Temperature and Magnetic Field Dependences of the Josephson Tunneling Current

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A search has been made for Josephson[1] tunneling in nearly 100 sandwich junctions of various combinations of Al, Sn, Pb, and Nb. Some zero-voltage tunneling has been seen in virtually all of these. Detailed studies of this tunneling as a function of temperature and magnetic field confirm and extend the observations of Anderson and Rowell.[2] A zero-voltage tunnel current periodic in magnetic field and having the temperature dependence calculated by Ambegaokar and Baratoff[3] lends strong support to the reality of Josephson's prediction.

The junctions reported here were made by evaporating the metals onto glass substrates at room temperature to a thickness of 1000–3000 Å in vacuums of 2×10^{-5} Torr. The insulating layer of the sandwiches was made by oxidation in controlled atmospheres of air or oxygen plus water vapor. Parallel, superposed strips were used, 0.025 cm wide, with the upper insulated from the lower by an SiO film, except at the junction.

The current–voltage curve of higher resistance junctions (order 1–10 Ω for normal tunneling) was characterized by an initial zero-voltage current, followed by a region in which voltage (at constant current) fluctuated erratically, following which the junction resumed typical superconducting tunneling. The magnitude of the zero-voltage current I_J was typically small in these junctions, not reproducible and strongly affected by magnetic fields and external voltage transients.

Much more suitable for systematic studies of magnetic field and temperature dependences were the lower resistance parallel-strip junctions (0.01–1 Ω) for which the I_J was reproducible either precisely or to within a few percent. In these junctions the conventional tunneling voltage appeared immediately I_J was exceeded. In many junctions I_J was greater than 30% of the theoretical Josephson current

$$J = (\pi/R_{NT})\,\Delta_1\Delta_2/(\Delta_1 + \Delta_2)\ ,$$

where R_{NT} = normal tunneling resistance, and Δ_1 and Δ_2 are half the energy gaps. In one $I_J = 0.8\ J$. In none was $I_J > J$. The results reported here were obtained with lower resistance junctions. However, so far as could be discerned, similar phenomena occurred in the higher resistance junctions as well.

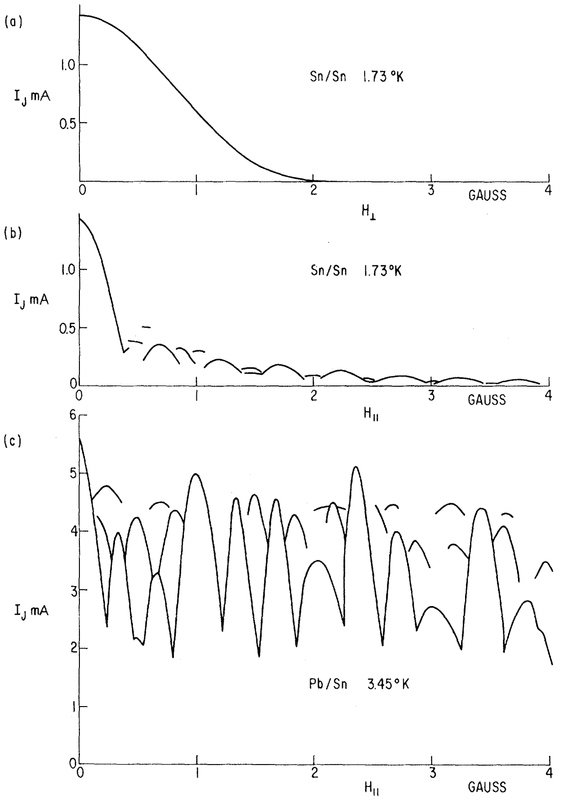

FIG. 1. Zero-voltage currents through superposed, parallel-strip junctions as a function of applied magnetic field in plane of films. (a) H perpendicular to Sn/Sn strips, ~0.01-cm tunneling width normal to $H_\perp$. (b) H parallel to same strips, 0.01-cm tunneling width normal to $H_\parallel$. (c) H parallel to Pb/Sn strips of width 0.025 cm having a multistep tunneling characteristic.

Figure 1 shows recorder tracings which illustrate the behavior of a Sn/Sn junction in a magnetic field in the plane of the films, either parallel to their length ($H_\parallel$) or normal to them ($H_\perp$). Field orientation is important where the self-fields of the tunneling currents are larger than ~0.2 G, which occurs in these junctions at currents above ~10 mA. In some junctions of very low resistance (~0.02 Ω) the tun-

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[1] B. D. Josephson, Phys. Letters 1, 251 (1962).

[2] P. W. Anderson and J. M. Rowell, Phys. Rev. Letters 10, 230 (1963).

[3] Vinay Ambegaokar and Alexis Baratoff, Phys. Rev. Letters 11, 104 (1963).

neling currents were large enough to determine the initial slope of the I_J vs H curve. Field orientation is important also where the junction cross section varies with aspect, and with it the amount of flux threading the junction.

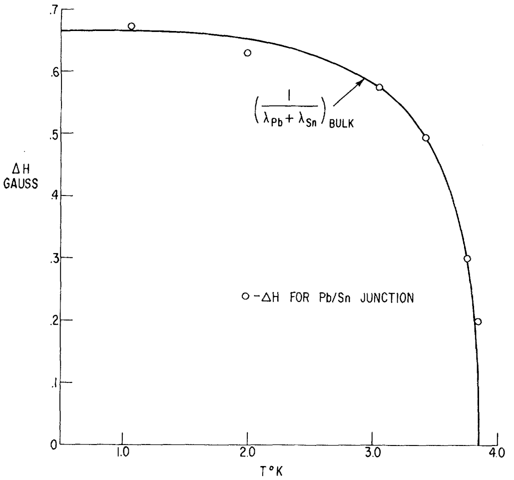

FIG. 2. Temperature dependence of magnetic field intervals ΔH between maxima in I_J vs $(\lambda_{Pb} + \lambda_{Sn})^{-1}$ fitted to ΔH at 3.4°K.

Figure 1(b) shows that I_J is periodic in H with an interval $\Delta H = 0.52$ G between maxima. The area A of the junction through which flux can thread is twice the penetration depth in Sn (λ_{Sn}) times the strip width (0.025 cm). If the bulk penetration depth of 510 Å is used, the flux increment $A\,\Delta H$ between maxima is 1.3×10^{-7} G cm^2. Since the penetration depth in these films should be larger than 510 Å, it is reasonable that the flux increment is identical with the flux quantum $hc/2e = 2.07 \times 10^{-7}$ G cm^2.

The junction length along the film of Fig. 1(a) was ~0.01 cm, requiring a field $H_\perp$ larger than $H_\parallel$ to produce a flux through the junction equal to a flux quantum as borne out in the graph.

A convenient method of varying the cross-sectional area of the junction is to make use of the temperature dependence of the penetration depth, which varies as $[1 - (T/T_c)^4]^{-1}$. Figure 2 is a plot of ΔH vs T for a Pb/Sn junction compared with $(\lambda_{Pb} + \lambda_{Sn})^{-1}$, showing that $A\,\Delta H$ is independent of T.

Some junctions displayed a current–voltage characteristic in which the conventional tunneling characteristic was reached not by a single discontinuous jump, but in a series of steps, each of which occurred at constant voltage. The currents I_{Ji} at which these steps occurred were both temperature- and field-dependent. Evidence of these additional steps can be seen around the minima in Fig. 1(b). They are, however, much more evident in Fig. 1(c), showing three sets of maxima in I_{Ji} vs H in a Pb/Sn junction. This periodic structure continued as a function of field out to the film critical field. The intervals ΔH in each of the first two sets are all quite precisely 0.33 G; the interval in the last set is 0.49 G. The temperature dependence of ΔH fits within experimental error the temperature dependence of $(\lambda_{Pb} + \lambda_{Sn})^{-1}$. Although this structure is not yet understood in detail it seems probable that the steps are associated with modes in the alternating currents which are developed across the junction at nonzero dc voltages as required by Josephson.[1]

Figure 3 shows the temperature dependence of I_J for a Pb/Sn and a Sn/Sn junction in comparison with the calculation of Ambegaokar and Baratoff.[3] Within experimental error, the slope of I_J/I_{J_0} vs T/T_c at T_c for Sn/Sn agrees with their theoretical value of 2.66, and the tangent for Pb/Sn is vertical as predicted.

The following conclusions can be drawn:

1. A zero-voltage current can pass through a superconducting tunnel junction which may approach but does not exceed the theoretical Josephson current, and which is destroyed or materially altered in a magnetic field larger than order 1 G.
2. The temperature dependence of the zero-voltage current is in agreement with the calculation of Ambegaokar and Baratoff.
3. The zero-voltage current is periodic in an applied magnetic field. The incremental flux through the junction per period is approximately equal to one flux quantum.

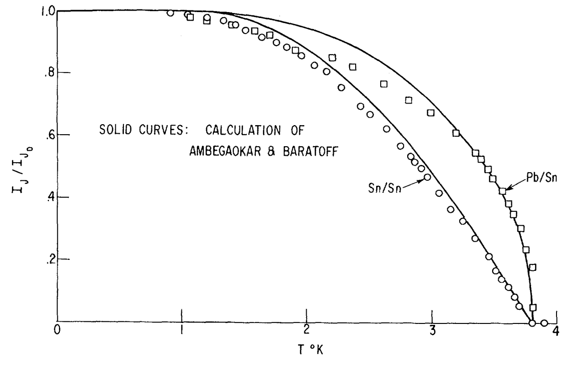

FIG. 3. Temperature dependence of zero-voltage current of a Sn/Sn and a Pb/Sn junction in comparison with calculation of Ambegaokar and Baratoff.

4. The step structure observed in some tunneling characteristics is also periodic in a magnetic field in a manner similar to that for the zero-voltage current.

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