MAGNETIC FIELD DEPENDENCE OF THE JOSEPHSON TUNNEL CURRENT

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When two superconductors are separated by a thin insulating layer (<20Å thick), the form of the tunneling characteristic (current I vs voltage V) can be simply explained in terms of single-particle density-of-states vs energy diagrams.[1] On the basis of these "semiconductor" diagrams the tunneling is regarded as being due to single particles (electrons or holes), and the initial and final density of states enter directly into the tunneling probability for each particle. However, after considering terms others had neglected in the tunneling expression, Josephson[2] predicted that in addition to the "single-particle" currents mentioned above, a second type of tunnel current should be observed. This current is a flow of "Cooper pairs" between the Fermi surface of the two superconductors through the insulating layer. It should be observed as a direct current of limited magnitude flowing through the junction when there is no voltage between the superconductors. When a voltage V is established across the junction, the current alternates at a frequency $2eV/h$. The direct current has been reported previously[3] and arguments presented to differentiate it from currents which might be expected in junctions containing fine metallic shorts. The alternating current, or its interaction with applied microwave fields, has been reported by Shapiro.[4] Reported here is a study of the effect of magnetic fields on the direct current in a number of tunnel junctions of different dimensions. It is found that the current is reduced to minimal values whenever the junction contains integral numbers of flux units and that "self-limiting" affects "cross" junctions with any dimension greater than the "Josephson penetration distance."

The currents were first observed in Sn-I-Pb junctions (Sn evaporated first) but recently more strikingly in Pb-I-Pb junctions. The fabrication of the junctions follows established techniques[5] and the insulator is a thermally grown oxide. The dimensions of the junctions have been varied considerably but the resistance is consistently $\sim 3\times10^{-2}$ ohm mm^2 (see Fig. 2). The current voltage characteristics were taken on an X-Y recorder, using a dc supply of much higher resistance than any of the junctions.

The junctions were immersed in liquid helium at 4.2 or 1.3°K, the magnetic field being provided by a copper-wound solenoid surrounded by a Mu-metal can, both immersed in the helium bath. The production of 40 gauss involves negligible heat input. The solenoid was calibrated at room temperature using a Hall effect probe. The Mu-metal shield reduces the field at the sample from other sources to $<10^{-2}$ G.

Josephson[6] and Ambegaokar and Baratoff[7] have pointed out that the maximum magnitude of the current J_1 is equal to the flowing when the junction has both films normal and is at a bias $\frac{1}{2}\pi\Delta$. This current will only be observed, however, for a given junction under ideal conditions. As pointed out by Anderson[3,8] and by Ferrell and Prange,[9] the phases of the gap functions on the two sides of the junction are coupled by an energy $hJ_1/2e$. This coupling is reduced by magnetic fields and by current flow through the unit. In order to maintain the flow of Josephson current against thermal and circuit fluctuations, the value of J_1 should be as large as possible. This can be done by making the junction resistance low (the insulator as thin as possible and the junction area large) and by using superconductors with large Δ. The junction area cannot be increased indefinitely, however; apart from the difficulty of making large-area thin insulating layers, the smaller dimension of the junction should remain $\lesssim 2\lambda_J$ where λ_J is the "Josephson penetration distance." This is a consequence[6,9] of the self-magnetic fields generated by the Josephson current, which contain the current flow to within a distance $2\lambda_J$ from the edges of the junction with

$$\lambda_J = (16\pi\lambda e^2 J_1/hc^2)^{-1/2},$$

where λ is the penetration depth, 390 Å for lead films.[10]

The unit in which the ratio of the observed Josephson current I_0 to the maximum magnitude (I at $\frac{1}{2}\pi\Delta$) was largest was one of dimensions 0.24×0.24 mm; as can be seen from the current-voltage characteristics of Fig. 1, this ratio is 0.55. Figure 2 gives the relevant data for two other junctions. The one of smaller area had

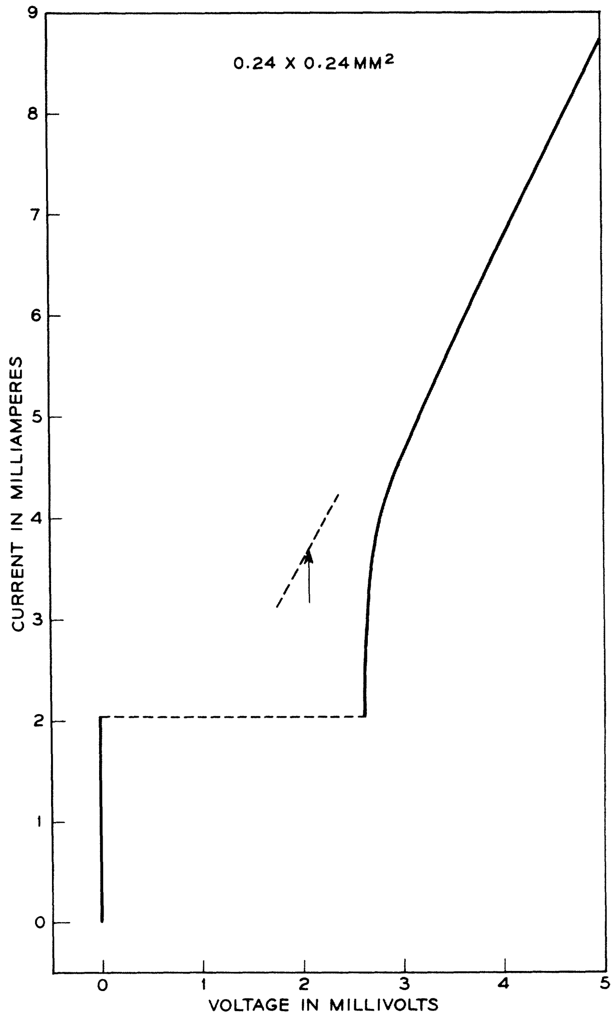
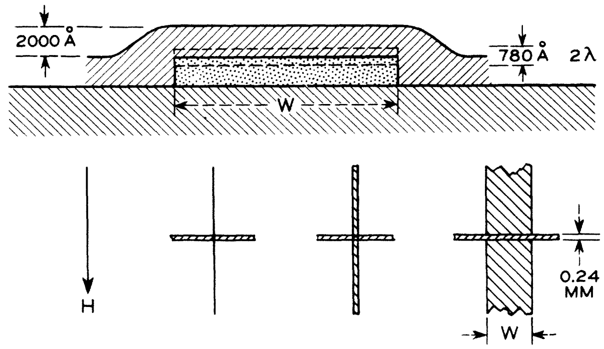


FIG. 1. Current-voltage characteristic for a Pb-I-Pb junction at 1.3°K. The arrow marks the predicted maximum magnitude of the Josephson current.



WIDTH W	0.04 MM	0.24 MM	2.40 MM
FIELD PERIOD	6.5 GAUSS	1.1 GAUSS	0.4 GAUSS
FLUX	2.0×10^{-7} G · CM²	2.1×10^{-7} G · CM²	7.5×10^{-7} G · CM²
I AT $\frac{\pi}{2}\Delta$	0.5 MA	3.7 MA	38 MA
I_0	0.17 MA	2.0 MA	4.5 MA

FIG. 2. Comparison of the dimensions of three junctions and the magnitude and field dependence of the Josephson current.

the ratio 0.35, whereas the other, of much larger area, had 0.1. This is surprising at first sight as one film of this unit is still only 0.24 mm wide ($\sim\lambda_J$), and self-limiting of the current should not be serious. The junction is not, however, identical to the idealized model used by Ferrell and Prange[9] in which current flow in the two superconducting films is parallel and opposite. In the "cross" junction of Fig. 2 the current flows along the top narrow film down through the junction and away from the junction along the lower wide film in a direction perpendicular to the current flow in the top film. As the current density will be greatest in the narrow film, the field in the junction will be generated almost solely in the direction and plane of the wide film. If the field due to current in the wide film is assumed zero, then the new penetration depth is $\sqrt{2}\lambda_J$ and current is confined to a width $2\sqrt{2}\lambda_J$ of the junction. For this junction λ_J is calculated as 0.22 mm, $2\sqrt{2}\lambda_J=0.62$ mm. This indicates that only one quarter of the junction is carrying current and explains the low observed current of 4.5 mA.

It has been observed by Josephson[6] that the effect of an external magnetic field (or a current flowing along one film of the junction) would be to reduce the direct current to a minimum whenever the junction contained integral numbers of flux units ($hc/2e=2.1\times10^{-7}$ gauss cm²). We have observed this effect in junctions of various dimensions, but it is most striking when the film along the field direction is as narrow as possible. Figure 3 shows the variation of observed current I_0 as a function of magnetic field for a Pb-I-Pb junction made of films 0.040 and 0.24 mm wide, the 0.040-mm wide film being roughly along the field direction. When a field of 6.5 gauss is applied, the Josephson current is reduced by a factor >600 and cannot be measured with the existing experimental sensitivity. At 13.0 and 19.5 gauss, the current again goes through minima with successive-

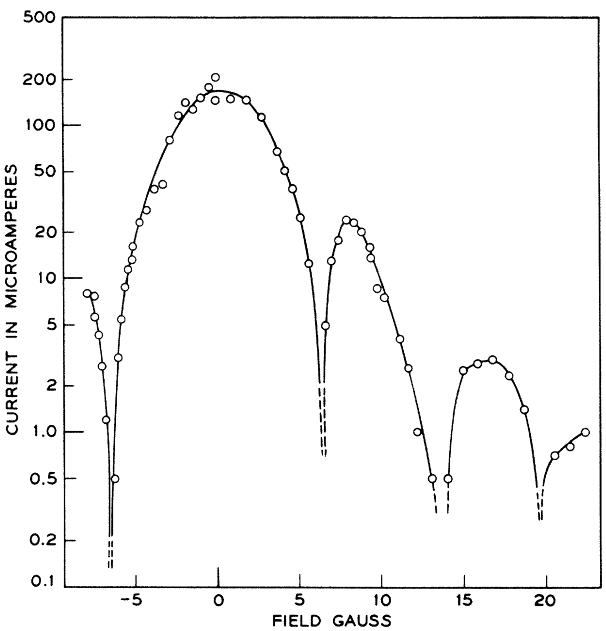


FIG. 3. The field dependence of the Josephson current in a Pb-I-Pb junction at 1.3°K.

ly decreasing maxima between. The area of junction containing flux is the width $W\times 2\lambda = 3.1 \times 10^{-8}$ cm^2 (see cross section of junction, Fig. 2). Thus a field of 6.5 gauss corresponds to a flux of 2.0×10^{-7} gauss cm^2 in the junction, which is indeed the flux unit. Considering screening and demagnetizing effects of the films, it is surprising that such a good value is obtained. A larger junction, 0.24×0.24 mm, had a period of 1.1 gauss, but the minima were not so well defined as the current did not reduce so effectively to zero. Again this corresponds to one flux unit being in the junction. For the large-area junction, 2.4×0.24 mm, the minima were poorly defined with approximately a 0.4-gauss period. If the full width of the junction is effective in carrying current, one obtains the flux as 7.5×10^{-7} gauss cm^2, but if $2\sqrt{2}\lambda_J$ is effective then the flux is 1.9×10^{-7} gauss cm^2. This appears to confirm the conclusion above that the Josephson current flow is confined to a width $2\sqrt{2}\lambda_J$ at the edge of the junction.

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[7]V. Ambegaokar and A. Baratoff, Phys. Rev. Letters 10, 486 (1963). In a correction to this Letter [Phys. Rev. Letters 11, 104(E) (1963)], the authors point out that the temperature dependence of J_1 for a symmetrical junction is given by

$$J_1 = \tfrac{1}{2}\pi R_N^{-1}\Delta(T)\tanh\tfrac{1}{2}\beta\Delta(T),$$

but for Pb-I-Pb at 1.3°K this correction is negligible.

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EXCITED STATES OF THE F-CENTER ELECTRON

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In the past few years, interest in the excited states of the F center has been stimulated by the discovery of the L bands by Luty[1] and by the work of Swank and Brown[2] on the lifetime of the excited level responsible for the emission band of the center. Luty has attributed the L bands to excited levels lying above the K and F levels, and Swank and Brown have pointed out that their long-lifetime (~10^{-6} sec) results could be understood if an excited state existed, of the same symmetry as that of the ground state, lying just below the F excited level. The K band has long been attributed to an excited level of the F center.

Some time ago the present author[3] carried out calculations on the electronic structure of the F center in LiCl using the LCAO method in which the wave functions of the ground and excited states were expressed as linear combinations of