27
7-13-81
JUL 15
240 NTLS
B5561

(1)

IS-M 297

CONF - 800839 - - 2

SUPERCONDUCTING PROXIMITY EFFECT FOR IN SITU AND MODEL LAYERED SYSTEMS

D. K. Finnemore

MASTER

The submitted manuscript has been authored by a contractor of the U. S. Government under contract No. W-7405-eng-82. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so for U. S. Government purposes.

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

fy

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

SUPERCONDUCTING PROXIMITY EFFECT FOR IN SITU AND MODEL LAYERED SYSTEMS

D. K. Finnemore

Ames Laboratory-USDOE* and Department of Physics, Iowa State
University, Ames, Iowa 50011, U.S.A.

I. MODEL SYSTEMS

With the development of commercial scale fabrication techniques for in situ composites [1], there now appears to be a good chance that these materials will be well suited for large scale magnets in the 8 to 14 Tesla range. The critical currents are above 10^4 A/cm^2 at 14 Tesla [2,3,4] and the strain tolerance is very attractive [3,5]. Even at the present stage of development, these composites appear to be a good choice for dc or slowly ramped magnets.

The primary draw back for in situ materials is that the ac losses are higher than for mechanically produced multifilamentary wire [4]. This arises because the filaments are much more tightly coupled partly through the proximity effect and partly through touching of adjacent filaments. Because the average spacing between fibers is comparable to the superconducting pair potential decay length, λ_N^{-1} , (that is about 1000Å) one expects rather strong proximity effect coupling. If one is to control these ac losses, it is essential to develop a quantitative

*Operated for the U.S. Department of Energy by Iowa State University under contract No. W-7405-Eng-82. This research was supported by the Director for Energy Research, Office of Basic Energy Sciences, WPAS-KC-02-02-02.

understanding of the proximity effect so that analytical expressions are available for design. To this end, it would be helpful to have model systems which illustrate the basic physics involved.

Two essential features to consider in the choice of model systems are the magnitude of the pair potential at the superconductor-normal metal (SN) boundary, $\Delta_N (X=0)$, and the value of K_N^{-1} . For in situ composites based on Nb_3Sn -Cu, the pair potential in the superconductor should be about 3 meV and there will be an abrupt drop going across the boundary. Following de Gennes [6], one expects the wave function, ψ , to be continuous at the boundary and $\Delta = \psi nV$ where NV is the BCS parameters. Hence $\Delta_S / (NV)_S = \Delta_N / (NV)_N$. Using $\Delta_S = 3$ meV, $(NV)_S = 0.37$, and $(NV)_N = 0.05$ [7], one finds $\Delta_N (X=0) \approx 0.4$ meV. In addition $K_N^{-1} = (\hbar v_F) / (2\pi kT) \approx 400$ nm for Cu at 4.2K. These values are illustrated in Fig. 1.

For a model system Pb-Cd is chosen for a number of reasons. Pb has been very thoroughly studied; it is easy to prepare; it has a strong electron phonon interaction; and there are a number of laminar eutectic alloys which can be easily grown in bulk. Cd is a good choice for the normal metal component because there is less than 0.1 at. % solubility of Pb in Cd so diffusion into the normal matrix is not a problem. In addition $\Delta_N (X=0)$ is about 0.5 meV [8] and K_N^{-1} is about $1500 \text{ \AA}$ at 4.2K so there is a good match to the properties of Cu adjacent to Nb_3Sn .

In this work it is necessary to prepare a variety of different geometrical arrangements for various experiments. Thin film double layer SN junctions are needed for electron tunneling studies of the density of states $N(\omega)$ and the electron phonon spectral function, $\alpha^2 F(\omega)$. Triple layer, SNS, junctions are needed to measure the magnitude of the

supercurrent which can pass through a normal barrier as a function of thickness, (d_N), temperature (T) and magnetic field (B). Multilayer laminar junctions are needed to model flux pinning in bulk structures. As shown in Fig. 2 aligned layer structures 50 μm thick by 1 cm wide by 10 cm long can be grown by directional solidification. Because all of these configurations are possible for PbCd, it was selected for a systematic study of proximity coupling.

II. BOUNDARY CONDITIONS AT SN INTERFACE

A. Electron Tunneling

A series of $\text{Al}/\text{Al}_2\text{O}_3/\text{Pb}/\text{Cd}$ and $\text{Al}/\text{Al}_2\text{O}_3/\text{Cd}/\text{Pb}$ thin film junctions on the order of 50 nm thick were prepared in order to measure the tunneling density of states $N(\omega)$ to obtain the energy gap Ω_N and some measure of the pair potential Δ_N [8]. At 0.34K, K_N^{-1} is about 15,000 nm so $d_N \ll K_N^{-1}$ and Δ_N is essentially constant across the Cd region. Results near the gap edge are shown in Fig. 3 for both injection into the S side (solid line) and injection into the N side (dashed line). Ω_N is found to be 0.43 and 0.38 meV respectively which is close to the de Gennes prediction [6]. For these junctions the $N(\omega)$ data fit the McMillan tunneling model [9] rather well and give values of Δ_N ranging from 0.40 to 0.77 meV for a series of four films with different thickness combinations [8]. This is a direct experimental verification that the de Gennes boundary conditions are correct to about 20%.

B. Thermal Conductivity

A series of Pb-Cd aligned laminar eutectics similar to those shown in Fig. 2 were prepared in order to test the de Gennes boundary conditions using transport properties [10]. For these aligned composites, the Pb

region has 1.4% Cd dissolved in it and the electron mean free path is less than 500Å. The Cd regions, on the other hand, are very clean and have electron mean free paths on the order of 30,000Å [11]. This means that heat transported parallel to the lamina is carried almost entirely by electrons in the Cd region. Phonon conduction and electron conduction in the Pb region is relatively minor. Using this fortunate circumstance Δ_N can be estimated by fitting the thermal conductivity to a Bardeen, Rickayzen, and Tewaradt expression as shown in Fig. 4. The data show a much smaller value of $2\Delta_N/kT$ than BCS and indeed show Δ_N to be about 0.4 meV in agreement with the tunneling result. There seems to be little doubt of the basic correctness of the de Gennes boundary conditions.

III. PHONON SPECTRAL FUNCTION, $\alpha^2 F(\omega)$

A series of measurements of $\alpha^2 F(\omega)$ were made for SN junctions in which the thickness of the S side was reduced from 100 nm to 30 nm in order to determine the cause of the suppression in T_c [8]. In this range, T_c drops by about a factor of 2. It is found that simple unfolding of the $N(\omega)$ data using the Eliashberg equation does not give a self-consistent unfolding procedure. Instead, one must modify the renormalization factor to account for the fact that Cooper pairs in the Pb can decay by escaping into the Cd [9]. If one adds the usual life-time for phonon absorption factor, Z_0 , to the life-time broadening factor in the form suggested by the McMillan tunneling model [9] $Z = Z_0 + i\Gamma_S / (\omega^2 - \Omega_N^2)^{1/2}$, then the data are internally consistent. That is, $\alpha^2 F(\omega)$ determined from $N(\omega)$ at 0.34K gives the measured T_c . As shown in Fig. 5, there is very little change in $\alpha^2 F(\omega)$ induced by the presence of the Cd and the entire depression in T_c of about a factor of 2 arises from increased life-time broadening of Cooper pairs because they escape from S into the N region.

IV. SUPERCURRENTS THROUGH NORMAL BARRIERS

A. Thickness Dependence

A series of SNS triple layer junctions were studied [12] in order to determine the thickness dependence of the critical current density, J_c , and to study the temperature and magnetic field dependence of K_N^{-1} . The voltage-current characteristics show a well defined supercurrent out to a characteristic J_c where the voltage rises abruptly and roughly follows a resistively shunted junction model. Values of J_c , for several different thicknesses are shown on Fig. 5. The values of J_c of most interest in the study of in situ materials is on the order of 10^0 to 10^3 A/cm^2 and it is seen that normal metal regions as thick as 1600 nm can easily carry 10^3 A/cm^2 at temperatures very close to T_c . It is only for thickness on the order of 3400 nm that J_c is as low as 10^3 A/cm^2 at 4.2K.

B. Temperature Dependence

If one assumes that J_c is governed by the minimum value of Δ_N in the center of N then

$$J_c = J_0 (1 - T/T_{CS})^2 e^{-K_N d_N} \quad (1)$$

where K_N^{-1} varies as $K_N^{-1} = \hbar v_F / 2\pi kT$ for a clean materials and $K_N^{-1} = (\hbar v_F \ell / 6\pi kT)^{1/2}$ for dirty materials. These J_c data are dominated by a term of the form of the form $J_c = J_1 e^{T/T_0}$ and indeed, Eq. (1) is well obeyed [12].

C. Magnetic Field Dependence

If a magnetic field is applied parallel to the plane of the film the V-I characteristics retain the same form as for $B=0$ except the J_c is suppressed as $J_c = J_2 e^{-B/B_0}$. This means that the dominant effect of B is to depress K_N linearly with B . This rapid decrease in J_c with B arises because the magnetic field provides an additional pair breaking mechanism

of the form $\Gamma = DeB/c$ where D is the diffusivity, $D = 1/3 v_F \ell$, e is the charge on the electron v_F is the Fermi velocity, and c is the speed of light.

In normalized units the pair breaking parameter for the normal metal region is $\alpha_N = K_N^2 \xi_N^2$, the pair breaking mechanism for the magnetic field is $\alpha_B = DeB/c\pi kT$ and one can add them to get

$$K_N = \xi_N^{-1} [6(1/2 + DeB/c\pi kT)]^{1/2} \quad (2)$$

If $DeB/c\pi kT \ll 1$ then a series expansion gives a term in K_N proportional to B and $J_c = J_{c2} e^{-B/B_0}$ for small B . This is shown by the data on Fig. 7.

V. FLUX ENTRY FIELDS

For laminar composites the normal metal regions at the surface provide exposed weak spots where flux can enter. Because the vortex scatters electrons effectively, thermal conductivity of laminar Pb-Cd composites has proved to be a useful tool to study this initial entry of magnetic flux into the specimen. As the magnetic field is raised there is an abrupt drop in thermal conductivity when vortices first enter and this signature can be used to map out the phase boundary. Dobrosavljevic and de Gennes [13] showed that the flux entry field for $K_N^{-1} \ll d_N$ would be

$$H_{c1}^* = \frac{\phi_0}{8\lambda_N} \left(\frac{K_N}{\frac{d_N}{2} - \rho} \right)^{1/2} (\cosh K_N \frac{d_N}{2})^{-1} \quad (3)$$

where ϕ_0 is the flux quantum, λ_N is the penetration depth at the SN boundary $\rho = K_N^{-1} [\ln 1/K_N \lambda_N - 0.116]$. It is important to note here that H_{c1}^* depends only on λ_N , K_N^{-1} and d_N . For both Pb-Cd [14] and Sn-Cd [13] eutectics there is rough agreement with the model for large $d_N/2$ where the model applies. For Pb-Cd, measurements also were made for the small d_N case and it was found that H_{c1}^* at 4.2K ranged from 3 mT at 1560 nm to 40 mT at 110 nm and in this regime varies approximately as d_N^{-1} as shown by Fig. 8.

VI. IMPLICATIONS FOR IN SITU COMPOSITES

For the in situ composites of practical importance, the filaments are long enough and thin enough that the current density passing through the Cu at discontinuity in the Nb_3Sn filament is less than 10 A/cm^2 . For the Cu thicknesses involved of 100 to 500 nm, measurements on the model system indicate that these current densities are easily carried as a supercurrent. Therefore at $B=0$, the phase locking between filaments is very tight even if none of the filaments touch. As a magnetic field is applied, the experimental fact is that J_c vs. B for in situ materials is essentially the same as for continuous filament wire. This seems to indicate that J_c is controlled by the grain size of the Nb_3Sn and not by the supercurrent coupling. This is consistent with the idea that there is more than adequate phase coupling between filaments all the way out to the 12 to 14 Tesla range. At fields above 12 Tesla J_c falls below continuous filament values but there is as yet no definitive experiment showing that the fall of J_c is exponential in B as expected for proximity coupling. Too many other factors such as prestress of the material cloud this issue. On the basis of the model system measurements, however, one certainly expects a decoupling of the filaments at large magnetic field.

Hysteresis [15] and ac loss measurements [4,15] clearly indicate a substantial shielding against magnetic flux entry and exit from the Cu regions of the matrix. For values of Δ_N on the order of 0.4 meV, for K_N^{-1} on the order of $1500 \text{ \AA}$, and d_N ranging from 100 to 1000 nm, measurements show flux entry fields ranging from 10^{-2} to 10^{-1} Tesla. It is only when the normal metal spacing is on the order of 10 nm that the entry field is as high as 1 Tesla. It may be therefore that one wants the filaments

rather uniformly spaced at 100 nm and that the closely spaced filaments of say 10 nm are actually very detrimental to the ac losses.

REFERENCES

1. J. D. Verhoeven, F. A. Schmidt, E. D. Gibson, J. E. Ostenson, and D. K. Finnemore, Appl. Phys. Lett. 35, 555 (1979); J. D. Verhoeven, E. D. Gibson, C. V. Owen, J. E. Ostenson, and D. K. Finnemore, Appl. Phys. Lett. 35, 270 (1979).
2. D. K. Finnemore, J. D. Verhoeven, E. D. Gibson, and J. E. Ostenson, IEEE Trans. on Magn. MAG 15, 693 (1979).
3. J. L. Fihey, M. Neff, R. Roberger, M. C. Flemings, S. Foner, and B. B. Schwartz, Appl. Phys. Lett. 35, 715 (1979).
4. J. Bevk, J. P. Harbison, F. Habbal, G. R. Wagner, and A. I. Braginski, Appl. Phys. Lett. 36, 85 (1980).
5. J. W. Ekin, IEEE Trans. Magn. MAG 15, 197 (1979).
6. P. G. de Gennes, Rev. Mod. Phys. 36, 225 (1964).
7. J. Clarke, S. M. Freake, M. L. Rappaport, and T. L. Thorp, Sol. State Commun. 11, 689 (1972).
8. J. R. Toplicar and D. K. Finnemore, Phys. Rev. 16, 2072 (1977).
9. W. L. McMillan, Phys. Rev. 175, 537 (1968).
10. M. P. Zaitlin, Phys. Rev. 18, 3298 (1978).
11. C. R. Spencer, P. Martinoli, E. D. Gibson, J. D. Verhoeven, and D. K. Finnemore, Phys. Rev. 18, 1216 (1978).
12. T. Y. Hsiang and D. K. Finnemore, Sol. State Commun. 33, 487 (1980); T. Y. Hsiang and D. K. Finnemore, Phys. Rev. (accepted).
13. L. Dobrosavljevic and P. G. de Gennes, Sol. State Commun. 5, 177 (1967); L. Dobrosavljevic, C. Petipus-Dupuis and R. Racek, Phys. Stat. Sol. 38, 159 (1970).
14. M. P. Zaitlin, Phys. Rev. 18, 3305 (1978).

15. S. S. Shen, ICMC Conference at Brookhaven (1980).

FIGURE CAPTIONS

- Fig. 1. Spatial dependence of the pair potential for $\text{Nb}_3\text{Sn-Cu}$ and Pb-Cd junctions.
- Fig. 2. Laminar Pb-Cd composites. The Cd is the light color and Pb is dark. The repeat distance is 500 nm.
- Fig. 3. $N(\omega)$ near the gap edge for thin Pb-Cd bilayers. The dashed line shows injection into the N side and the solid line shows injection into the S side.
- Fig. 4. Thermal conductivity of aligned composites.
- Fig. 5. Phonon spectral function $\alpha^2 F(\omega)$ changes which occur for thicknesses less than a coherence distance.
- Fig. 6. Thickness dependence of the critical current for SNS junctions.
- Fig. 7. Magnetic field dependence of J_c for SNS junctions.
- Fig. 8. Flux entry field as a function of normal metal width.

Figure 1. Spatial dependence of the pair potential for $\text{Nb}_3\text{Sn-Cu}$ and Pb-Cd junctions.

Figure 2. Laminar Pb-Cd composites. The Cd is the light color and Pb is dark. The repeat distance is 500 nm.

Figure 3. $N(\omega)$ near the gap edge for thin Pb-Cd bilayers. The dashed line shows injection into the N side and the solid line shows injection into the S side.

Figure 4. Thermal conductivity of aligned composites.

Figure 5. Phonon spectral function $\alpha^2 F(\omega)$ changes which occur for thicknesses less than a coherence distance.

Figure 6. Thickness dependence of the critical current for SNS junctions.

Figure 7. Magnetic field dependence of J_c for SNS junctions.

Figure 8. Flux entry field as a function of normal metal width.