Superconducting Properties of Pb/Ag Multilayers

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The electrical resistivity, ac susceptibility, critical current density, and Josephson tunneling of Pb/Ag multilayers have been measured in wide temperature ranges in order to study the proximity effect. A resistivity drop was found to occur at T_c of Pb in ρ versus T measurement and, at low temperature, the multilayers show proximity effect. The I-V characteristic of the multilayer shows voltage steps, indicating a resistive state has occurred in the sample. The superconducting properties of the multilayer were analyzed with the bilayer theory of the proximity effect.

1. INTRODUCTION

Artificially prepared multilayer, such as Nb/Ge,¹ Nb/Cu,² and V/Ag³ are new class of superconducting materials. These multilayers exhibit interesting physical properties. In Nb/Ge multilayer, the Nb layers are coupled by the well-known Josephson effect through the semiconducting Ge layer. In Nb/Cu and V/Ag, on the other hand, the Nb layers are coupled by the proximity effect and a strong coupling between the superconducting layers allows a normal layer with a thickness of about 100 Å. In this work we have measured the temperature dependence of the electrical resistivity, ac susceptibility, critical current density, and Josephson tunneling for the Pb/Ag multilayers in order to study the proximity effect of the Pb layer with Ag.

2. EXPERIMENTS

The Pb/Ag multilayers were prepared in a high vacuum system with a pressure of about 1×10^{-7} torr during evaporation. The Pb and Ag films were alternatively deposited on a glass substrate (Corning 7059) which is cooled by liquid nitrogen. In preparing the Josephson junction with a multilayer in one bank, a bottom Pb-strip was first evaporated on a glass

substrate. The sample was then exposed to air for about one day so that a thin layer of oxide can be grown on the surface of the Pb film. A third multilayer of Pb/Ag was then deposited across the oxidized Pb strip. The Josephson junction has a cross-type configuration and the width of the sample was about 600 μm . Several samples were studied in this work. Data reported here are typical experimental results.

3. RESULTS AND DISCUSSION

Data characterizing the electrical properties of the Pb/Ag multilayers are shown in Table I. $T_{c\rho}$ is the superconducting transition temperature derived from the resistivity data at 50% resistive transition, and $T_{c\chi}$ is the superconducting transition obtained from the ac susceptibility data at 50% magnetic transition.

Figure 1 shows the temperature dependence of the electrical resistivity for several samples. The configuration of the sample is shown in the inset. Several new features were found. First, a finite resistance drop was found to begin at about $T_0 = 7.35\text{ K}$, which is close to the zero resistance temperature $T_c = 7.24\text{ K}$ of Pb films in a separate run. Secondly, the resistance remains nearly constant at $T_2 < T < T_1$. Finally, the resistance goes to zero at T_3 . These features are common to all the samples in this study and can be interpreted as follows. The samples consist of two regions: one has the transition temperature of pure Pb (perhaps the edges, or other agglomerated Pb) and the other is influenced by the proximity with Ag. The resistance drop at T_0 is due to the effects of the edges or other agglomerated Pb, and

TABLE I
Sample Parameters of Pb/Ag Multilayer^a

Samples	$d_{\text{Pb}}/d_{\text{Ag}}$ (Å/Å)	$T_{c\chi}$ (K)	$T_{c\rho}$ (K)	T_c (theory) (K)	Ratio of $\rho(300\text{ K})$ to $\rho(7.6\text{ K})$	$\rho(7.6\text{ K})$ ($\mu\Omega\text{ cm}$)	No. of layers
1	39/29	5.85	6.77	5.15	6.11	1.73	10
2	44/13	—	5.59	6.21	3.12	14.1	10
3	32/15	3.68	5.8	5.75	3.40	64.3	10
6	47/28	6.08	6.63	5.46	8.10	2.24	10
7	103/21	7.2	7.14	6.42	38.6	0.401	20
8	1610/0	6.94	7.30	7.2	20.4	0.861	1
9	0/1600	—	—	—	3.98	0.803	1
10	38/23	—	5.97	5.43	—	4.11	100
12	20/15	—	4.68	5.13	—	11.12	40
13	22/11	—	6.18	5.68	—	6.44	40
14	70/30	—	5.84	5.85	—	5.81	5

^a $T_{c\rho}$ is the superconducting transition temperature at 50% resistive transition, and $T_{c\chi}$ is the superconducting transition at 50% magnetic transition.

Fig. 1. Temperature dependence of resistivity. The inset shows the geometry of the sample.

Fig. 2. χ_{ac} as a function of temperature for several samples.

the zero resistance at T_3 is due to the Pb/Ag proximity. The Pb/Ag proximity at low temperatures was also verified in the χ_{ac} measurement with the surface of the film perpendicular to the applied field as shown in Fig. 2.

To study the effect of the Pb/Ag proximity on the critical current density J_c a variation of J_c as a function of the temperature was measured. Figure 3 shows a temperature dependence of J_c as a function of the reduced temperature for a multilayer. Also shown is J_c versus T/T_c for pure Pb film. An increase in J_c was found in the proximity coupled sample. Indeed, the J_c value increases by about a factor of 2 compared to that of pure Pb film.

The bilayer theory of the Werthamer⁴ can be extended to analyze the superconducting transition T_c of a multilayer system. By symmetry, a multilayer can be reduced to a bilayer consisting of a superconductor and a normal metal of thickness d_s and d_n as shown in Fig. 4. The modulation length is defined as $\Lambda_{Pb+Ag} = 2(d_s + d_n)$. The individual transition temperature of the bilayer is T_{cs} and T_{cn} , respectively. The solution of the spatial variation of the order parameter $\Delta(x)$ is $\Delta(x) = \exp(\pm ik_s x)$ in the superconducting state and $\Delta(x) = \exp(\pm k_n x)$ in the normal state, where $k_{s,n}$ satisfies

$$\chi(\xi_s^2 k_s^2) = \ln(T_{cs}/T_c) \quad (1a)$$

$$\chi(-\xi_n^2 k_n^2) = \ln(T_{cn}/T_c) \quad (1b)$$

$$\chi(Z) = \psi(1/2 + Z/2) - \psi(1/2) \quad (1c)$$

where ψ is a digamma function, and ξ_l is the effective coherence length⁵ of the considered layer, $\xi_l = (\pi \hbar k_B / 6 e^2 T_c \rho_l \gamma_l)^{1/2}$, where $l = s$ or n ,

Fig. 3. J_c as a function of T/T_c for samples 1 and 8.

Fig. 4. Configuration of the Pb/Ag multilayer.

and γ_1 and ρ_1 are the normal state electronic specific-heat coefficients and the resistivities of the superconductor s and the normal metal n .

By matching the boundary conditions⁶

$$d\Delta(x)/dX = 0 \quad \text{at free surface,}$$

$$\Delta(x)/(NV) \text{ and } (D/V)d\Delta(x)/dX \quad \text{continuous at the interface} \quad (2)$$

where D is the electron diffusion coefficient, N is the density of states, and V the attractive interaction between the electrons.

The application of the previous boundary conditions leads to the solution

$$N_s D_s k_s \tan(k_s d_s) = D_n N_n k_n \tanh(k_n d_n) \quad (3)$$

If $\rho_s = \rho_n$, i.e., $N_s D_s = D_n N_n$, we recover the original equation of Werthamer⁴ given by

$$k_s \tan(k_s d_s) = k_n \tanh(k_n d_n) \quad (4)$$

Equations (1) and (2) are sufficient to calculate the transition temperature of the multilayers, and the results are shown in Table I. In the calculation, we have used $\gamma_{\text{Pb}} = 2.98 \times 10^{-3} \text{ mJ/mole} \cdot \text{K}^2$, $\gamma_{\text{Ag}} = 0.646 \times 10^{-3} \text{ mJ/mole} \cdot \text{K}^2$. ρ_{Pb} and ρ_{Ag} are calculated from the relation

$$\frac{d_{\text{Pb}}}{\rho_{\text{Pb}}} + \frac{d_{\text{Ag}}}{\rho_{\text{Ag}}} = \frac{d_{\text{Pb+Ag}}}{\rho_{\text{Pb+Ag}}} \quad (5)$$

where $\rho_{\text{Pb+Ag}}$ is the resistivity of the multilayer, d_{Pb} the thickness of the Pb layer, d_{Ag} the thickness of the Ag layer, and $d_{\text{Pb+Ag}} = d_{\text{Ag}} + d_{\text{Pb}}$. We have assumed $\rho_{\text{Pb}}/\rho_{\text{Ag}} = d_{\text{Ag}}/d_{\text{Pb}}$ in the multilayer. That is, $\rho_{\text{Ag}} = A/d_{\text{Ag}}$ and $\rho_{\text{Pb}} = A/d_{\text{Pb}}$, where A is a constant. The assumption is based on the following: the mean free path of the sample is proportional to the layer thickness because it is dominated by the boundary scattering in each layer. This assumption is reasonable and should not introduce too much error in determining T_c 's. Indeed, calculations show T_c 's depend strongly on the layer thickness and weakly on the resistivity of the layer.

Figure 5 shows the I - V characteristics of the sample 7 at various temperatures. Several new features were found. First, the I - V curve changes gradually from the linear behavior at $T > T_c$ to the steplike behavior as one decreases the temperature. Secondly, the I - V curve is symmetric, voltage steps and hysteresis were found in these curves. A detailed view of the I - V curve is shown in Fig. 6. The voltage steps in the I - V characteristic can be explained in terms of the resistive state in the flux flow model.^{7,8} In this model, the channels of normal state consist of array of flux tubes moving rapidly from the edge to the center of the strip, where they are annihilated by normal channels of opposite sign. So an abrupt creation of one channel or more channels of normal states at distinct current level will result in resistive voltage steps. The flux-flow model, we believe, can be applied to the multilayers because the samples have a strip structure with a width of $600 \mu\text{m}$ and thickness of $0.25 \mu\text{m}$. The dimensions of the sample are comparable to or larger than the superconducting coherence length.

To study the proximity effect in the Pb/Ag multilayer more carefully, a Josephson tunneling junction with Pb/PbO_x/multilayer structure was prepared simultaneously. Figure 7 shows the I - V characteristics of the junction at various temperatures. Several new features were found. 1. The I - V curve changes gradually from the linear behavior at $T = 7.467 \text{ K}$ to the Josephson behavior at low temperatures. 2. A nonsymmetric I - V curve was

Fig. 5. I - V characteristics of sample 7 at various temperatures.

Fig. 6. Detailed view of I - V curve at $T = 7.038$ K for sample 7.

found at low temperatures. The nonsymmetric current-voltage characteristics is probably due to the nonuniformity of the junction. 3. The I - V characteristic of the junction at T near T_c is compared to sample 7 but still with slightly different features. For instance, the I - V characteristic of the junction at $T = 7.241$ K contains two major parts: a linear I - V curve and a nonlinear I - V curve. The nonlinear I - V characteristic is similar to that of a typical I - V curve of weak links

$$V = R(I^2 - I_c^2)^{1/2} \quad (6)$$

where I_c is the critical current and R is the normal state resistance. This nonlinear I - V characteristic of weak link is even obvious at low temperature, which suggests a weak link behavior of the junction.

Figure 8 shows a temperature dependence of the Josephson supercurrent in different temperature ranges. A linear dependence of J_c was found at T near T_c , and the temperature dependence of J_c changes to a saturation behavior at low temperature. The observed temperature dependence of J_c is somewhat like that of SIS junction. To analyze the temperature dependence of J_c , we assume the superconducting multilayer should couple to form a superconductor S' . This is a reasonable assumption and has been verified in the experiment reported here. Therefore a junction with a multilayer on a bank can be effectively considered to be a junction with SIS'

Fig. 7. I - V characteristics of the junction at various temperatures.

structure where S' has the coupled superconducting properties of the multilayer. For the sample reported here the superconducting transition of S' is at $T_c = 7.1$ K which is very close to the transition temperature of S , therefore the observed linear behavior of J_c is like that of SIS junction.^{10,11}

4. CONCLUSION

The superconducting properties of the Pb/Ag multilayer have been reported, and the results are consistent with the bilayer theory of the proximity effect. Voltage steps were found in the I - V characteristic indicating a resistive state existing in the multilayer. The Josephson tunneling of the sample with a multilayer structure show a linear temperature dependence and the results are consistent with a Josephson tunneling theory.

Fig. 8. Temperature dependence of J_c for a junction with a Pb/PbO_x/multilayer structure. The geometry of the junction is shown in the inset.

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