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Proximity Effect Between Superconducting and Normal Metals

Semi-Annual Report

October, 1971

Hans Meissner

NASA Grant No. NGL 31-003-020

Office of Research Grants and Contracts

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Abstract

The investigation of proximity effects between normal metals and superconductors has been continued in its second phase - the investigation of the three-terminal, thin-film, SNS device as an amplifier ("superconducting transistor").

The problem of films cracking which had been vapor-deposited onto a substrate precooled to $4.2^{\circ}K$ had been overcome during the last report period by using thinner films. Unfortunately, the thinner films of tin sometimes had critical currents which were smaller than the Josephson critical current, thereby destroying the Josephson effect. This difficulty has been surmounted by vapor-depositing the films onto a $273^{\circ}K$ precooled substrate which is immediately cooled to $77^{\circ}K$ after deposition to prevent significant interdiffusion between gold and tin.

Much of this report is devoted to the description of the new electrical characteristics of these films. Such favorable characteristics include shiny and smooth films, higher Josephson critical currents, smaller electronic mean free paths, and consistent I-V curve shapes. One unfavorable characteristic is a much steeper increase of the Josephson critical current with decreasing temperature.

The functional variation of the Josephson current with the control current is described. There have been two functional forms observed and a brief description as to possible mechanisms for this behavior has been included.

Introduction

A Josephson junction is a device wherein two superconductors are separated by either an insulating or normal metal barrier. Henceforth the junction with the insulator will be termed SIS and the one with the normal metal barrier SNS. The barrier thickness is critical to the operation of the device (e.g., the normal metal barrier may be as thick as 10,000 Å, whereas the insulating barrier is restricted to thicknesses less than 50 Å). The purpose of the barrier is to provide a weak coupling between the phase of the Cooper pairs in one superconductor with respect to that in the other superconductor.

The present SNS junction consists of a sandwich of films, with tin forming the outer two superconducting layers and gold the normal metal barrier. The junction geometry is in the form of two "legs" of tin intersecting with a gold film between them. We had chosen the thin-film junction over the point-contact junction as a consequence of a paper by Stewart[1], wherein it was shown that for a Josephson junction it was more likely to obtain current-voltage (I-V) traces with ranges of large dynamic resistance, and perhaps even negative resistance for larger areas which have larger junction capacitances. The large dynamic resistance is a requisite for power gain in a three-terminal SNS device (a transistor-like device wherein each film has an electrical terminal attached to it). Films, because of their larger area, can carry larger currents than point contact junctions - at least up to a point where magnetic fields generated

1. W. C. Stewart, <u>Appl. Phys. Lett. 12</u>, 277 (1968).

by this current in the junction tend to confine the current. The attributes of larger current-carrying areas range from easier current detection to a better immunity to thermal fluctuations.

Metal films vapor-deposited onto a substrate cooled to $4.2^{\circ}K$ tend to crack to relieve built-up stress if the film thickness exceeds a critical value. Unfortunately, the critical values were only about 3000 Å for tin (only twice $\lambda_L(0)$, the London penetration depth) and about 1000 Å for gold. The advantage of a thicker film of tin is the resulting larger supercurrent carrying capability of the tin.

As a result, we have converted from a substrate temperature of $4.2^{\circ}K$ during deposition to one of $273^{\circ}K$. The improved film quality for thicker films is described in section A. Section B continues with a description of the consistent I-V curves due to the better quality of the film. The functional dependence of the Josephson critical current on temperature as well as the elimination of too low a critical current of the tin which would make the device inoperative is described in section C.

Section D is devoted to describing the variation of I_1 with the control current I_2.

Results

A. Thin Films

Previously the SNS films were vapor-deposited onto a sapphire substrate precooled to 4.2 K, and their electrical characteristics were subsequently measured in situ. With this 4.2 K deposition there is an inherent upper limit of the film thicknesses caused by mechanical stress buildup in the microcrystalline films during deposition (e.g. gold films thicker than 1000 Å would tend to crack to relieve the stress). This has been overcome by depositing the SNS films onto a substrate precooled to 273 K. As before, the films are deposited onto a substrate with preconnected electrical leads so as to allow immediate cooling to 77°K within 5 minutes and to 4.2 K within 20 minutes and to minimize any possible interdiffusion between the metal films. The films deposited at 273°K show no signs of cracking with thicknesses of tin presently up to 6000 Å! At 273°K the metal atoms have much more mobility as they deposit on the substrate than at 4.2°K resulting in a more ordered atomic array. This is evidenced by the data in table I.

Table I

	4.2°K deposition	273°K deposition
Gold resistivity at 4.2°K	30×10^{-6} Ω cm	6×10^{-6} Ω cm
Gold electronic mean free path	35 Å	350 Å
Tin electronic mean free path	200 Å	1000 Å
SNS junction resistance in the ohmic region with the tin superconducting	$<50 \times 10^{-3}$ Ω	$<1 \times 10^{-3}$ Ω

The effect of electronic mean free path on $\lambda_L(0)$ has been measured by Pippard[2] for tin and treated theoretically by Miller[3] showing that $\lambda_L(0)$ increases rapidly with decreasing mean free path. Increasing the film thickness has the same effect as increasing the mean free path[4]. Hence for the present films which are thicker and have longer mean free paths the magnetic field penetration depth is at minimum allowing a better definition of the area where magnetic fields are present and a more accurate analysis.

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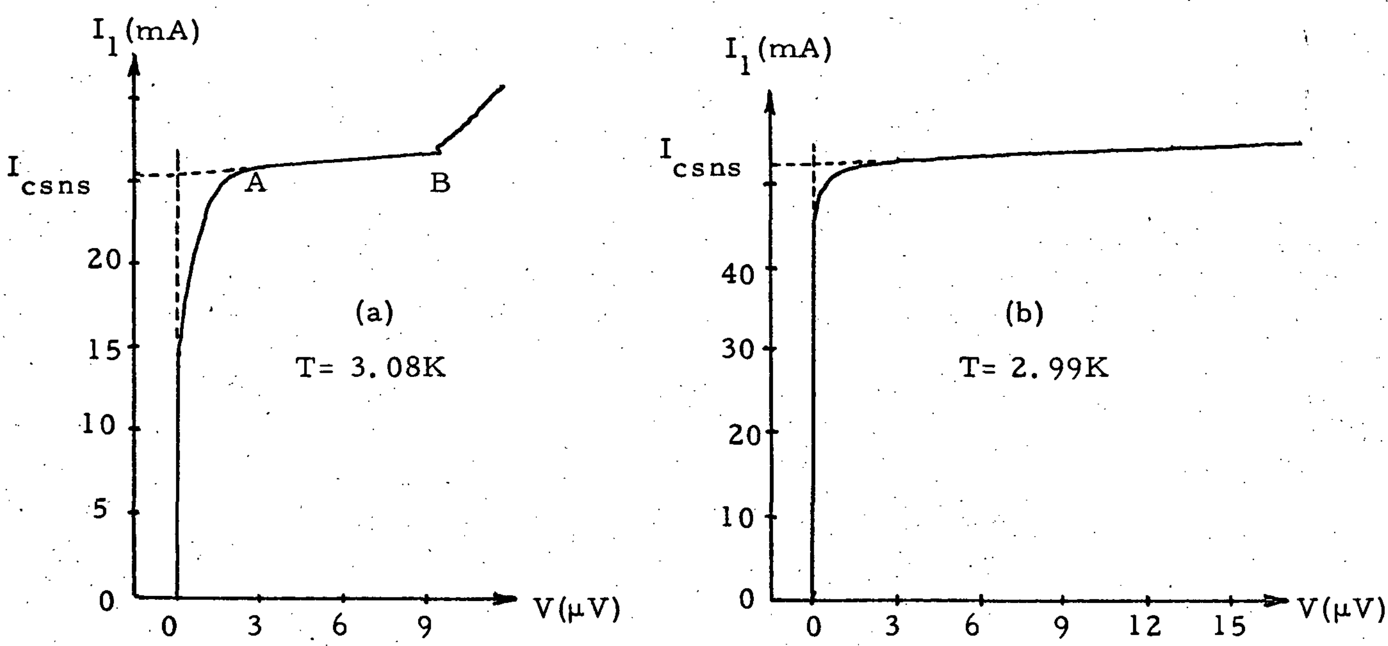
2. A. B. Pippard, Proc. Roy. Soc., A216, 844 (1956).
3. P. B. Miller, Phys. Rev., 113, 1209 (1959).
4. e.g., R. H. Blumberg, Jour. Appl. Phys., 33, 1822 (1962).

B. I-V Characteristics

The current-voltage (I-V) characteristics of the films deposited at 273 K have been consistent in shape (contrary to those deposited at 4.2°K) and are represented in Fig. 1.



sample 19, 550Å gold thickness

Fig. 1. I-V characteristics typical of these films deposited at 273 K.

There exists a region of "large" dynamic resistance (>10 mΩ) in the I-V curve denoted by line AB. It is the slope of this region of larger resistance which is important to eventual power gain.

The power gain of the three-terminal device is given by

$$G_p = \frac{\alpha^2 R_o^{\ 2}}{(R_o + R_L)^2} \frac{R_L}{R_i}, \tag{1}$$

where $\alpha \equiv \left.\frac{\partial i_1}{\partial i_2}\right|_{v_1} = \text{const.}$

and R_L, R_o, and R_i are the load, output, and input resistances repectively (See NASA report SIT P260 5/71 for a more complete description). For a gain greater than one (with $\alpha \sim 1$) it is necessary to maximize the ratio R_o/R_i. With this ratio in mind one should realize that the dynamic resistance in Fig. 1 increases rapidly with decreasing temperature until the slope passes the zero value (note, R_o^{-1} = slope here) and the resistance becomes negative. This increasing dynamic resistance along with the possibility of reducing R_i (the resistance path through the gold leg) by utilizing possibly an SNSNS geometry are necessary steps toward eventual power gain.

The static resistance (V/I) at point B for films deposited at 273 K has been on the order of $0.5 \times 10^{-3}\Omega$, whereas it was on the order of $10 \times 10^{-3}\Omega$ for the films deposited at 4.2 K. The resulting smaller voltages have uncovered an unexplained voltage shift of the I-V curves due to I_2. The resistance involved in this voltage shift is $\sim 2 \times 10^{-3}\Omega$, and its origin is presently being investigated.

C. Josephson Critical Current

The Josephson critical current has been found to vary as $I_c \alpha (1 - t)$ for $t \equiv T/T_{CSNS}$ not close to 1 (see Fig. 2, page 10); where T_{CSNS} is the zero-current transition temperature of the SNS junction. This is not to be confused with an SIS junction where the temperature dependence of the critical current goes as $I_{CSIS} \alpha (1 - t)$ for t near 1. Clarke[5] has published curves of I_c versus t for SNS junctions; and for t near 1 he reported the expected SNS dependence of $I_{CSNS} \alpha (1 - t)^2$ (for $t \lesssim 1$), but for $t \ll 1$ his curves exhibit also the linear variation with t.

In the past we had been restricted to the use of superconducting tin films thinner than 3000 Å. Unfortunately, such thin films of tin exhibited critical currents which sometimes were less than the Josephson critical currents. The Josephson critical currents are determined by the first onset of voltage appearing across the junction while the tin legs remained superconducting. However, if one of the tin legs should have a critical current less than that of the Josephson critical current then a voltage will appear across the junction due to both a resistance appearing in the tin near the junction, where previously there had been a resistance-free metal (a superconductor), and to the elimination of any supercurrent flowing through the gold due to the absence of superconducting electron pairs in the neighboring tin. So if the tin should enter the normal state due to too large a current load the Josephson effect will be destroyed through the elimination of the superconducting state in at least one of

5. J. Clarke, Proc. Roy. Soc., A308, 447 (1969).

the tin films. Actually, it was found that the tin film did not become normal-conducting instantly but did so in steps visible as voltage steps in the I-V characteristic (each step was seen to exhibit a $(1 - t)^{1/2}$ temperature dependence). Because of the junction geometry the potential leads sense a voltage only at the junction and not in the current leads not immediately touching the gold film (see Fig. 3); but for a uniform superconducting tin film touching a normal metal film at the SNS junction, the first section of the tin to become normal conducting will be at the tin-gold interface due to the lowering of the tin supercurrent because of the suppression of the density of superconducting electrons near the SN interface[6].

An example of both an SNS critical Josephson current and a critical tin current for a sample vapor-deposited at 4.2°K can be seen in Fig. 2a. For $3.9\text{K} \lesssim T < 4.3\text{K}$ both the Josephson and the tin critical currents appear, with the tin critical current larger than the Josephson current so as not to mask the Josephson critical current. But for $T \lesssim 3.9\text{K}$ the tin critical current becomes smaller than the Josephson critical current and destroys the superconducting state in one of the superconductors (whichever had a lower critical current) and hence destroys the conditions necessary for a SNS junction and Josephson tunneling. The critical current of the tin legs varies as $I_{CTIN} \propto (1 - t)^{1/2}$ for t not close to 1. The variation of the tin leg critical current with temperature was confirmed by measuring the critical currents of the SNS junction without the normal

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6. e.g. P. G. deGennes, Superconductivity of Metals and Alloys, Benjamin, N.Y. (1966).

metal layer (i.e. an SS junction).

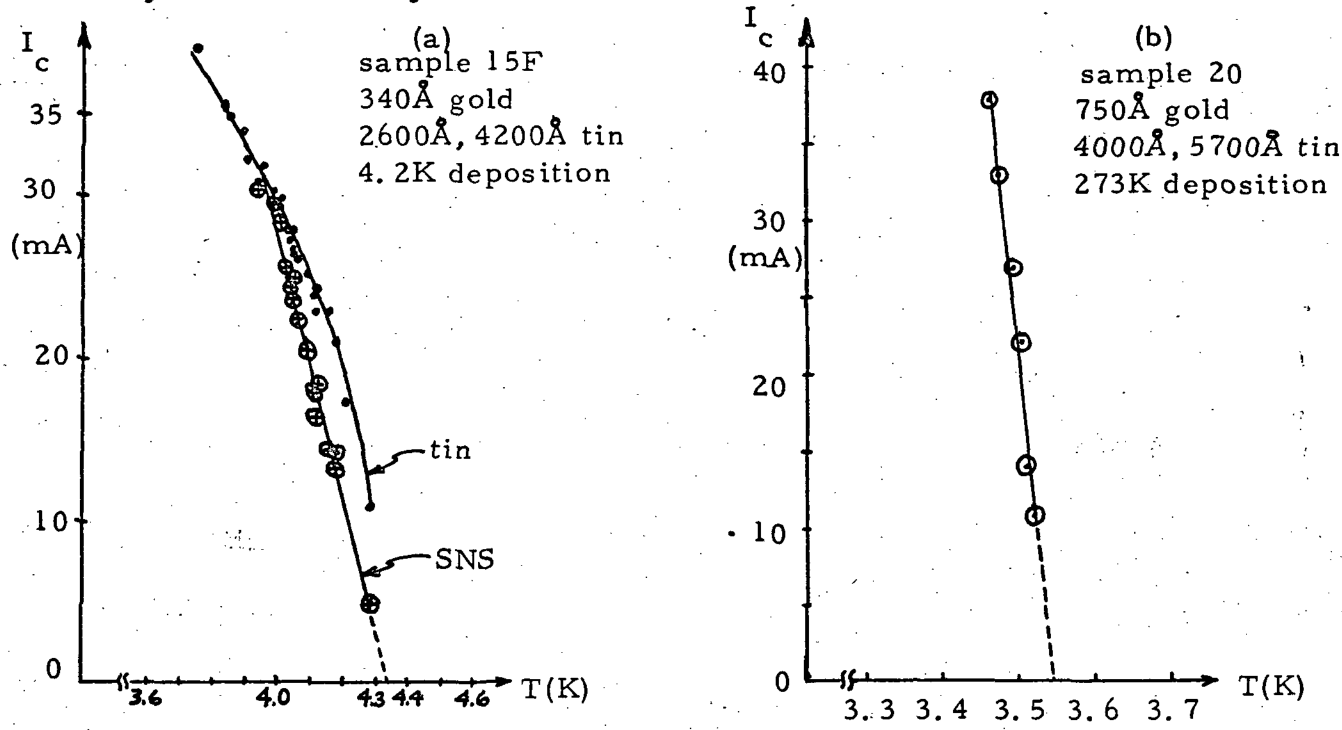

Fig. 2. Observed critical currents versus temperature for films deposited at (a) 4.2K and (b) 273K.

Figure 2b shows the variation of the Josephson critical current with T for films deposited at 273K. The critical Josephson current, I_C, increases at a rate of about $1\%/10^{-3}$K with decreasing T (which is similar to the data of Clarke[5] for the linear region of his curves). For the films deposited at 4.2K the rate of I_C increase was only about $0.2\%/10^{-3}$K. The steeper rise of I_C with decreasing temperature requires tighter temperature stabilization if we insist on operating in this region.

Another difference in the I-V characteristics between the films deposited at 4.2K and 273K is a shift of the linear portion of the $I_C(T)$ curve to much lower temperatures for the present films. For example, the extrapolation of the linear portion of the $I_C(T)$ curve to the abscissa yields a characteristic temperature of 4.2K for the SNS junction deposited at 4.2K and a temperature of 3.2K for the junction deposited at 273K (both junctions 600 Å gold, 3000 Å tin).

Such a decrease in this characteristic temperature might well be attributable to the decrease in T_{CS}, the transition temperature of the tin. The transition temperature of the tin films deposited at 4.2K was in the vicinity of 4.4K which is in agreement with the value of 4.5K obtained by Buckel and Hilsch[7] for tin deposited onto a liquid helium cooled substrate. The transition temperature of the tin films deposited at 273K, though, have a transition temperature below 4.2°K, but the exact value has not yet been measured. Garland and co-workers[8] have explained this shift of T_C from the bulk value for Buckel and Hilsch from the change in the phonon density of states with increased lattice disorder.

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7. W. Buckel, R. Hilsch, Z Phys., 138, 109 (1954).

8. J. W. Garland, K. H. Bennemann, F. M. Mueller, Phys. Rev. Lett., 21, 1315 (1968).

D. Dependence of the Josephson Critical Current on I_2.

Fig. 3 illustrates the geometry of the metal films in the vicinity of the SNS junction. The Josephson current is I_1 and the control or signal current is I_2. The variation of I_1 with I_2 at constant junction voltage is defined as $\alpha \equiv (\partial i_1/\partial i_2)_v$ = constant.

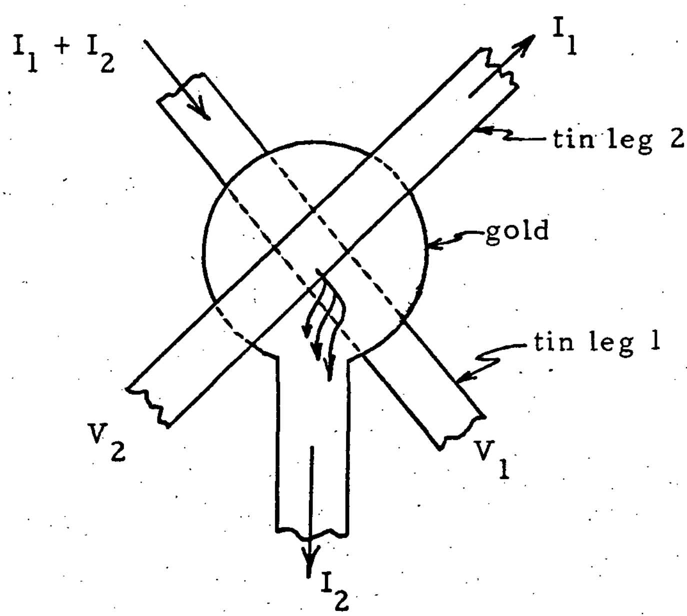

Fig. 3. SNS junction showing current paths. (with directions of positive current shown).

An example of the variation of the Josephson current (I_1) with the control current (I_2) is shown in Fig. 4.

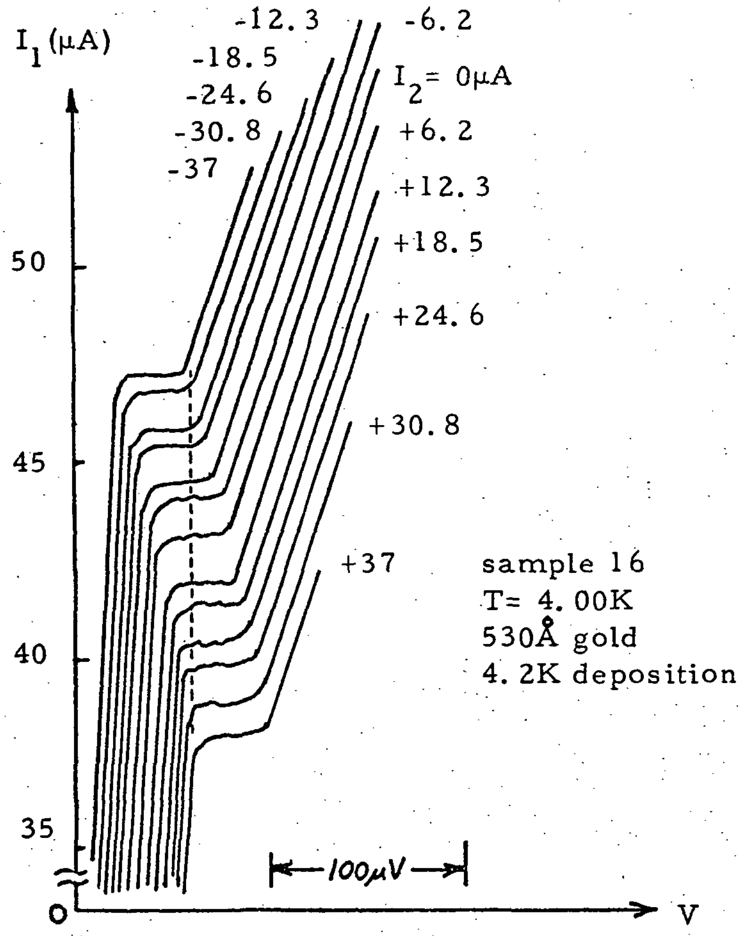

Fig. 4. $I_1 - V$ characteristic illustrating I_2 effect on I_1.

Using Fig. 4 one may calculate α for various values of I_2 along a constant voltage line (shown dashed in Fig. 4). When plotted against I_2, α has shown two functional forms: a constant (Fig. 5a) or a linear variation almost passing through the origin (Fig. 5b, where the slope appears to vary with temperature).

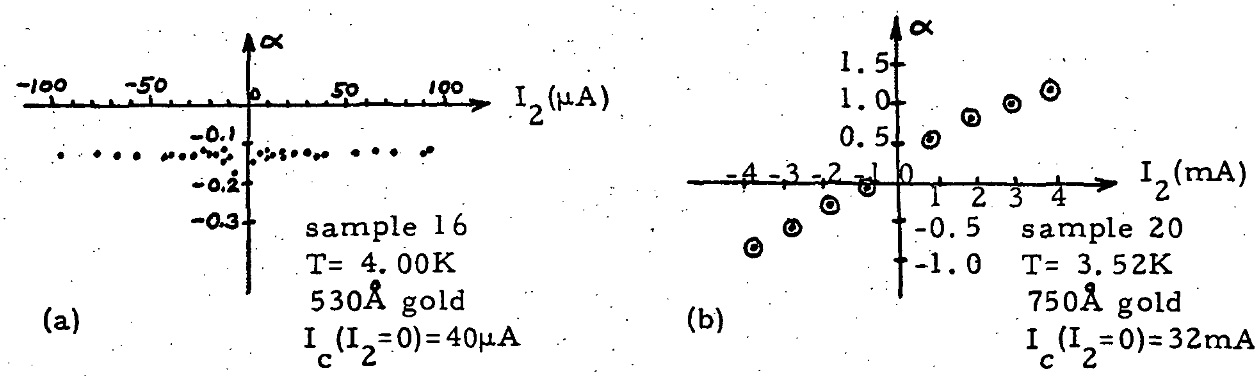

Fig. 5. Two observed dependences of α on I_2.

It is surmised that these two different forms originate from different current paths: In the first phase of this investigation, using crossed tin wires which made firm electrical contact with a film of gold only at the intersection of the tin wires (see NASA Report SIT-P251, 6/70 for a complete description of this point-contact Josephson junction) Rockefeller obtained a $\alpha (I_2)$ = constant dependence. Because the point contact geometry forced I_2 to cross the gold/tin interface only at the SNS junction proper and not before, it is expected that the change of I_1 with I_2 is a result of a contribution of I_2 toward the total critical current I_C of the SNS junctions (i.e. $I_C = I_1 \pm aI_2$, where $a < 1$ and represents the loss of some of I_2 to outside the junction due to "fringing"). Hence for the point contact junction we would expect α to be essentially constant with I_2. The path of I_2 in the thin film SNS junction, however, is not necessarily through the junction. From the geometry of Fig. 3 one would expect that the control current, I_2, flowing from the tin leg 1 to the gold film would take the path of least resistance - a path along the tin leg 1 past the junction and some distance into the voltage sensing portion of the tin leg before entiring the gold film. Now because the film of tin has been chosen sufficiently thick such that the combination of $I_1 + I_2$ does not exceed the critical current of the tin leg, then apparently the only effect I_2 will have on the junction will be either a magnetic effect or some lowering of the order parameter in the tin film due to increased supercurrent density[9] and, hence, smaller superconducting wave functions at the SN interface which results in a lowering of the maximum allowable Josephson supercurrent[10].

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9. Ref. 6, Eq. (6-35).

10. Ibid., Eq. (7-71).

Further investigation of the variation of α (I_2) and the underlying physical mechanism is important for the construction of a workable "superconducting transistor" device. The effect of magnetic fields on the junction, and hence, perhaps, the effect of I_2 on the junction, is illuminated by considering the dependency of I_C on an external magnetic field. The shape should determine how much self-field limiting the junction experiences. Figure 6 shows a curve of junction voltage verses external magnetic field (in the junction plane) for a fixed I_1. Steps in the VI curve (see Fig. 1) will show up in Fig. 6 and can easily be corrected for as shown by the dashed lines. From a theoretical point of view I_C vs H is the more fundamental dependence. It can be obtained from Figs. 6 and 1 by extrapolating to zero voltage as indicated by Fig. 1. Assuming that the superposition of a magnetic field moves the curve in Fig. 1 down, one can find from the intercept at V (I_1) of Fig. 6, the value of I_C, the value of I_1 at $V \rightarrow 0$.

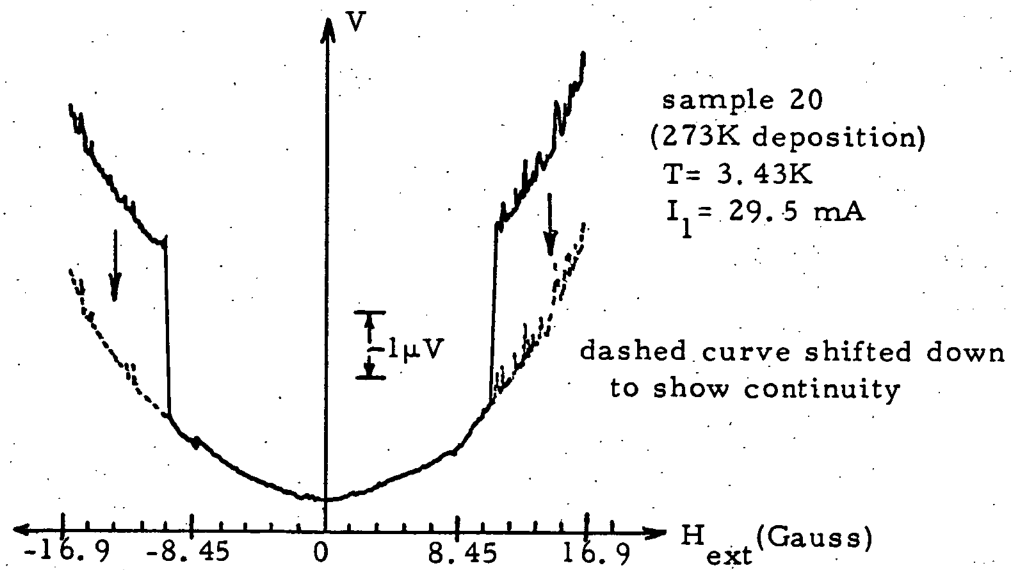

Fig. 6. Voltage change across SNS junction with applied magnetic field and fixed I_1.

E. Conclusions

A substrate temperature of 273K has been used during vapor deposition of the SNS junction thin films. The resulting films exhibit no macroscopic flaws for film thicknesses up to 6000 Å, twice those of previous films deposited at 4.2K. Thicker films of tin allow larger supercurrent capability so that the SNS junction is not limited by the critical current of the tin legs.

Another result of a thicker tin film with longer mean free path is that the London penetration depth is smaller, giving better magnetic shielding and simplifying the analysis of the junction. If thicker gold films are used the Josephson critical current density will decrease and the Josephson penetration depth will increase allowing a more even distribution of current in the junction and simplifying its analysis. Since this decrease in the current density goes exponentially with the gold thickness, the effective voltages across the junction will decrease and the phase-lock voltage detection system may have to be used again for increased sensitivity.

Finally, two functional dependences of α (I_2) have been found; one may be due to a direct interaction of the control current while the other is due to the magnetic field of the control current. Since the operation of the "superconducting transitor" as a linear amplifier depends upon α (I_2) = constant (see Eq. (1)), this latter, indirect, interaction of I_2 may have to be eliminated; and one solution may be the introduction of I_2 through a superconducting tin leg sandwiched between two gold films (an SNSNS device).