Supercurrent versus Temperature Characteristics of Cross-Type Josephson Junctions near T_c

H. C. Yang

Department of Physics, National Taiwan University, Taipei, Taiwan

H. E. Horng

Department of Physics, National Taiwan Normal University, Taipei, Taiwan

(Received June 10, revised August 20, 1987)

The temperature dependence of the maximum Josephson supercurrent is studied in ranges near T_c . The results are discussed in the framework of an approximate analysis for proximity systems based on the de Gennes theory and its application to several junctions.

1. INTRODUCTION

The supercurrent and its temperature dependence have been experimentally investigated by many authors¹⁻³ for various Josephson junctions. However, the temperature dependence of J_c near T_c is still nontrivial for the proximity Josephson junctions.

To take into account the temperature dependence of a Josephson junction near T_c , a simplified proximity theory⁴ following Clarke's model⁵ based on the de Gennes theory⁶ was proposed. This approximate analysis is particularly useful for the temperature dependence of J_c near T_c for proximity systems.⁴ In this paper we present experimental results on the temperature dependence of proximity Josephson junctions with superconductor-normal metal-superconductor (SNS) and superconductor-normal metal-insulator-superconductor (SNIS) structures. The data are discussed within the framework of the analysis developed in ref. 4.

2. EXPERIMENTAL

2.1. SNS Junction

The samples were cross-type Pb/Ag_{1-x}Mn_x/Pb junctions. The detailed description of the sample preparation for SNS junctions is similar to that

reported previously.² The superconducting layer (Pb) had a thickness of about 7000 nm, with a mean free path l_s of about 360 nm at 7.4 K determined from the resistivity measurement using the relation⁷ $(\rho l_s)^{-1} = 9.4 \times 10^{10} \Omega^{-1} \text{ cm}^{-2}$, where ρ is the resistivity. The normal layer with magnetic impurities was prepared by a pellet dropping method similar to that used by Clarke⁵ in preparing the normal layer containing nonmagnetic impurities. It was hoped that this method would produce a uniform normal layer. The normal layer, which was effectively square, was prepared by subsequently dropping tiny alloy pellets into a hot molybdenum boat and completely evaporating each pellet, giving a thickness increase per pellet of about 5–10 nm. The thickness of the normal layer varied from 200 to 600 nm. The mean free path of the normal layer was calculated from⁷ $(\rho l_n)^{-1} = 8.6 \times 10^{10} \Omega^{-1} \text{ cm}^{-2}$ for each sample. The mean free path is somewhat larger than the coherence length $\xi_n = (\hbar v_F l / 6 \pi k T)^{1/2}$, which indicates that all the N layers were in the dirty limit, where v_F is the Fermi velocity, l is the mean free path, $\hbar$ is Planck's constant divided by 2π , and T is the temperature. The Fermi velocity used in the calculation is $v_F = 1.38 \times 10^6 \text{ m/sec}$.

2.2. SNIS Junctions

The Pb/Al/AlO_x/Pb junctions were prepared by a technique similar to that used in making the SNS samples. A bottom Pb strip was first evaporated on a glass substrate and a second later of Al with a thickness of about 100 nm was evaporated on the top of the Pb strip. The sample was then exposed to air for about 10 min. Finally, the cross-type junction was completed by evaporating another Pb strip across the top of the film.

3. RESULTS AND DISCUSSION

3.1. SNS Junctions

The junctions show sharp I - V characteristics. There are no voltage steps or kinks in the curves. The junctions also show nice Fraunhofer diffractions, which indicate the uniformity of the junctions. Figure 1 shows the J_c and $J_c^{1/2}$ versus T for a typical SNS junction with 1.5% Mn impurity in the normal layer. The J_c value increases monotonically as the temperature decreases and reaches saturation at low temperature. This saturation behavior is similar to the theoretical prediction for SIS junctions. Figure 2 shows the experimental $J_c^{1/2}$ for various SNS junctions near the critical temperature. For SNS junctions, the temperature dependence of I_c near T_c reported in ref. 4 is

$$I_c \propto [\xi_n / (\xi_{GL})^2] F_0^2 \exp(-d_n K_n) \quad (1)$$

Fig. 1. Plot of J_c and $J_c^{1/2}$ versus T for a typical SNS junction with 1.5% impurity of Mn in the normal layer and $d_n = 280$ nm.

where ξ_n is the coherence length, ξ_{GL} is the Ginzburg-Landau coherence length, F_0 is the condensation amplitude of finding Cooper pairs, and d_n is the thickness of the normal layer. For the samples reported here, the normal layer contains magnetic impurities; therefore, the coherence length ξ_n is

$$\xi_n^{-1} = K_n = \xi_c^{-1} [T/T_c + \hbar/(\pi k_B T_c \tau_s)]^{1/2} \quad (2)$$

where $\xi_c = (\hbar V_{Fn} l_n / 6 \pi k_B T_c)^{1/2}$, τ_s is the spin-flip scattering time, V_{Fn} is the Fermi velocity, l_n is the mean free path, and T_c is the transition temperature. For temperature close to T_c , ξ_{GL} and F_0 vary as $(1 - T/T_c)^{-1/2}$ and $(1 - T/T_c)^{1/2}$, respectively, and ξ_n is a slowly varying function of temperature. In fact, Eq. (1) is the same as the formula derived by de Gennes for SNS junctions, given by

$$J_c = [32eN_s\pi^2k_B^2D_sN_sT_c^2/7\zeta(3)\hbar K_nD_nN_n] \times (1 - T/T_c)^2 \exp(-K_nd_n) \quad (3)$$

Fig. 2. Plot of $J_c^{1/2}$ versus T near T_c for several SNS junctions with magnetic impurities in the normal layer. The numbers in in parentheses refer to the electronic mean free path of the N layer at 4.2 K.

where $N_{s,n}$ are densities of the normal metal at the Fermi surface, $D_{s,n} = \frac{1}{3} V_{Fs,n} l_{s,n}$, $\zeta(3) = 1.202$, and e is the electronic charge. There is only one parameter τ_s in Eq. (3). If one fits the J_c data near T_c to Eq. (3), one derives the spin-flip scattering time τ_s as shown in Table I. The J_c versus T dependence is shown in Fig. 3; the solid curves are the theoretical results based on Eq. (3). Good agreement between experiment and theory is found.

In Eq. (3) the variation of J_c depends on the terms $(1/K_n) \exp(-K_n d_n)$ and $(1 - T/T_c)^2$. For T near T_c , $(1 - T/T_c)^2$ decreases by a factor of about

TABLE I
Spin-Flip Scattering Time
 τ_s Derived from Fitting the J_c Data near T_c to Eq. (3)^a

	Mn, %	l_n , Å	τ_s , sec	$\hbar / \pi k_B \tau_s$, K
Sample B	2.0	370	3.84×10^{-13}	6.33
Sample A	1.5	415	4.40×10^{-13}	5.54
Sample C	0.8	684	1.93×10^{-12}	1.27

^aNumerical values used to evaluate the theory are $N_{pb} = 1.32 \times 10^{47} \text{ J/m}^3$, $N_{Ag} = 1.0 \times 10^{47} \text{ J/m}^3$, $V_{F,pb} = 0.41 \times 10^6 \text{ m/sec}$, $V_{F,Ag} = 1.38 \times 10^6 \text{ m/sec}$, and $l_{pb} = 3950 \text{ Å}$.

Fig. 3. Temperature dependence of J_c for the samples. (—) Theoretical curves based on Eq. (3).

36 as one varies the temperature from 6.5 to 7.0 K, while the term $(1/K_n) \exp(-K_n d_n)$ decreases by a factor of about 1.2 for the samples reported here. Therefore $(1 - T/T_c)^2$ dominates the temperature dependence of J_c . The dominance of $(1 - T/T_c)^2$ in J_c is demonstrated in Fig. 2. In fact, the $J_c^{1/2}$ versus T is a straight line down to 5.5 K for the sample with 0.8% Mn impurity.

Fig. 4. Plot of $J_c^{2/3}$ and J_c versus T for a typical Pb/Al/AlO_x/Pb junction. The thickness of Al is 105 nm.

Fig. 5. Plot of $J_c^{2/3}$ versus T near T_c for the Pb/Al/AlO_x/Pb junction.

3.2. SNIS Junction

The SNIS junctions show hysteresis in the I - V curve that is similar to those observed in SIS junctions. In Fig. 4 J_c and $J_c^{2/3}$ versus T are indicated for Pb/Al/AlO_x/Pb junctions. The temperature dependence of I_c near T_c for SNIS junctions derived from the calculation reported in ref. 4 is

$$I_c \propto F_0^2 (D_s K_n^{-1} / D_n \xi_{GL}) [1 / \sinh(K_n d_n)] \quad (4)$$

where $D_{s,n}$ are the diffusivities and K_n^{-1} is the pair penetration depth. The temperature dependence of F_0 and ξ_{GL} in Eq. (2) dominates the temperature dependence of I_c near T_c . Therefore, $I_c \propto (1 - T/T_c)^{3/2}$ near T_c for SNIS junctions. This temperature dependence is demonstrated in Fig. 5 for Pb/Al/AlO_x/Pb junctions.

4. CONCLUSION

In summary, we have demonstrated the temperature dependence of I_c near T_c for various Josephson junctions in cross-type configuration; the results agree well with the theory of proximity effects.

REFERENCES

1. T. Y. Hsiang and D. K. Finnemore, *Phys. Rev. B* **22**, 154 (1980).
2. S. Nagata, H. C. Yang, and D. K. Finnemore, *J. Appl. Phys.* **53**, 5798 (1981).
3. E. P. Balsamo, G. Paterno, A. Barone, M. Russo, and R. Vaglio, *Phys. Stat. Sol. (a)*, **35**, K173-175 (1976).
4. S. Nagata and H. C. Yang, *Physica* **108B**, 997 (1981).
5. J. Clarke, *Proc. R. Soc. A* **308**, 447 (1969).
6. P. G. de Gennes, *Rev. Mod. Phys.* **36**, 225 (1964).
7. R. G. Chambers, *Proc. R. Soc. Lond. A* **215**, 481 (1952).