, 3.05, 3.44, 3.72, and 4.21°K). However, it proved to be somewhat difficult to adjust the automatic temperature control such that it would settle exactly at the desired temperature (e.g., 1.49°K) and the actual temperature usually was somewhat different (e.g., 1.46° to 1.51°K). In all tables below only the "standard" temperatures will be given, while the actual temperatures may have been slightly different and can be obtained from the resistance *vs* current diagrams contained in the report of reference 4.

III. EXPERIMENTAL PROCEDURE

The tin wires were electrolytically polished and immediately plated with the desired metal. The efficiency of the plating was determined by prolonged plating and weighing. The thicknesses were calculated from the plating time. The solutions and their calibrations are listed in the report of reference 4. Several of them were commercial solutions. It was learned only very recently that commercial nickel solutions may contain some cobalt. A check for cobalt was made in the nickel solution used and it was found that it did indeed contain some cobalt. The copper wires were also electrolytically polished and then plated with various thicknesses of tin, while the gold wires were only electrolytically cleaned before the tin plating. The arrangement used for the measurement of the (longitudinal) resistance of tin plated copper or gold wires will be described with the measurements.

All wires were immediately installed, the Dewar vessel was closed, evacuated and filled with dry helium gas. It was precooled by means of an inserted well, which was filled with liquid nitrogen. After the well was removed the helium siphon was connected with

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[1] Hans Meissner, Phys. Rev. **109**, 686 (1958).

[2] William R. Callahan and Hans Meissner, Suppl. Physica 24, 154 (1958).

[3] Hans Meissner, Phys. Rev. Letters 2, 458 (1959).

[4] "Studies of Contacts with Barriers in Between," by Hans Meissner, on file at the Armed Services Technical Information Agency (ASTIA), Air Research and Development Command, U. S. Air Force, Arlington Hall Station, Arlington 12, Virginia (Document No. AD-225 070). It has also been deposited as Document No. 6131 with the ADI Auxiliary Publications Project, Photoduplication Service, Library of Congress, Washington 25, D. C. A copy may be secured by citing the Document number and by remitting $7.50 for photoprints, or $2.75 for 35-mm microfilm. Advance payment is required. Make checks or money order payable to: Chief, Photoduplication Service, Library of Congress.

[5] Clement, Logan, and Gaffney, Phys. Rev. **100**, 743 (1955). See "Note added in proof."

its valve closed and the Dewar reevacuated before filling with liquid helium. The contacts were closed only after the siphon was removed and everything was ready for the run. The time which elapsed between the cleaning or polishing of the wires and the closing of the contacts was less than two hours.

Usually a contact load of 50 to 60 g (weight) was used. Only in a few runs much larger loads were used in order to check the dependence of various quantities on contact area.

It should be noted that the electrical circuitry is such that the potential across the contact can never exceed 50 millivolts, even if the contact is open. Any possibility of the formation of a metallic bridge due to coherer action is therefore excluded (see reference 1).

IV. MEASUREMENTS ON CONTACTS BETWEEN PLATED TIN WIRES

The data obtained are much too numerous to permit publication in detail. Instead it has been tried to classify the resistance *vs* current diagrams as well as the diagrams of state according to their appearance.

The resistance *vs* current diagrams (see Figs. 1–3) have been classified according to the abruptness with which the resistance appears when the current through the contact is increased at a temperature well below the transition temperature of tin. Contacts of type A show a very abrupt increase of the resistance such that one is under the impression that for currents slightly smaller than the "critical current" the resistance of the contact is not only immeasurably small but truly zero. Contacts of type B (see Fig. 2) show some "tails" at the low current side of the resistance *vs* current curves. For these it is debatable whether the resistance attains only immeasurable small but finite values or whether it becomes truly zero. Contacts of type C show resistance *vs* current curves with very long "tails" and it seems unlikely that their resistance vanishes even at the lowest temperatures and smallest currents.

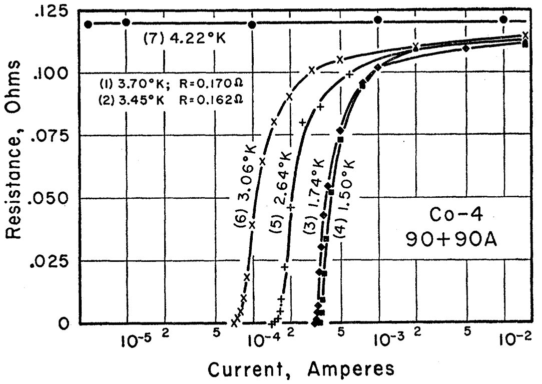

FIG. 1. Resistance *vs* current diagram of cobalt-plated contact Co 4, representative of diagrams type A.

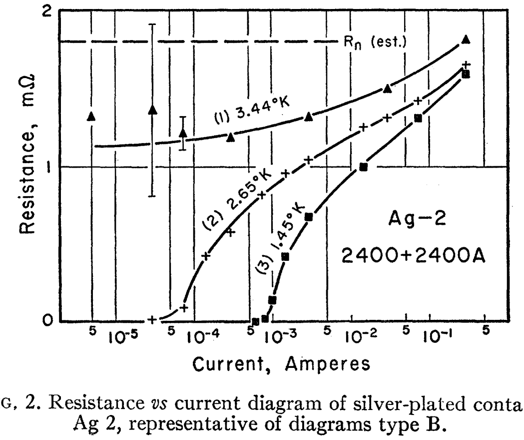

FIG. 2. Resistance *vs* current diagram of silver-plated contact Ag 2, representative of diagrams type B.

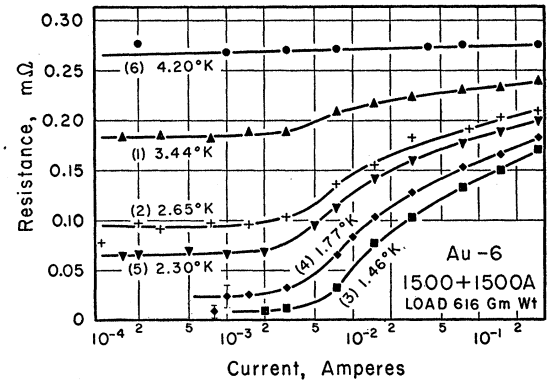

FIG. 3. Resistance *vs* current diagram of gold-plated contact Au 6, representative of diagrams type C.

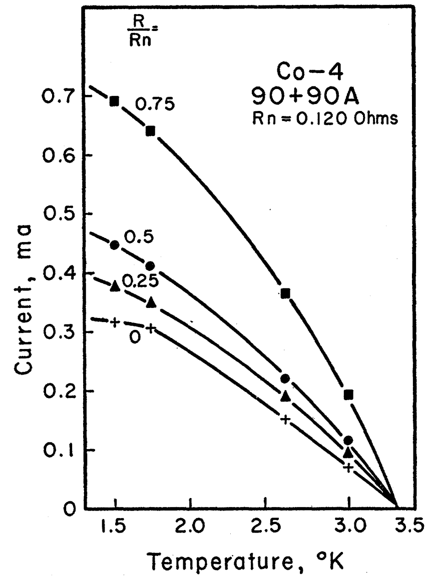

FIG. 4. Diagram of state of cobalt-plated contact Co 4, representative of diagrams type I.

The diagrams of state, that is curves of constant R/R_n in I-T space (R_n=resistance in normal conducting state) have been divided into three classes (see Figs. 4–6):

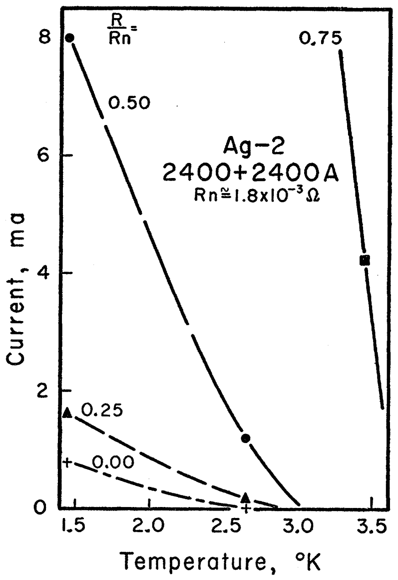

FIG. 5. Diagram of state of silver-plated contact Ag 2, representative of diagrams type II.

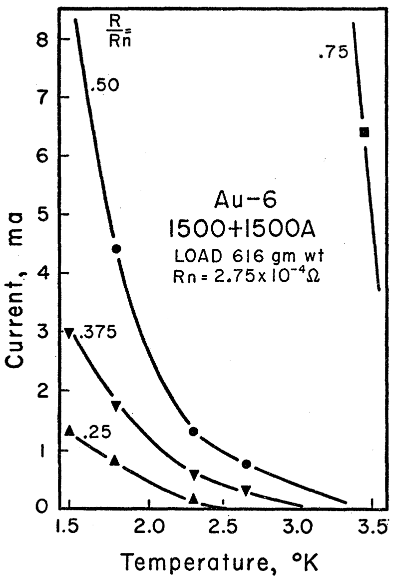

FIG. 6. Diagram of state of gold-plated contact Au 6, representative of diagrams type III.

Type I (see Fig. 4) are diagrams where the curves for values of R/R_n equal to 0, 0.25, and 0.5 are all three approximately parabolic and intersect the temperature axis very closely in one point, defining a critical temperature T_c independent of the choice of the value of R/R_n.

Type II (see Fig. 5) are diagrams where the curves of constant R/R_n within the range $0\leqslant R/R_n\leqslant 0.5$ approach the temperature axis with decreasing slope, such that the slope becomes approximately zero for all curves at about the same temperature, thus again defining a critical temperature independent of the choice of R/R_n.

Type III (see Fig. 6) are diagrams where the curves of R/R_n equal to 0, 0.25, and 0.5 do not intersect or touch the temperature axis at the same temperatures such that the definition of the critical temperature depends strongly on the choice of the value of R/R_n.

As in reference 1 and for the reasons given there the "critical current" shall be defined as the current which restores the resistance to a value of $R=0.25\ R_n$. Whenever the critical temperature depends on the choice of the value of R/R_n for its definition (such as in diagrams of type III) the critical temperature shall be defined as the temperature at which the curve $R=0.25\ R_n$ intersects or touches the temperature axis.

Table I lists the plated metal, the thickness of the plating, the normal resistance, the contact load, critical currents at various temperatures, the critical temperature, and the types of *R vs I* diagram and diagram of state. For purposes of comparison the list contains also data for two clean tin contacts and for 4 symmetrical copper-plated contacts which were described already in detail in reference 1.

V. DISCUSSION OF THE DATA ON CONTACTS BETWEEN PLATED TIN WIRES

It is usually assumed, that the contact resistance is the sum of three parts: The channel resistance R_{ch} on one side, the barrier resistance, R_B and the channel resistance on the other side. If the metal has a resistivity ρ, the barrier a resistivity per unit area σ and the radius of smallest constriction of the current is α_{ch}, one finds

$$R_{\text{ch}}=\rho/4\alpha_{\text{ch}}, \tag{1}$$

and

$$R_B=\sigma/\pi\alpha_{\text{ch}}^2. \tag{2}$$

The current bearing radius α_{ch} can be compared with the load bearing radius α_L which one calculates from the force F on the contact and the flow pressure P:

$$\alpha_L=(F/\pi P)^{\frac{1}{2}}. \tag{3}$$

One can consider the narrow current channel as a piece of a thin wire and apply the criteria for the destruction of superconductivity in thin wires to it. If the radius α_H of this hypothetical wire is large compared to the superconducting penetration depth δ, the critical current I_c is connected with the critical field H_c by Silsbee's rule:

$$I_c=2\pi\alpha_H H_c. \tag{4}$$

Since the temperature dependence of H_c is approximately given by

$$H_c=H_{c0}[1-(T/T_c)^2], \tag{5}$$

and α_H in Eq. (4) is presumably temperature independent, one expects that the temperature dependence of the critical current is the same as that of the critical field as long as $\alpha_H\gg\delta$. The contacts which have dia-

Table I. Data on contacts between plated tin wires.

				Critical current in ma							
Contact	Thickness 10^{-6} cm	R_n milliohms	Load g(wt)	I_1 1.49°	I_2 2.30°	I_3 2.65°	I_4 3.08°	I_5 3.44°	T_c °K	R *vs* I type	Diagram of state type
A	0+0	148	60	⋯	⋯	4.8	2.8	0.65	3.55	B	I
B	0+0	1050	60	⋯	⋯	0.19	0.12	0.017	3.51	B	I
(Cu-)5	5.0+5.0	80	60	⋯	⋯	0.28	0.090	0.005	3.489	B	II
(Cu-)7	10+10	1.44	60	⋯	⋯	0.35	0.043	⋯	3.30	A	II
(Cu-)8	25+20	0.90	60	0.13	⋯	⋯	⋯	⋯	~3.3	A	II
(Cu-)13	50+50	2.0	60	slight decrease of resistance at 50 μa and 1.45°K							
Ag 1	12+12	1.25	60	9.5	⋯	0.09	⋯	⋯	2.68	B	II
Ag 2	24+24	1.8	60	1.6	⋯	0.15	⋯	⋯	2.85	B	II
Ag 3	36+36	2.8	60	0.32	⋯	0.01	⋯	⋯	2.74	C	III
Au 1	1.0+1.0	592	60	0.45	0.32	0.22	0.010	⋯	3.45	B	I
Au 2	3.0+3.0	12.5	60	32	26	21	15.5	2.2	3.48	B	I
Au 3	10+10	1.26	60	12	3.0	1.4	0.2	⋯	3.2	B	II
Au 4	10+20	11.1	60	0.09	0.001	⋯	⋯	⋯	2.5	C	III
Au 5	15+15	1.0	50	5.9	1.6	⋯	⋯	⋯	2.7	C	III
Au 6	15+15	0.27	616	13	1.5	⋯	⋯	⋯	2.5	C	III
Au 7	15+15	0.22	934	22	4	0.7	⋯	⋯	2.8	B	III
Au 8	30+40	1.55	60	<0.002	⋯	⋯	⋯	⋯	1.5	C	⋯
Au 9	100+100	5.9	60	normal conducting at 5 μa and 1.5°K							
Cr 1	0.5+0.5	2.4	60	⋯	⋯	160	69	4.9	3.52	A	II
Cr 2	0.75+0.75	22.6	60	⋯	⋯	23	13	1.5	3.52	B	I
Cr 3	1.0+1.0	380	60	⋯	⋯	1.8	0.8	0.09	3.50	B	II
Cr 4	1.0+1.0	5.7	60	180	⋯	101	⋯	18	3.72	A	I
Cr 5	2.0+2.0	22.5	60	0.58	⋯	0.20	⋯	0.03	3.72	A	II
Cr 6	2.0+2.0	33	60	normal conducting at 5 μa and 1.48°K					⋯	⋯	⋯
Cr 7	3.0+3.0	56.1	60	0.15	⋯	0.070	0.033	⋯	3.45	A	I
Cr 8	5.0+5.0	7.6	60	normal conducting at 5 μa and 1.48°K					⋯	⋯	⋯
Cr 9	5.0+5.0	26.5	60	normal conducting at 5 μa and 1.48°K							
Cr 10	10+10	41.0	60	normal conducting at 5 μa and 1.48°K							
Fe 1	0.5+0.5	460	60	0.56	⋯	0.15	0.056	⋯	3.3	A	II
Fe 2	0.5+0.5	240	60	0.022	⋯	⋯	⋯	⋯	1.49	B	⋯
Fe 3	1.0+1.0	14.7	60	normal conducting at 5 μa and 1.49°K							
Fe 4	2.0+2.0	19.2	60	normal conducting at 5 μa and 1.49°K							
Fe 5	2.0+2.0	69.0	60	normal conducting at 5 μa and 1.49°K							
Co 1	0.45+0.45	3200	60	normal conducting at 5 μa and 1.48°K							
Co 2	0.5+0.5	18.6	60	⋯	⋯	⋯	15	2.3	3.52	B	II
Co 3	0.5+0.5	193	60	0.033	⋯	0.001	⋯	⋯	2.7	B	III
Co 4	0.9+0.9	120	60	0.38	⋯	0.19	0.095	⋯	3.38	A	I
Co 5	1.0+1.0	34	60	⋯	⋯	10	6	1.05	3.52	B	I
Co 6	1.0+1.0	10.8	60	0.044	⋯	⋯	⋯	⋯	2.2	B	III
Co 7	2.0+2.0	68.2	60	⋯	⋯	2.8	0.8	0.3	3.52	B	II
Co 8	2.0+2.0	66	60	normal conducting at 5 μa and 1.48°K							
Co 9	2.0+2.0	0.76	60	⋯	⋯	350	210	45	3.60	C	I
Co 10	5.0+5.0	4.4	60	normal conducting at 5 μa and 1.48°K							
Co 11	8.0+8.0	11.5	60	normal conducting at 5 μa and 1.48°K							
Ni 1	0.5+0.5	1940	60	0.114	0.068	0.042	0.018	⋯	~3.7	C	II
Ni 2	0.5+0.5	205	750	0.22	0.095	0.066	⋯	⋯	~3.2	B	III
Ni 3	0.5+0.5	600	60	⋯	0.42	0.28	0.12	⋯	~3.5	B	III
Ni 4	0.5+0.5	650	500	⋯	0.30	0.28	0.18	0.13	3.58	B	I
Ni 5	0.5+0.5	8	830	⋯	0.30	0.29	0.27	0.04	3.45	B	II
Ni 6	0.75+0.75	4000-12 000	60	normal conducting at 5 μa and 1.5°K							
Ni 7	0.75+0.75	38.7	670	0.11	⋯	⋯	⋯	⋯	~2.3	C	III
Ni 8	0.75+0.75	96.3	1000	Resistance always larger than 0.25 R_n					~1.5°K	C	III
Ni 9	1.0+1.0	76.6	60	0.038	0.001	⋯	⋯	⋯	~2.3°K	C	III
Ni 10	1.0+1.0	485	670	only small decrease of resistance at 5 μa and 1.45°K							
Ni 11	3.0+3.0	9.8	60	normal conducting at 5 μa and 1.49°K							
Ni 13	5.0+5.0	2500	60	normal conducting at 5 μa and 1.49°K							
Ni 14	10+10	430	60	small decrease of resistance at 1.44°K and 2.66°K, not very stable							
Ni 15	30+30	10	60	normal conducting at 5 μa and 1.47°K							
Pt 1	0.5+0.5	1590	60	0.66	⋯	0.44	⋯	0.075	3.56	B	I
Pt 2	1.0+1.0	412	60	2.05	⋯	1.40	⋯	0.20	3.53	B	I
Pt 3	1.5+2.0	88	60	10.5	⋯	6.5	⋯	0.25	3.46	B	I
Pt 4	3.0+3.0	1580	60	0.29	⋯	0.19	⋯	0.002	3.49	C	III
Pt 5	5.0+5.0	78	60	2.8	⋯	1.9	⋯	0.29	3.56	C	I
Pt 6	7.5+7.5	1400	60	0.026	⋯	⋯	⋯	⋯	~2	C	⋯
Pt 7	10+10	5600	60	normal conducting at 5 μa and 1.49°K							
Pt 8	20+20	107	60	normal conducting at 5 μa and 1.49°K							
Pt 9	30+30	460	60	normal conducting at 5 μa and 1.49°K							

grams of state type I have approximately this temperature dependence and one will therefore expect that for them $\alpha_H \gg \delta$.

As discussed in reference 1, the pressure on the contact shifts the critical temperature to lower values and one finds good agreement between the flow pressure calculated from this pressure shift and direct measurements of the flow pressure. Since the force on the contact is known, one can calculate α_L from Eq. (3) and finds values of about 10^{-3} cm.

One can show (see the report of reference 4) that for the bare tin contacts A and B the major part of the resistance cannot be channel resistance but must be barrier resistance. It is very likely that tin exposed to the atmosphere within a matter of a few seconds is covered with a very thin oxide film and that this oxide film contributes most of the resistance. If one compares the absolute values of plated contacts one observes that frequently the total resistance decreases with increasing thickness of the plated metal: The plating moves the tin oxide film from the point of narrowest current construction to a wider part of the channel where its contribution to the resistance is smaller (see contact Cu 5, Cu 7, Cu 8; Au 1, Au 2, Au 3). Most of the other metals, if freshly cleaned, do not seem to have such a high resistance surface film.

On the other hand, one can show that the resistance of the heavily gold-plated contacts Au 5, Au 6, and Au 7 varies approximately as the square root of the force and one can conclude that according to Eqs. (1) and (3) the major part of their resistance must be channel resistance. The critical currents (at $T=1.49$°K) vary also approximately as the square root of the force and one may conclude that this results from Eqs. (3) and (4) indicating that $\alpha_H \gg \delta$. Unfortunately, the critical current curves are not parabolic (they are labelled type III because the critical temperature depends strongly on the choice of R/R_n), which indicates $\alpha_H \ll \delta$ (see below). It is of course possible that for these contacts $\delta \approx \alpha_H$ such that the critical current is still approximately proportional to α_H, but that the critical current curve is already markedly nonparabolic.

If the contacts are plated with a thin layer of normal metal, the density of the superconducting electrons will decrease in the layer of the normal metal. The effective critical field in Eq. (4) will not have the bulk value but will be smaller by a factor of n_s/n_{s0}, where n_{s0} is the density of superconducting electrons in the tin and n_s their density at the point of narrowest current constriction. Since n_s/n_{s0} is probably temperature independent, the critical field curves will still be parabolic.

For larger values of the thickness of the normal metal a new effect comes in: The penetration depth is connected with the density of the superconducting electron by an equation of the type

$$\delta = (mc^2/4\pi n_s e^2)^{\frac{1}{2}}, \qquad (6)$$

where m and e are the effective mass and charge of the electrons of number density n_s, c the velocity of light, all in cgs units. As n_s decreases δ increases and can become of the order of and larger than α_H. This causes a breakdown of Eq. (4) which is only valid as long as $\alpha_H \gg \delta$. The only calculation for critical currents through wires whose diameter is small compared to the penetration depth is by von Laue.[6] As explained in detail in reference 4 there is some doubt whether this calculation is entirely correct. Nevertheless, its results shall be used here for lack of a more satisfactory calculation. If expressed in terms of the critical field caused by the critical current, the result is given by[7]

$$H_{cI} = H_{c\,\mathrm{bulk}}[-iJ_1(i\alpha_H/\delta)]/J_0(i\alpha_H/\delta) \qquad (7)$$

where J_0 and J_1 are the Bessel functions of zeroth and first order. If $\alpha_H \ll \delta$ Eq. (7) reduces to

$$H_{cI} = H_{c\,\mathrm{bulk}}\alpha/2\delta. \qquad (8)$$

With the temperature dependence of $H_{c\,\mathrm{bulk}}$ Eq. (5), and the temperature dependence of δ [see reference 1, Eq. (4)] one obtains for $\alpha_H \ll \delta$ the temperature dependence of I_c [see reference 1, Eq. (5)] which is in good agreement with the shape of the experimental curves found for contacts with larger thicknesses. In the range where $\alpha_H \approx \delta$ one could expect that it is possible to deduce the ratio of α_H/δ from the shape of the critical current curve by use of Eq. (7) by assuming that δ and $H_{c\,\mathrm{bulk}}$ have their usual temperature dependences. Unfortunately, this procedure requires that the critical current curve is very accurately known in the neighborhood of T_c. Since this is not the case it is impossible to obtain even the order of magnitude of

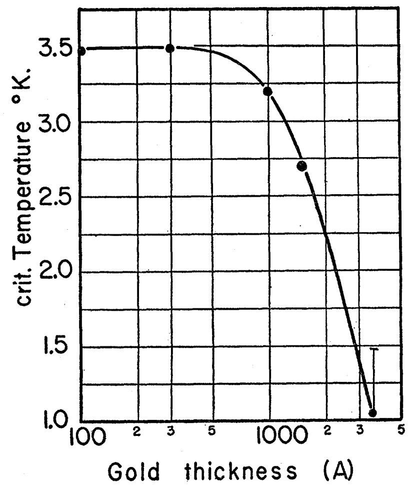

FIG. 7. Dependence of the critical temperature of the contact on the thickness of the gold plating.

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[6] M. von Laue, *Theory of Superconductivity* (Academic Press, Inc., New York, 1952), p. 115, Eqs. (16)–(18).

[7] There have been two misprints in Eqs. (2) and (3) of reference 1; these equations should read the same as Eqs. (7) and (8) of this paper.

α_H/δ. For these reasons it is impossible for any of the contacts to give values for α_H or α_{ch}. The numerical values of α_H and α_{ch} should be the same and should be smaller than the value of α_L.

Equation (8) can be written in terms of the critical current[8]:

$$I_c = 2\pi\alpha_H H_{cI} = H_{c\,\mathrm{bulk}} 2\pi\alpha_H^2/2\delta. \tag{9}$$

According to Eq. (9) one expects that the critical currents decrease with plating thickness because n_s decreases and δ increases. This is indeed frequently observed, at least if one excludes contacts with very high resistances which presumably had additional barriers. The critical current should increase with the contact area. According to Eqs. (9) and (3) the critical current should be proportional to the force on the contact if $\delta \gg \alpha_H$, while according to Eqs. (4) and (3) it should be proportional to the square root of the force if $\alpha_H \gg \delta$. As mentioned above, the critical currents of the gold-plated contacts Au 5, Au 6, and Au 7 at $T = 1.49$°K vary as the square root of the force indicating $\alpha_H \gg \delta$, which seems to be at variance with their temperature dependence.

It was tried very hard to find a good criterion for the limiting thickness of the plating, above which superconductivity of the contact is no longer observed. However, only for the gold-plated contacts was it possible to obtain anything like a systematic procedure to arrive at a numerical value. Figure 7 shows a plot of the critical temperature as a function of the thickness of the gold plating. One can see that up to about 1000 angstroms the transition temperature changes only slightly with the thickness of the gold plating, but that at larger thicknesses it decreases rapidly. For all other metals such a dependence is very likely, but could not be clearly established, because the data scatter too much. This scattering is very likely due to the presence of additional oxide layers.

A word should be said about the contacts plated with the ferromagnetic metals Fe, Co, and Ni. With nonferromagnetic metals the cutoff comes presumably when the thickness of the normal metal film becomes large compared to the "absorption length" of the superconducting electrons in the normal metal. With ferromagnetic films, however, superconductivity may be quenched in the neighborhood of the contact by the high magnetic field emerging from the ferromagnetic film. The saturation magnetization depends on the film thickness, and the cutoff comes presumably when the saturation magnetization is high enough, so that quenching takes place. For the reasons given above it is of course somewhat difficult to give a meaningful table of cutoff values of the thickness of the plated metal. Table II represents the best estimate of these values with the understanding, that up to the given thickness a very large reduction of the resistance, but not necessarily truly zero resistance will usually be found at low enough temperatures and small currents. However, it is entirely possible that for exceedingly clean contacts which are free of any additional barriers superconductivity of contacts with somewhat larger thicknesses may be found.

TABLE II. Limiting thickness in 10^{-6} cm of plated metal.

Group	IB	VIA		VIII	
Metal	Cu:30	Cr:4	Fe:0.7	Co:2	Ni:1.0
	Ag:40	···	···	···	···
	Au:35	···	···	···	Pb:7.5

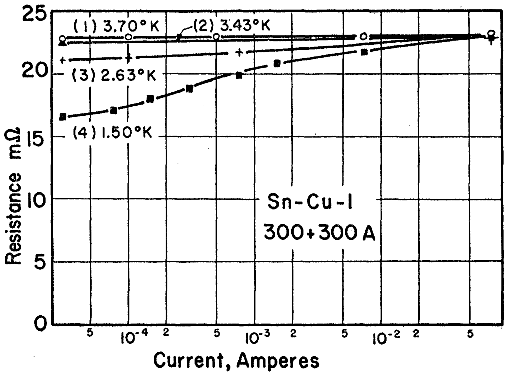

FIG. 8. Resistance *vs* current diagrams of contacts between tin-plated copper wires.

VI. MEASUREMENTS ON CONTACTS BETWEEN WIRES OF NORMAL CONDUCTING METAL PLATED WITH A SUPERCONDUCTING METAL

Figures 8–10 show three resistance *vs* current diagrams for contacts between tin-plated copper wires. One can see that only at 1500 A tin thickness superconductivity is found at low temperatures.

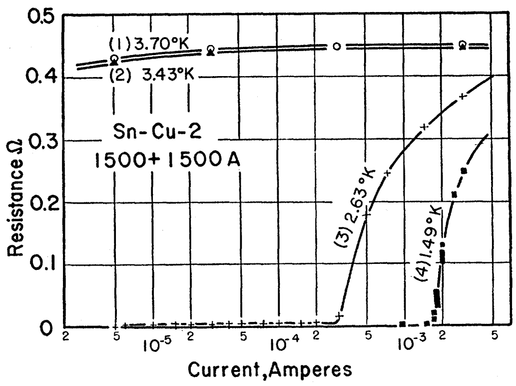

FIG. 9. Resistance *vs* current diagrams of contacts between tin-plated copper wires.

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[8] There has been an unfortunate mistake in Eq. (7) of reference 1; the equation should read the same as in this paper. The sentence following Eq. (7) is incorrect, because the critical current does depend on the contact area.

Simultaneously with the measurements on contacts also the (longitudinal) resistance of tin-plated copper wires was measured. The arrangement is shown in Fig. 11: Pieces of about 1-cm length were clipped off the tin-plated copper wires and with some In-Sn solder (with a transition temperature of about 5.5°K) soldered to current and potential leads of tin. The resistance of the wires was measured by reversing the current through the chain and observing the deflection of a galvanometer connected to the appropriate pair of potential leads.

Figure 12 shows a resistance *vs* current diagram for a piece of tin-plated copper wire clipped off the wires used for contact Sn-Cu-2. It should be noted that while the contact resistance becomes immeasurably small at 1.49°K and low currents, the (longitudinal) resistance of the wire decreases but remains finite. This may be due to the doubling of the thickness of the tin when the two wires are crossed to make the contact. Figures 13–15 show resistance *vs* current diagrams for contacts between tin-plated gold wires. One can observe that despite the much larger thicknesses the resistance does not become immeasurably small. Figures 16–17 show similar diagrams for pieces of tin-plated gold wires. It can be seen that only the wire with 10 000 angstrom tin becomes fully superconducting with a transition temperature between 1.47 and 2.64°K.

The absence of superconductivity for thin films of tin or lead plated onto Constantan was already observed by Burton, Wilhelm, and Misener,[9] by Misener and Wilhelm,[10] and by Misener.[11] Their measurements were usually believed to be unreliable (see the remark by Feigin and Shal'nikov[12] and by Shoenberg[13]) because they disagreed with the measurements on superconducting films evaporated onto glass or quartz surfaces.[14]

Figure 18 shows a comparison of their results with those obtained here. They extrapolated their critical field curves and determined the critical temperature, while the data here are somewhat too scant to permit doing this. Their data show that the critical temperature of tin films deposited onto Constantan goes to zero at a thickness of about 2000 angstroms. Since Constantan is an alloy of 60% Cu and 40% Ni, one would expect that the results of tin on copper should

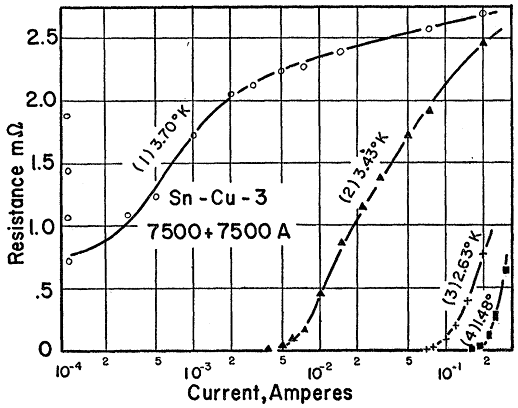

FIG. 10. Resistance *vs* current diagrams of contacts between tin-plated copper wires.

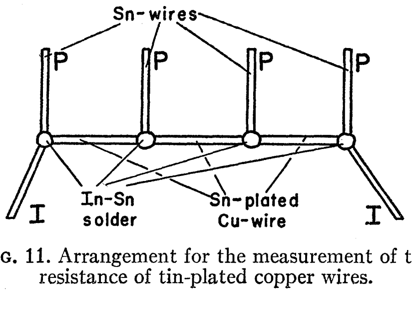

FIG. 11. Arrangement for the measurement of the resistance of tin-plated copper wires.

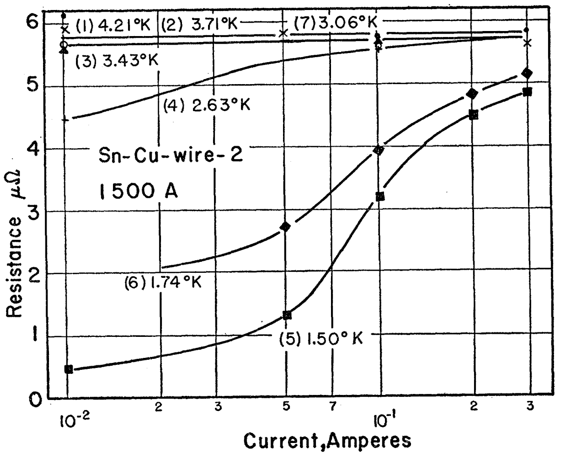

FIG. 12. Resistance *vs* current diagram of tin-plated copper wire.

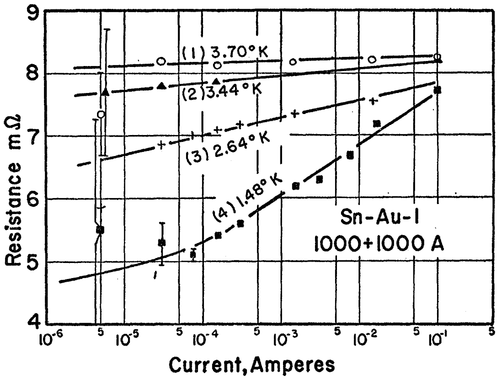

FIG. 13. Resistance *vs* current diagrams of contacts between tin-plated gold wires.

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[9] Burton, Wilhelm, and Misener, Trans. Roy. Soc. Can. **28**, 65 (1934).

[10] A. D. Misener and O. Wilhelm, Trans. Roy. Soc. Can. **29**, 5 (1935); also Univ. Toronto Studies **72**, 12 (1935).

[11] A. D. Misener, Can. J. Research **14**, 25 (1936).

[12] L. A. Feigin and A. I. Shal'nikov, Doklady Akad. Nauk S.S.S.R. **108**, 823 (1956) [translation: Soviet Phys. Doklady **1**, 377 (1957)].

[13] D. Shoenberg, *Superconductivity* (Cambridge University Press, Cambridge, 1952). See note at bottom of p. 166.

[14] N. E. Alekseyevsky, J. Phys. U.S.S.R. **4**, 401 (1941).

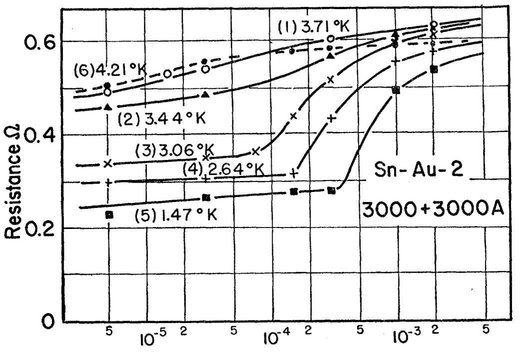

FIG. 14. Resistance *vs* current diagrams of contacts between tin-plated gold wires.

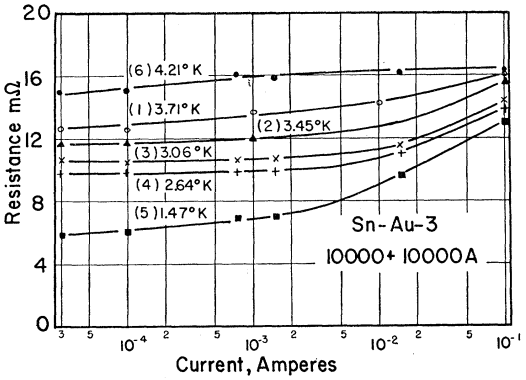

FIG. 15. Resistance *vs* current diagrams of contacts between tin-plated gold wires.

be very close to those of tin on Constantan. The tin-copper data here allow the plotting of three points: (1) A film of 7500 A was fully superconducting at 3.43°K (△). (2) The same film was normal conducting at 3.71°K (▲). The critical temperature therefore must be in between these temperatures in agreement with the Toronto data. (3) A film of 1500 A showed a great reduction of the resistance at 10 ma and 1.50°K, indicating that this is approximately the critical temperature of this film. The point actually lies very close to the curve drawn by the Canadian group. The data on tin films on gold are represented by three points: (1) A film of 3000-angstrom thickness remained normal conducting down to 1.47°K. (2) A film of 10 000 angstroms is superconducting at 1.47°K and 300 ma. (3) The same film shows resistance at 2.64°K and 1 ma. This indicates that the critical temperature for the latter film is between 2.64°K and 1.47°K. A probable shape for a curve of T_c *vs* film thickness of tin films on gold is shown dashed in Fig. 18.

VII. CONCLUSION

As mentioned in the introduction the aim of this investigation was to obtain an understanding of the mechanism which allows superconductivity of contacts. Previous investigations were carried out on contacts which had at least a gas layer in between, some had dielectric barriers. The contacts used in the previous investigations were so unstable, that it was impossible to decide whether the superconducting current really went through the barrier, or whether a thin metallic bridge existed.

The contacts investigated here had barriers of normal metal and, in addition, at least a gas layer and very probably in most cases thinner or thicker oxide barriers.

In the case of the copper, silver or gold plated contacts it is absolutely certain that the current went through the normal metal layer and not through a thin bridge of superconducting metal. The contact area is at most 100 micron^2 and the probability of matching two holes in the normal metal layers as regularly as superconductivity is observed, is practically zero.

The question arises, whether these contacts actually do become superconducting or whether the resistance attains only very small but finite values. The answer to this question is probably different for different contacts. A contact which has a resistance *vs* current diagram of type A very probably has truly zero resistance for currents somewhat smaller than the critical current, while a contact with a resistance *vs* current diagram of type C may exhibit even at the lowest temperatures a very small but finite resistance.

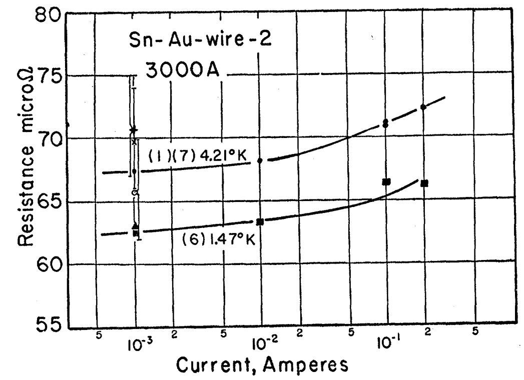

FIG. 16. Resistance *vs* current diagrams of tin-plated gold wires.

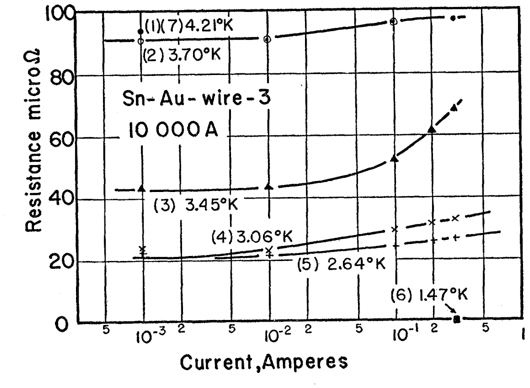

FIG. 17. Resistance *vs* current diagrams of tin-plated gold wires.

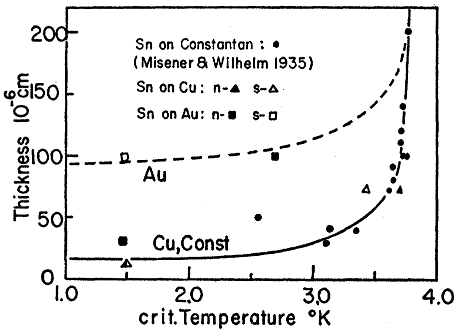

FIG. 18. Dependence of critical temperature of tin-plated wires of normal metal on thickness of the plated tin.

In the light of the new theory of superconductivity[15] which helped greatly to support Pippard's earlier nonlocal theory[16] one can understand the superconductivity of contacts with interposed barriers in the following manner: The density of superconducting electrons does not drop to zero at the boundary between superconductor and normal conductor, but decreases gradually in the normal conductor, and, for a dielectric barrier, perhaps even in the dielectric. This view obtains strong support from the observed change of the shape of the critical field curves. As the density of the superconducting electrons (at the point of narrowest current constriction) decreases, the superconducting penetration depth increases, leading to a nonparabolic critical current curve if the penetration depth becomes comparable to the contact radius.

The final cutoff comes when the barrier thickness becomes larger than the "absorption length" of the superconducting electrons. This "absorption length" (which in the case of a boundary between a superconducting phase and normal conducting phase of the same metal is identical with the length Δ associated with the interphase surface energy) is probably connected with the "range of order" of the superconducting electrons. One can actually interpret these measurements as a measurement of this "range of order."

In the case of metal barriers where the cutoff occurs at very small thicknesses, the interpretation is less certain. First of all, there is some uncertainty in the thickness itself, since the plating efficiency in the very beginning may have a different value from that averaged over a long time. It is also more likely that two holes in the plating come one on top of the other. Nevertheless, it is believed that this hardly ever occurred in these measurements. With ferromagnetic barriers additional scattering is caused by the variation of the magnetization of the film. Depending on the domain structure in the neighborhood of the contact, magnitude and direction of the magnetization, magnetic quenching of the superconductivity may occur at somewhat different thicknesses of the ferromagnetic film.

The measurements on contacts between normal conducting wires plated with tin were undertaken in order to see how thick a tin layer has to be in order to make a contact superconducting. They led, as a side result, to the confirmation of the absence of superconductivity in thin films of tin in contact with a normal metal, found previously by the Toronto group.

Some of the criticism of the earlier experiments as well as the experiments reported here involved alloying of the tin films by diffusion of the base metal. In the experiments here the time between plating and measurement was kept very short so that solid diffusion at least during this time is negligible. Aside from this critics have tried to explain the superconducting properties of copper-plated contacts by claiming a sufficiently high diffusion of the tin into the copper and have at the same time tried to explain the absence of superconductivity in thin tin films on copper by claiming a sufficiently high diffusion of the copper into the tin. It is quite clear that both assumptions cannot simultaneously be correct.

It is much more likely that the presence of the free conduction electrons in the base metal inhibits the superconductivity of the thin tin film. There are two mechanisms possible for this inhibition: (a) the drift rate of the superconducting electrons from the film into the normal metal is larger than the rate at which they can be created in the film; (b) the presence of the free electrons from the normal metal actually changes the distribution function of the electrons in the film such that superconductivity is no longer favored.[17]

Wherever the term "superconducting electrons" was used in this paper, it was of course fully realized that this term has to be taken in the sense of a two-fluid model and that such a model represents real superconductors only in a certain approximation.

VIII. ACKNOWLEDGMENTS

The liquid helium used for this research has been supplied by Professor G. H. Dieke's group. The following students have helped with the measurements at one time or another: Samuel P. Cook, Wilbur Perdew, Ram Sarup, Gilbert J. Labbe, William R. Callahan, David J. S. Greene, and Guy Errol Barasch. Mr. Barasch has helped greatly with a critical evaluation of all the data gathered over the years, and with preliminary and final drawings.

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[15] Bardeen, Cooper, and Schrieffer, Phys. Rev. **108**, 1175 (1957).

[16] A. B. Pippard, Proc. Roy. Soc. (London) **A216**, 547 (1953).

[17] *Note added in proof.*—R. H. Parmenter has developed a quantitative theory [Phys. Rev. **116**, 1390 (1959)] in which he extends the B.C.S. theory to include a spatial dependence of the energy gap.