Title
ELECTRIC THANSPORT CURRENTS ACROSS NORMAL-SUPER CONDUCTING INTERFACES

Author
Clarke, J.

Publication Date
1970-08-01

Presented at the 12th International
Conference on Low Temperature,
Kyoto, Japan - Sept. 4-10, 1970

UCRL-20312
Preprint c.2

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August 1970

AEC Contract No. W-7405-eng-48

UCRL-20312 c.2

LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

ELECTRIC TRANSPORT CURRENTS ACROSS NORMAL-SUPERCONDUCTING INTERFACES

J. Clarke*

Department of Physics, University of California and

IMRD, Lawrence Radiation Lab., Berkeley, Calif. 94720

ABSTRACT

The electric resistance of Pb/Bi-Cu-Pb/Bi sandwiches is independent of temperature in the range 1-4K whereas that of Pb/Bi-Zn-Pb/Bi drops markedly. The difference occurs because the induced pair potential in the Cu is small compared with kT whereas in the Zn it is comparable with kT. The resistance of the Zn junctions is strongly dependent upon current and magnetic field whereas that of the Cu junctions is not.

When[1] a normal metal (N) is in contact with a superconductor (S), a finite pair amplitude (F_N) is induced in N. At finite temperatures, F_N decays exponentially, except near the interface.[1] In a clean normal metal whose transition temperature (T_{cN}) is zero, the decay length is[2] $k_N^{-1} = \hbar v_F/(2\pi kT) \sim 3000$ Å at 4K. If T_{cN} is finite, $k_N^{-1} \sim \hbar v_F[2\pi kT(1-T_{cN}/T)]^{-1}$. This paper is concerned with the transport of an electric current across the SN interface[3,4] and the way in which the dissipative flow in the normal metal is transformed into superfluid flow in the superconductor.

Consider first a normal metal with $T_{cN}=0$. The effective pairing interaction, λ_N^*, and the pair potential, $\Delta_N(X)=\lambda_N^* F_N(X)$ are both zero (Fig. 1). Consider an electron in a state $\underset{\sim}{k}_e$ incident on the SN interface from the N-side, at an energy $\varepsilon(k_e)$ which is less than the value of the pair potential, $\Delta_S^{(i)}$, at the interface. The electron will be scattered into a hole state $\underset{\sim}{k}_h$ by the pairing potential which can pair the incident electron with one inside the Fermi sea, leaving a hole excitation.[5-7] A hole propagates back across the normal metal while a Cooper pair propagates into the superconductor. The conversion from normal current to supercurrent occurs at the SN interface.

In the case where $0 < T_{cN} < T$, both λ_N^* and Δ_N are finite (see Fig. 1). An electron incident from the N-side with an energy $\varepsilon(k_e)$ which is less than the value of Δ_N at the interface, $\Delta_N^{(i)}$, will encounter a finite pair potential well inside N. As the electron moves into a region of increasing Δ_N, its group velocity will decrease, becoming zero where $\varepsilon(k_e)=\Delta_N$. The electron is scattered as before effectively at this point and the conversion from normal to superfluid flow occurs inside the normal metal, at a position depending upon the energy of the incident electron.

Since Δ_N decays exponentially, in principle a finite value of Δ_N extends indefinitely into N. In practice Δ_N will be broken up by thermal fluctuations at a finite distance from the SN interface. Electrons with zero or very small $\varepsilon(k_e)$ will be reflected at a point determined by these fluctuations. This distance may be estimated empirically by considering an SNS junction[8] in which N is sufficiently thin for it to carry a supercurrent. The critical current (i_c) is proportional to $\exp(-k_N d)$, where d is the thickness of N. As d is increased, i_c will decrease and the phase-coupling of the junction will be broken when[9] $i_c \phi_o \sim kT$, where ϕ_o is the flux quantum. An experimental study of the critical currents of SNS junctions[8] suggests that at 4K, Δ_N is broken up by thermal fluctuations at a distance of roughly 8 k_N^{-1} from the SN interface.

Experiments have been performed in which the resistances of SNS sandwiches were measured as a function of temperature, current density and magnetic field. Specimens consisted of a clean normal metal, either Cu or Zn, sandwiched between two superconducting electrodes (Pb/Bi). The resistance of Pb/Bi-Cu-Pb/Bi junctions (Fig. 2) was independent of temperature in the range 1-4K. λ^*_{Cu} is known to be sufficiently small that $\Delta_{Cu} << kT$, whereas $\Delta_S^{(i)}$ is large enough that most of the incident electrons are reflected at the SN interface over this temperature range. The measured resistance is therefore independent of temperature.

The results for Pb/Bi-Zn-Pb/Bi specimens are also shown in Fig. 2. The resistance drops markedly as the temperature is lowered towards the zinc transition, 0.88K. The value of λ^*_{Zn} is such that a significant number of electrons are reflected by the pair potential in the zinc. As the temperature is lowered, the decay length increases while the electron energies decrease. Both mechanisms move the points of reflection away from the SN interface and lower the resistance.

The resistance of the Pb/Bi-Cu-Pb/Bi junctions was independent of the current used in the resistance measurement over the range 1-50 mA. On the other hand, the resistance of the Pb/Bi-Zn-Pb/Bi junctions was strongly current-dependent as shown in Fig. 3 (with ambient magnetic field < 5 mG). This would be expected because the current quenches F_N at the extremities of the exponential tails in the zinc. As the current is increased, the points at which superconductivity is destroyed move towards the SN interfaces. The exponential decay of Δ_N does not however imply that the dependence of resistance upon current is logarithmic because the contribution to the resistance of the very low energy excitations is affected more than that of the higher energy excitations. Presumably the resistance at very low currents is set by thermal fluctuations.

The variation of resistance of the Pb/Bi-Zn-Pb/Bi specimens with magnetic field (applied perpendicular to the current flow) is also shown in Fig. 3. The marked dependence again arises from the quenching of the low values of F_N. The resistance of the Pb/Bi-Cu-Pb/Bi junctions was independent of magnetic field.

Experiments have also been performed on In-Cu-In junctions. Near T_c(In), Δ_{In} may be much less than kT and many of the incident electrons have a finite probability[6] of being transmitted into the superconductor in which they will decay dissipatively. The measured resistance of the junctions increased markedly as T was increased towards T_c(In), in qualitative agreement with the model.

A detailed model of these effects should take account of the finite

E-field which must exist over part of the condensate in the normal metal. The condensate is time-dependent and there arises the possibility of vortex motion contributing to the observed resistance. A proper calculation of the effect of fluctuations on the resistance would also be interesting as it seems likely that these effects are observable, at least at low values of measuring current.

Finally, measurements of this type at very low temperatures provide a very sensitive test of whether or not N becomes superconducting at even lower temperatures.

This work was done under the auspices of the U. S. Atomic Energy Commission.

REFERENCES

1. P. G. de Gennes, Rev. Mod. Phys. 36, (1964), p. 225.
2. P. G. de Gennes, Superconductivity of Metals and Alloys (W. A. Benjamin, New York, 1966).
3. J. Bardeen, Proc. International Conference on the Science of Superconductivity, Stanford (1969).
4. R. Kümmel, Z. Physik, 218 (1969), p. 472.
5. A. F. Andreev, Soviet Phys. JETP 19 (1964), p. 1228.
6. W. L. McMillan, Phys. Rev. 175 (1968), p. 559.
7. W. L. McMillan and P. W. Andersen, Phys. Rev. Letters 16 (1966), p. 85.
8. J. Clarke, Proc. Roy. Soc. A308 (1969), p. 447.
9. P. W. Anderson and J. M. Rowell, Phys. Rev. Letters 10 (1963), p. 230.

* Sloan Fellow.

FIGURE CAPTIONS

Fig. 1. Variation of Δ across SN interface for $\lambda^*=0$ and $\lambda^* > 0$. The points of reflection for incident electrons are indicated.

Fig. 2. Variation of resistance with temperature of Pb/Bi-Cu-Pb/Bi and Pb/Bi-Zn-Pb/Bi junctions.

Fig. 3. Variation of resistance with current and magnetic field of Pb/Bi-Zn-Pb/Bi junctions.

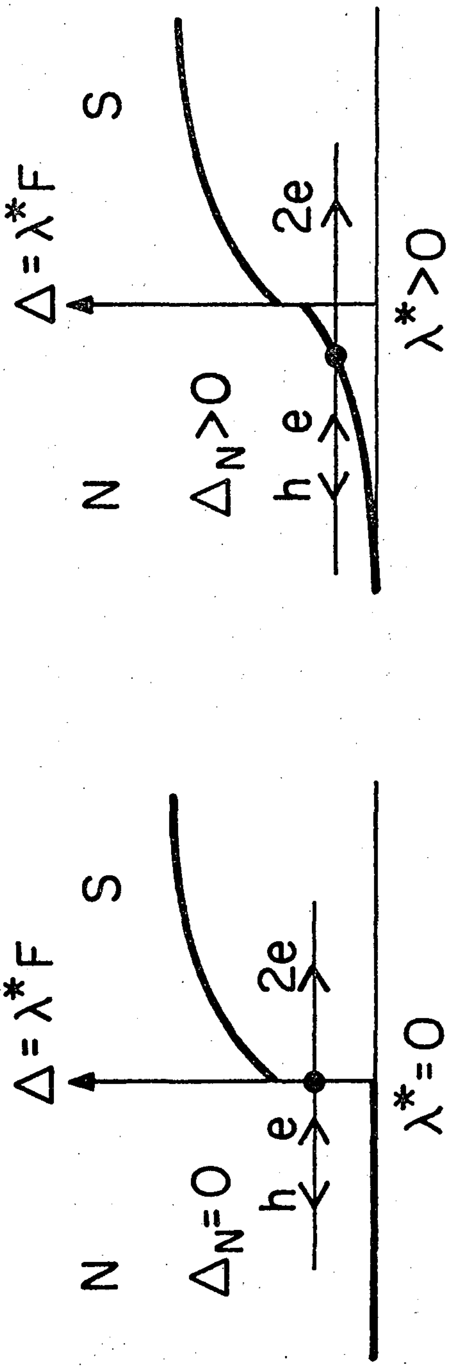

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Fig. 1

	Zn	Cu
C/S AREA (cm^2)	7.9×10^{-2}	
THICKNESS OF NORMAL METAL (cm)	1.8×10^{-2}	1.0×10^{-2}
APPROX. M.F.P. OF NORMAL METAL (mm)	0.05	0.2
CALC. RESISTANCE OF NORMAL METAL (Ω)	8.1×10^{-10}	4.5×10^{-11}
MEASURING CURRENT (mA)	20	
AMBIENT MAGNETIC FIELD (mG)	<5	

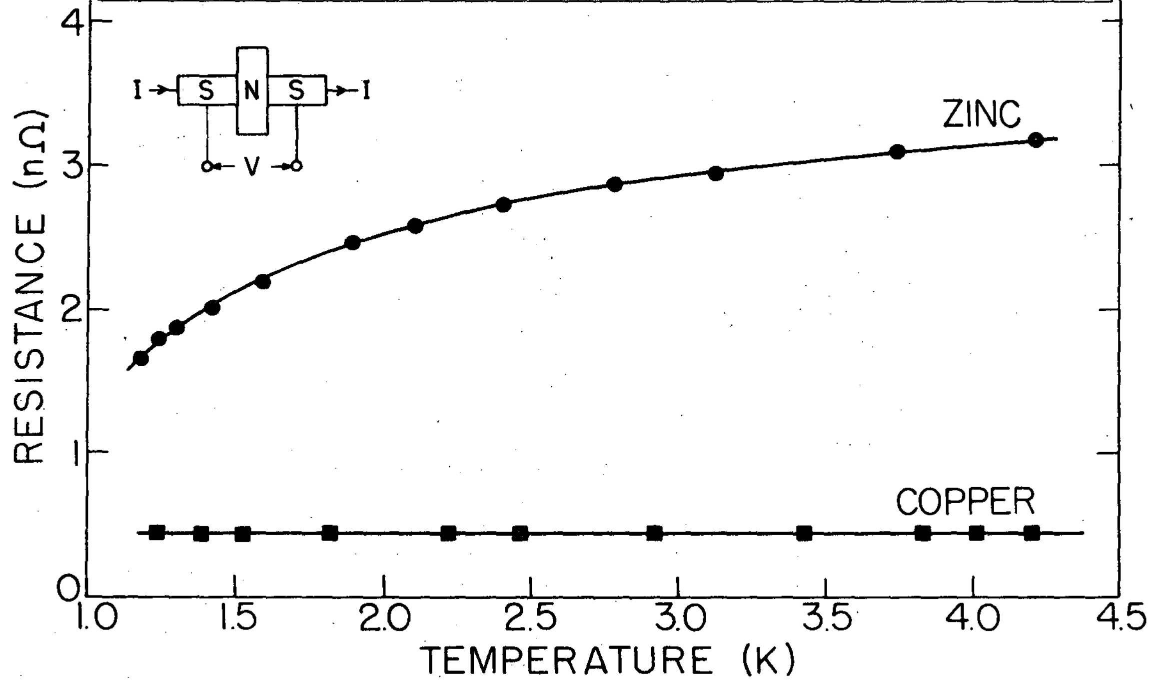

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Fig. 2

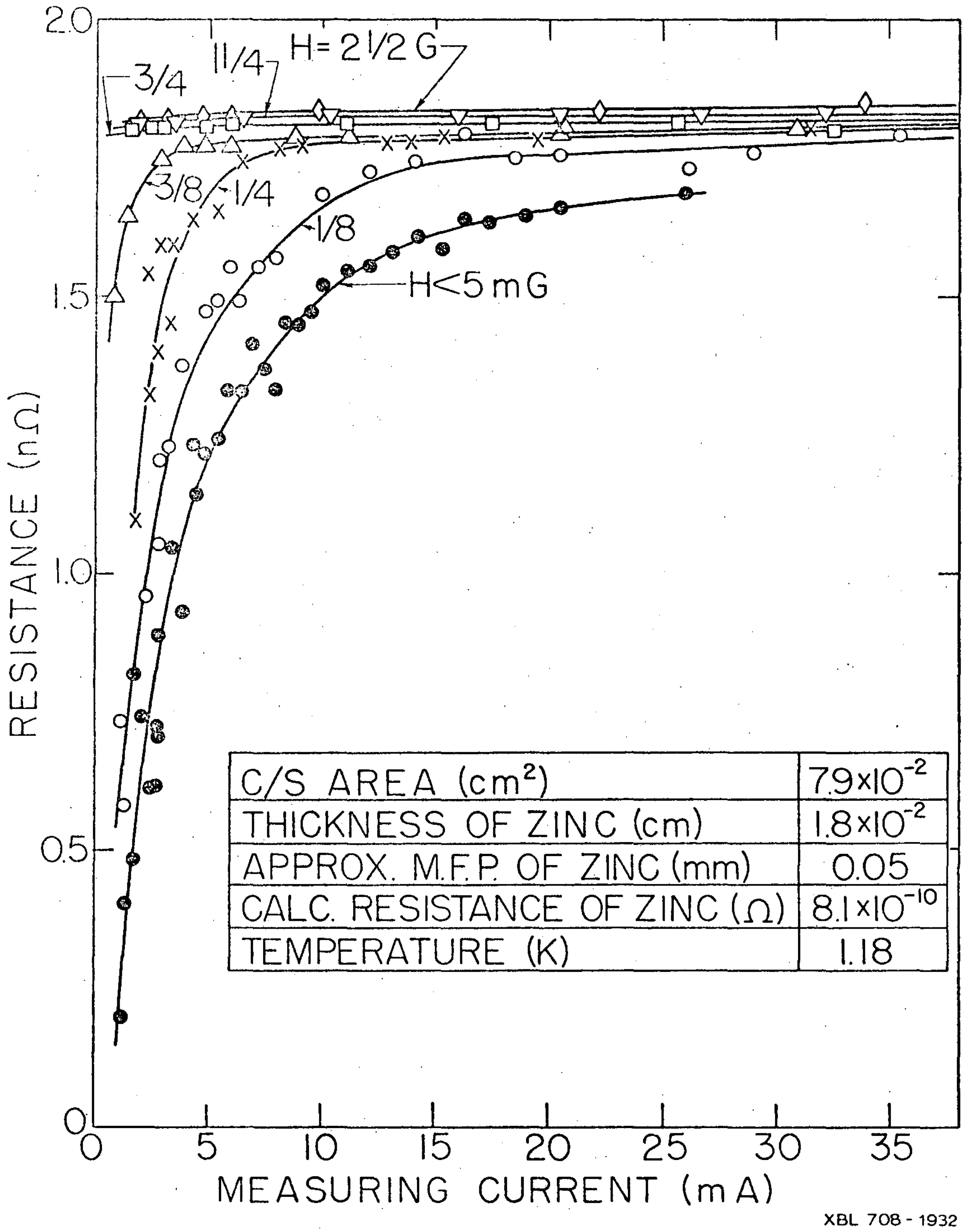
2.0
1.5
1.0
0.5
0
RESISTANCE (nΩ)
0
5
10
15
20
25
30
35
MEASURING CURRENT (mA)
H= 2 1/2 G
1 1/4
3/4
3/8
1/4
1/8
H<5 mG
C/S AREA (cm²) 7.9×10⁻²
THICKNESS OF ZINC (cm) 1.8×10⁻²
APPROX. M.F.P. OF ZINC (mm) 0.05
CALC. RESISTANCE OF ZINC (Ω) 8.1×10⁻¹⁰
TEMPERATURE (K) 1.18
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Fig. 3

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LAWRENCE RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720