# SUPERCONDUCTING CHARACTERISTICS OF SUPERIMPOSED METAL FILMS

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The electrical properties of superimposed films of superconductors and normal metals have been examined in a series of experiments employing the techniques of resistance measurement, persistent currents, and electron tunneling. The results indicate that the normal metal, e.g., Ag in a Ag-Pb pair, does in fact go superconducting and that the system behaves as does a superconductor with a transition temperature determined both by the constituent materials and by their relative thicknesses. It is argued that the observations are not due to alloying, diffusion, or similar effects. The experiments are compared with those of Meissner[1] on the contact resistance between crossed plated wires of normal and superconducting metals.

Measurements of resistance, critical temperature, critical current, and critical field vs temperature were made on long thin films prepared by vacuum deposition on glass substrates at pressures lower than $2\times10^{-5}$ mm Hg. Typically these samples were made by superimposing along the length of an Ag film, 1 cm long and 0.3 mm wide, a longer Pb film, 0.15 mm wide, to the ends of which potential and current connections were soldered. Several such samples were deposited simultaneously on the same substrate with, if desired, different thicknesses of either metal. There was a negligible delay and no exposure to the atmosphere between successive depositions. Table I shows the thicknesses of two typical sets of films of "open-faced" and "closed" sandwich construction, illustrated in Fig. 1(b). In general, the longitudinal resistance of the samples was 1 or 2 ohms at room temperature and lower by a factor of 4 at a temperature just above $T_C$.

Table I. Total thickness in angstroms.

| Sample No. | Lead | Silver |
|---|---|---|
| 1A-1 | 484 ±30 | 110 ±30 |
| 1A-2 | 490 ±30 | 362 ±30 |
| 1A-3 | 518 ±30 | 886 ±30 |
| 1A-4 | 598 ±30 | 1840 ±30 |
| 35-1 | 508 ±30 | ... |
| 35-2 | 417 ±30 | 7100 ±30 |
| 35-3 | 487 ±30 | 7140 ±30 |

Resistance was measured by passing a low-frequency current through the sample and displaying its voltage-current characteristic on an oscilloscope. Critical temperatures were determined to within a few millidegrees by the first appearance of zero slope, corresponding to zero resistance, at the origin of the trace. Isothermal critical fields were determined similarly by applying an external magnetic field,

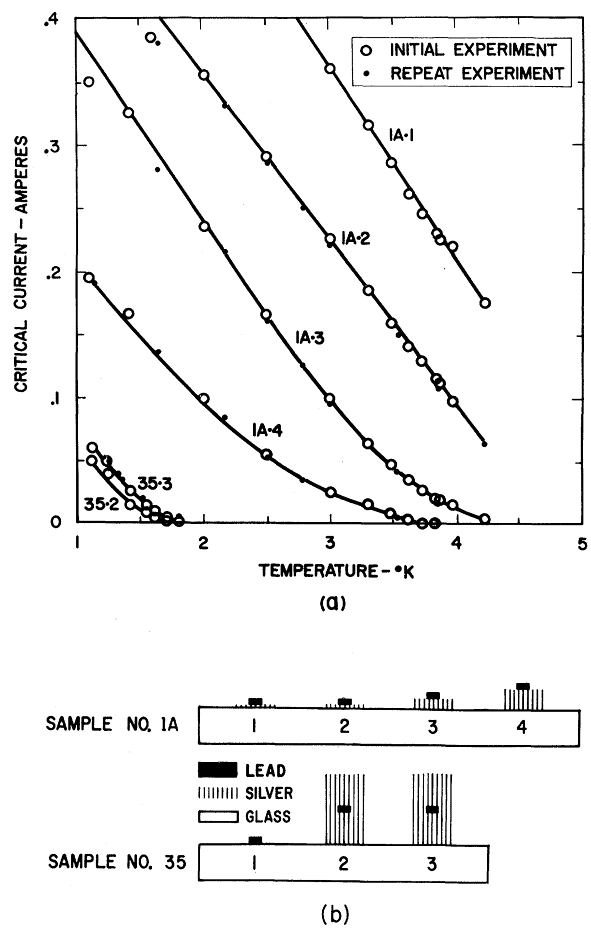


FIG. 1. (a) Critical current vs temperature for Ag-Pb samples of different geometry and silver thickness. The repeat data were obtained one week after the initial experiment. (b) Schematic cross section of the samples showing geometry and relative thickness. The critical current for sample 35-1 (pure lead) was 0.35 ampere, and was virtually independent of temperature.

tangential to the films and normal to the direction of current flow. Critical currents were obtained by noting the value of the instantaneous current at which the characteristic deviated from zero slope. Near the critical temperature critical currents as small as 25 microamperes were measured.

Figure 1(a) shows the variation with temperature of the critical currents of the samples described in Fig. 1(b) and Table I. The progressive depression of the transition temperature ($I_c = 0$) with increasing thickness of Ag for virtually constant thickness of Pb is to be noted; in particular the low transition temperature, 1.87°K, of samples 35-2 and 35-3. A progressive reduction in the critical currents, at a given temperature, also occurs with increasing thickness of Ag, but variation in total thickness complicates comparison between samples. All the curves show a linear relationship between $I_c$ and $T$, except for the gradual approach to the $T$ axis at small values of $I_c$. The latter may be indicative of intermediate-state effects. The reproducibility of the observations may be judged from the two sets of data points shown in Fig. 1. One set was obtained after cooling the specimens to 80°K within 10 minutes of deposition; the second set, in one case, was obtained one week later after storage at room temperature. No obvious change occurred in the properties of the films. So far, only preliminary data on the critical fields have been obtained but, as might be expected, the critical fields for the superimposed films are lower than for pure Pb films at the same temperature.

The systematic change of the transition temperature with increasing Ag on a constant thickness of Pb, the reproducibility, and the very low transition temperatures (e.g., the transition temperatures of samples 35-2 and 35-3 were approximately one-fourth that of pure Pb) make it unlikely that the effects are secondary in nature and the result of impurities, strains, diffusion, or alloying. All metals used were 99.999% pure. The nature of the effects was unchanged by the type of construction ("open-faced" or "closed" sandwiches) or by the sequence of deposition. The data did not change with the passage of time. Finally, the Pb-Ag phase diagram is well known[2] and the superconducting properties of the alloy system have been studied.[3] The solid solubility of Ag in Pb is extremely small (a maximum of 0.2 at.% at 300°C) and that of Pb in Ag is modest (a maximum of 2.8 at.% at 600°C, dropping to 0.8 at.% at 300°C). Further, any solid alloy of Pb and Ag is a mixture of the two solid solutions. Allen has shown that the transition temperature of Pb is substantially unaltered by the addition of Ag up to a Ag concentration of about 80% whereupon the mixture ceases to be superconducting. His results suggest that the superconductivity of the alloy is due to the presence of a continuous phase of Pb containing some Ag in solution; when this phase is not present in sufficient amount to form a continuous path through the specimen the alloy remains normal. It follows, therefore, that the maximum amount of Ag in Pb has a negligible effect on the transition temperature of Pb, whereas Ag containing the maximum amount of Pb remains normal.

The results reported in the preceding paragraphs indicate that a pure "normal" metal film in immediate contact with a film of a superconductor will depress the transition temperature of the superconductor, the depression being greater for increasing thickness of the normal metal. To determine if the "normal" metal actually becomes superconducting, two additional sets of experiments were performed.

In the first, Ag films of various thicknesses were sandwiched between Pb films in a persistent current loop, arranged so that the current flowed through the Ag. Since Sn was present elsewhere in the loop, persistent currents were observed only below 3.7°K. In one loop containing about 2800 A of Ag between two Pb films, each about 2000 A thick, a persistent current of 2.9 amperes at 3.64°K was observed. Although a change in current of a few percent would be easily detected, no change was observed in a period of $1\frac{1}{2}$ hours. From prior experience in the use of the persistent current loop and the associated measuring techniques,[4] the inductance of the loop is known to be less than $10^{-10}$ henry. Accordingly, the upper limit to the loop resistance can be set at $10^{-15}$ ohm, whereas the computed resistance of the Ag (using known area, thickness, and bulk resistivity) is greater than $10^{-12}$ ohm. Thus unquestionably a substantial reduction in the resistance of the Ag was observed. In a further experiment, a Au film was sandwiched between a Pb film and a Sn film. In this case, a persistent current could not be generated above 3.57°K, well below the transition temperatures of both Sn and Pb; thereafter the critical current increased smoothly to more than 2 amperes at 3°K.

In the final set of experiments, electron tunneling[5-7] from Pb and Sn films through a Formvar dielectric layer into the Ag side of a Pb-Ag sample was observed. These preliminary experiments have demonstrated the presence of an electron energy gap in the Ag, with a low-temperature limiting value of 0.00016 ev in a sample consisting of 5700 A Ag superimposed on 1500 A Pb and having a transition temperature above 4.2°K.

Following measurements of the contact resistance between crossed plated wires, Meissner[1] has reported the depression of the transition temperature of a superconductor by an adjacent normal metal and the possibility of passing a supercurrent through a thin normal metal film between bulk superconducting metals, but the conditions under which these effects occurred did not preclude the possibility of oxide barrier layer formation or physical penetration of the metal films. He therefore found difficulty in drawing clear-cut conclusions regarding the relationship between the various observations or their fundamental importance. On the other hand, the experiments reported in this Letter demonstrate that when a film of a normal conductor is placed in direct contact with a film of a superconductor, the combination exhibits the attributes of a superconductor, including the ability to pass a supercurrent through the otherwise "normal" metal, the presence of an energy gap throughout the sample,[8] and a transition temperature which depends upon the film thicknesses and the materials involved.

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[8]Tunneling experiments are being continued to obtain simultaneous measurements of the energy gap on opposite sides of a Ag-Pb sample, this information being pertinent to the question of a position-dependent energy gap, proposed by R. H. Parmenter [Phys. Rev. 118, 1173 (1960)].