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A SUPERCONDUCTING TRANSISTOR

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ABSTRACT

A three film superconducting tunneling device, analogous to a semiconductor transistor is presented, including a theoretical description and experimental results showing a current gain of four. Much larger current gains are shown to be feasible. Such a development is particularly interesting because of its novelty and the striking analogies with the semiconductor junction transistor.

INTRODUCTION

Although superconductors and semiconductors both have an energy gap in their electronic excitation spectrum, it is the difference in the electrical conductivity of the ground state which leads to the striking difference in their behaviors. The ground state of a superconductor (i.e. Cooper pairs) is a perfect conductor whereas the ground state of a semiconductor is a perfect insulator. Superconductors can, however, duplicate some of the functions of semiconducting devices if the conductivity of the ground state Cooper pairs can be made negligible. This can be accomplished by a thin insulating barrier which blocks Cooper pairs, but through which excitations can quantum mechanically tunnel. Such a superconducting tunnel junction has a non-linear current-voltage characteristic similar to a semiconducting p-n junction diode except that it is polarity independent.

Using two such barriers, we have constructed for the first time a superconducting device which is a very close analogy to the semiconductor junction transistor.

The superconducting transistor is a three terminal device with a current gain. Our device is constructed by stacking three thin films of aluminum on top of each other and oxidizing them to form two insulating barriers between the films. One junction, called the injector, is biased at a voltage greater than $2\Delta/e$, where 2Δ is the Cooper pair binding energy and e is the electron charge. The resulting current dissociates Cooper pairs and one excited electron (quasiparticle) is created in each of the films forming this junction for each electron transferred. The additional excitations thus created in the center film can tunnel through the second junction, called the collector. This junction is independently biased at $V < 2\Delta/e$ so that Cooper pairs are not dissociated.

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THEORY

We are interested in the current gain $\Delta I/I^i$, where ΔI is the excess collector current due to the injector current I^i . If the injector junction is biased at $V > 2\Delta$, the current is primarily due to processes which break a Cooper pair and inject one quasiparticle in each film of the injector junction for each electron transferred. Hence, the injection rate per unit volume I_0 is $I^i/e\Omega$ where Ω is the volume of the middle film common to the junction. The collector junction is biased below 2Δ so that pairs are not broken, but the current I is proportional to the quasiparticle density N , such that $I = \alpha N$, where α can be calculated using the tunneling Hamiltonian.^{1,2} In the presence of injection, the excess collector current is given by $\Delta I = \Delta N/2$, where ΔN is the excess quasiparticle density and the factor of two is because there is direct injection in only one of the films of the collector junction. Combining these expressions, the gain is given by $\Delta I/I^i = \alpha \Delta N / 2 I_0 e \Omega$.

There is nothing in the above which indicates whether or not a current gain, i.e., $\Delta I > I^i$, is possible. Physically a current gain corresponds to the following: A single electron is injected in the middle film creating a quasiparticle excitation which causes more than one electron to flow across the collector junction. This multiplying effect is however possible, and it is because of the nature of the two processes contributing to the collector current αN .

To see this, it is necessary to examine the relevant terms in the tunneling Hamiltonian.^{1,2} It is convenient to express the

Fig. 1. The two tunneling processes are shown for an initial energy E and a collector bias voltage $V_g < 2\Delta/e$.

normal state electron creation and annihilation operators in terms of quasiparticle operators using the Bogoliubov-Valatin transformation.³ For tunneling between identical superconductors a and b , at voltages $V_b - V_a < 2\Delta/e$, the only energy conserving processes are described by the terms $u_p^\dagger u_p \gamma_{p'}^\dagger \gamma_{p'}^\dagger$ and $v_p^\dagger v_p \gamma_{p'}^\dagger \gamma_{p'}^\dagger$ where u and v are the BCS coherence factors and $\gamma^\dagger(\gamma)$ is the quasiparticle creation (annihilation) opera-

tor. These are shown in Figure 1. Integrating over the Fermi function and reduced BCS density of states, one finds in thermal equilibrium the same net current from each term.² The first term destroys a quasiparticle in b and creates one in a , while the second term destroys a quasiparticle in a and creates one in b . Each term

transfers one electron across the barrier from a to b.

This clearly indicates that a current gain is possible since a quasiparticle starting in a can go to b and then enter the condensate in a process which returns a quasiparticle to a, etc., each time transferring one electronic charge across the barrier of the collector. In this somewhat more physical picture, the current gain should be the ratio of the tunneling rate Γ_T to the loss rate by recombination Γ_R , since the excess quasiparticles can no longer tunnel back and forth once they recombine into Cooper pairs. Now the tunneling rate of a given quasiparticle⁴ is $\alpha/2e\Omega$ and $\Gamma_R = I_0/\Delta N$. Substituting in our previous expression for the gain, we find $\Delta I/I^i = \Gamma_T/\Gamma_R$. Hence if $\Gamma_T \gg \Gamma_R$ the injected quasiparticles can tunnel across the collector junction many times before recombining, which implies a current gain.

To maximize the current gain, the smallest value of Γ_R is desirable, indicating that aluminum is a good choice.⁵ To evaluate Γ_T , it is a good approximation to set $\alpha = (2N(0)R)^{-1}$ (for collector voltages $\gtrsim \Delta$ and reduced temperatures $T/T_c \lesssim 0.5$). Here $N(0)$ is the single spin density of states and R is the resistance of the collector junction. Hence, $\Gamma_T = (4eN(0)R\Delta)^{-1}$, so it is desirable to have a small value for the specific junction resistance RA and the film thickness d . Note that RA cannot be too small because the Josephson coupling will interfere with the desired effects. Using reasonable values for aluminum ($\Gamma_R = 10^5 \text{ sec}^{-1}$, $d = 300 \text{ \AA}$, $RA = 10^{-5} \Omega \text{ cm}^2$ and $N(0) = 1.7 \times 10^{22} \text{ cm}^{-3} \text{ eV}^{-1}$), we calculate a transfer function $\Delta I/I^i \cong 30$.

EXPERIMENT

In our experimental setup, three aluminum films (thickness $300 \text{ \AA}$ each) are deposited in a stack on a sapphire substrate to form two tunnel junctions (Fig. 2a). The samples are mounted in a vacuum can on a copper block cooled by helium 3. The collector junction has $RA \cong 6 \times 10^{-6} \Omega \text{ cm}^2$ and the injector is about 16Ω . The IV characteristic of the injector in Figure 2b shows the onset of pair breaking at $\cong 360 \mu\text{V}$. For the collector, IV plots corresponding to various labeled injection currents are shown in Fig. 2c. The current axis is greatly magnified compared with Fig. 2b so that the current due to thermally excited quasiparticles as well as injected quasiparticles can be readily seen. Only the bottom portion of the vertical rising part of the characteristic at $V = 2\Delta/e$ is visible. The negative resistance is due to the non-uniform energy gap in the films which leads to an inhomogeneous distribution of the tunnel current once the voltage corresponding to the smallest gap is reached.⁶ For the transistor operation this feature is unimportant since it is the current at $V < 2\Delta/e$ which shows a gain.

In Fig. 2d, the current change in the collector ΔI is seen to increase linearly with injector current, but with a temperature dependent slope greater than unity. Note that ΔI is always less than $I(0)$, the collector current with $I^i = 0$. Therefore, the saturation effects accompanying overinjection⁴ are negligible and the response is linear. The temperature dependence of the

observed effect is a convenient check that recombination into Cooper pairs is being observed. The value of $R_{\text{eff}} = \Gamma_R/N(T)$ found from these data is in reasonable agreement with earlier measurements⁴ if allowance is made for the difference in film thicknesses. At the lowest temperature measured, the current gain is about 4.

Fig. 2 (a) Schematic experimental configuration. (b) Current-voltage characteristic of the injector junction. The labeled points refer to the injection current for the collector curves shown in (c). (c) The current voltage characteristics of the collector junction. (d) The change in collector current is plotted against injector current showing a temperature dependent slope $\Delta I/I^i$ greater than unity. The temperature is determined from the quasi-particle current $I(0)$ in the collector with $I^i = 0$: o 0.625 K; o 0.650 K; o 0.695 K; o 0.703 K.

DISCUSSION

Note that unlike semiconductor devices, the polarity of both bias voltages is arbitrary--the device works the same for any combination of polarities. For the device shown in Figure 2, the power gain could be as large as twice the current gain and it is a simple matter to achieve additional current gain by cascading several devices. The voltage gain depends on the bias conditions, but because of the low input impedance the device might first be used on low impedance sources like thermocouples.

Although the device described above is similar to a semiconductor transistor in the common base configuration it should also be possible to bias in the common emitter configuration. If the collector bias is across the entire stack of films as shown in Fig. 3, the same current I_c performs both functions I^i and I , and a small additional current across the injector junction I_b can control I_c . The current gain, β , can be determined from a calculation of the "base" current I_b applied across the injector junction: $I_b = I_c - I^i$. If I_c is replaced by the equivalent expression $I(0) + \eta I^i$, where

$\eta \equiv \Delta I / I^i$, the result is $I_b = I(0) + (\eta - 1) I^i$. Therefore the small signal β is just $(\eta - 1)^{-1}$ which can be made arbitrarily large, if $\eta \approx 1$. Thus $\eta = \alpha / 4e\Omega\Gamma_R = 1$, which can be achieved by using $RA \approx 10^{-4} \Omega\text{cm}^2$ and fine tuning Γ_R through its dependence on operating temperature and applied magnetic field.⁴

Fig. 3. The common emitter configuration in which the collector and injector are not biased independently.

The analogy with a semiconductor junction transistor can be carried even further. In the semiconductor transistor, minority carriers are injected into the base region from the forward biased emitter-base diode, and are collected at the back biased base-collector diode. However, the injected carriers must diffuse across the base region before recombining with the majority carriers which are always present in the base. Thus the diffusion time must be shorter than the recombination time. In the superconducting device, quasiparticles are injected at either polarity when the junction voltage is $2\Delta/e$ or greater. At lower voltages quasiparticles are only collected. Hence, the superconducting transistor uses different magnitudes of the bias voltages instead of the forward and back biased diodes in the semiconductor transistor. Because the middle film is so thin, the quasiparticles diffuse across it almost instantaneously, but they have a rather small probability of transmission through the tunnel barrier of the collector junction. Therefore the criterion for current gain is in the comparison of Γ_T with Γ_R indicated above.

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