EFFECT OF TEMPERATURE AND MAGNETIC FIELDS ON THE THIN-FILM dc SUPERCONDUCTING TRANSFORMER*

P. E. Cladis
Department of Physics and Astronomy, University of Rochester, Rochester, New York
(Received 5 June 1968)

Magnetically coupled tin films are found to exhibit the characteristic dc transformer effect first reported by Giaever only for reduced temperatures of the primary $0.925 < t < 1$. A striking dependence of the secondary voltage on magnetic fields is also observed. The temperature dependence of the depinning current and the critical current is discussed.

The resistance exhibited by a superconductor in either the mixed or intermediate state has been attributed to the motion of quantized vortices. This notion that current-induced flux-line motion could cause a dc voltage was most convincingly demonstrated by Giaever.[1] He was able to show that forcing vortices to move in one thin film results in the motion of vortices (and hence a voltage) in a nearby second film. The two films are electrically isolated and their coupling is effected by means of a magnetic field only. In fact, without invoking a mechanism such as vortex motion it is difficult to understand the origin of this secondary voltage.[2]

The purpose of the present work was to measure the effect of temperature and magnetic field on magnetic coupling in thin tin films. Giaever has noted[1] that, as one would expect, the dc transformer effect does depend on the applied magnetic field, but so far no detailed study has been published on the dependence of the dc transformer effect on magnetic field and temperature. We have observed a rather striking dependence on magnetic field and also the extinction of the secondary voltage at reduced temperatures $t < 0.925$ in the case of tin films.

The samples were made by vacuum deposition of two tin films separated by a thin layer of SiO. Primary films ranged in thickness from 1800 to 5000 Å, secondary films from 1000 to 2000 Å. The films were evaporated at 4×10^{-6} Torr onto nitrogen-cooled substrates. For the samples studied, the resistance ratios between room temperature and helium temperature were typically 20 to 30. This corresponds to a value of the Ginzburg-Landau parameter $\kappa \sim 0.26$.

The samples were made with either the primary film laid down first with the secondary on top or vice versa. The order of evaporation seemed to make no difference in the ultimate results. The only distinguishing feature between the two cases was that the transition temperature of the bottom film, whichever one it was, has, so far, in the case of pure tin always occurred at a higher temperature. It appears to be essential in these experiments that the geometry chosen be such that the secondary lies completely over a region of uniform primary width.

Typical results are shown in Fig. 1. Here we plot the induced secondary voltage as a function of primary current I_p for different values of the applied magnetic field. The current value at which the voltage just appears is called the depinning current I_d; the current at which the secondary voltage drops abruptly to zero, the maximum current I_c.

At constant h, I_d was found to vary linearly with temperature (Fig. 2). Deltour and Tinkham[3]

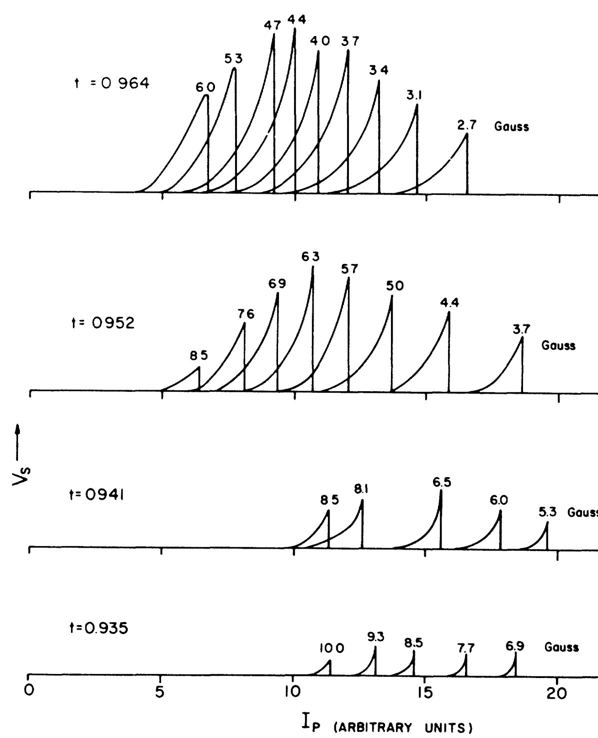

FIG. 1. Secondary voltages V_S versus primary current I_p as a function of reduced temperature and magnetic field for a dc transformer with 1800-Å Sn primary and 1000-Å Sn secondary.

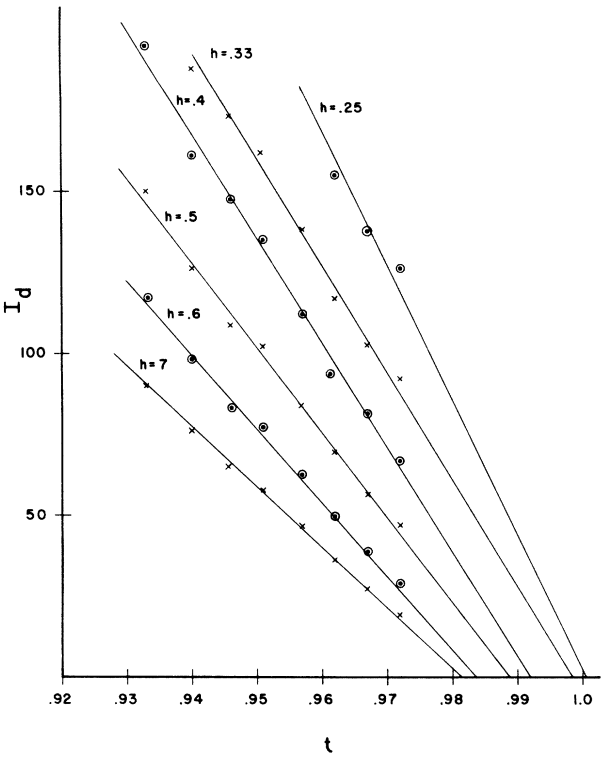

FIG. 2. Temperature dependence of I_d at constant h. The intercept corresponds to a reduction in T_c in the presence of the depairing mechanism H. The sample was a tin sandwich.

have postulated that the pinning force $F_p = k'\Delta_m^2$, where Δ_m is the maximum value of the gap parameter between vortex centers and k' is a constant (which may be temperature dependent). They verified this relation by measuring F_p as a function of the parallel component of the magnetic field as well as the perpendicular component for fixed temperature. The only effect of the parallel field was to affect Δ_m in a known way. The more general relation, of which the Deltour-Tinkham relation is the special case for fixed temperature, is presumably $F_p = k'' V(\Delta F_m)$, where k'' is a temperature-independent constant relating to the defect structure, $V = td^2(T)$ is the volume of the vortex core (t is the film thickness and d the core diameter), and ΔF_m is the maximum value of the condensation energy density between vortex centers. Since $d(T) \sim \xi(T) \propto (\Delta T)^{-1/2}$ and $\Delta F_m \propto H_c^2 \propto (\Delta T)^2$, the resulting temperature dependence of F_p is $F_p \propto \Delta T$ or $F_p \propto 1-t$ as obtained in Fig. 2.

Another interesting feature of Fig. 2 is the fact that the curves do not intersect the $I_d = 0$ axis at the same temperature. This is a consequence of the method of plotting the data. Although the curves are lines of constant reduced field h, the actual field H varies with temperature along the curve; consequently when $I_d = 0$, H is not necessarily zero. The presence of this nonzero H results in depairing of the superelectrons and, consequently, a lowering of the critical temperature. This is given by the universal pair-breaking equation[4]

$$\ln\frac{T_c}{T_{c0}} + \Psi\left(\frac{1}{2} + 0.14\frac{T_{c0}}{T_c}\frac{\alpha}{\alpha_{cr}}\right) - \Psi\left(\frac{1}{2}\right) = 0, \quad (1)$$

where T_c and T_{c0} are the transition temperatures in the presence of and in the absence of the pair-breaking perturbation, respectively, and the normalized pair-breaking parameter α/α_{cr} takes the form $H/H_{c2}(0)$ in the present case. The limiting form of Eq. (1) for small α is

$$T_c/T_{c0} = t = 1 - 0.69H/H_{c2}(0). \quad (2)$$

Values obtained from Eq. (2) compare well with values of t from Fig. 2.

We found that I_c^2 was proportional to the helium bath temperature for large h. This quadratic dependence of I_c suggests that it is determined by Joule heating, i.e., power dissipated $= IV = I^2R \rightarrow V = IR$ which is true for normal metals and for large values of current in superconductors under conditions of flux flow in the presence of pinning. Furthermore the slopes of the I_c^2-vs-t curves scale with $1/h$ for large h which is consistent with the well known observation that the flux-flow resistance in bulk superconductors is proportional to h in the linear region of the flux-flow I-V curves. From the observed I-V regime, it is apparent that the linear region (current-independent flow resistance) of bulk superconductors is not attained and consequently the implication that Ohm's law may be valid for these samples at I_c is puzzling since it is clearly not valid for $I < I_c$.

The abrupt nature of the normal-superconducting transition at I_c suggests that a thermal runaway mechanism triggers the transition. Since the power being dissipated by the primary is typically 3×10^{-5} W near T_c and even smaller (Fig. 1) just before extinction of the effect, we cannot suppose that the sample becomes normal because of heating by the current through T_c as seen from the following discussion. We can estimate the degree of heating produced by our typical power input. If q is the power being dissipated per cm^2 by the sample and ΔT the temperature difference between the helium bath and the sample, then

$$q = \theta \Delta T,$$

where θ is the heat transfer coefficient. Using Reeber's[5] measurement of θ found for a silver disk immersed vertically in helium at 4.0°K with $\theta = 0.020$ W/cm^2 °K under conditions of convective cooling only, $\Delta T \cong 1.5$ mdeg, clearly not enough to heat the sample through T_c.

Another odd feature of this "heating" phenomenon is that the transition is nonhysteretic with current. Slowly decreasing the current (in a properly annealed sample) will result in the sample retracing the original I-V curve, the normal-superconducting transition taking place at $I_c' \cong I_c$, the original superconducting-normal transition point. This feature does not seem to support the notion of thermal runaway and suggests that the exact mechanism leading to the transition is rather more complex than just heating.

The transport current provides a field gradient across the sample such that its magnetic field adds to the external field on one side of the sample and subtracts on the other side. When the net field within the superconductor combines to produce H_{c2} at one edge of the sample, a normal strip will result. Such a normal line has been observed by Solomon[6] and its appearance, we suspect, complicates the electrodynamics of flux flow for now we have two different regions—the normal region, subject to Ohm's law, in parallel with a superconducting region. An abrupt change in the current distribution at I_c (owing to the appearance of a normal region, say) could trigger large local thermal instabilities[7]; however, we do not understand the exact mechanism by which this combination of heating and critical magnetic fields effects the abrupt transition at I_c.

In passing, we mention that all of the measurements were made with an infinite resistance across the secondary and thus with no current flowing through the secondary. A negative biasing current through the secondary reduces the flux-flow voltage in the secondary as shown in Fig. 3. Here the secondary voltage is seen to

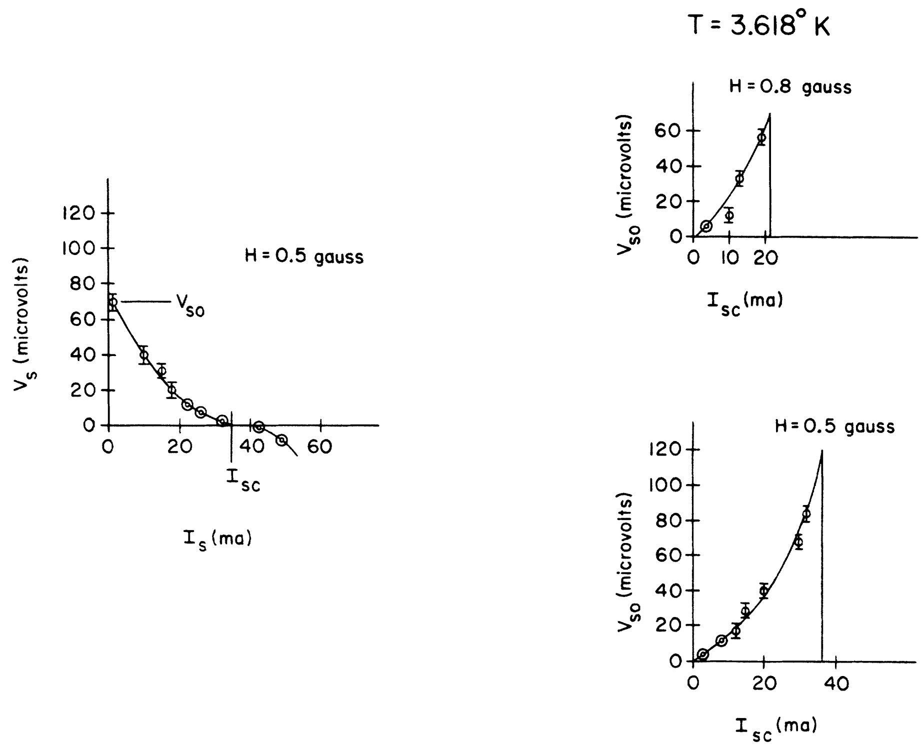

FIG. 3. The secondary voltage V_s for a particular value of the primary current I_p is shown as a function of the secondary current I_s. The value of I_s for which V_s is extinguished we call the compensating secondary current I_{sc}. Its value for a particular transformer and for a given magnetic field depends upon I_p and thus in turn upon V_{s0} (the value of V_s for $I_s = 0$). Shown on right is the functional relation between I_{sc} and V_{s0} for a particular temperature and for two values of H.

decrease steadily as the secondary current is increased. The interesting result of this study is the long range of biasing current values for which $V_S = 0$. This suggests that before the vortices could be moved again in the reverse direction it was necessary to give up the original depinning energy overcome by the primary current in the first place and reacquire it by means of the secondary current.

We conclude that the secondary voltages were not observed for $t < 0.925$ in the case of the Sn thin film superconducting transformer owing to the different temperature dependences of I_d and I_c. We have some understanding of the significance of I_d; however, the exact nature of I_c is to be elucidated.

I should like to thank Mr. C. E. Kelley for information concerning the evaporation of silcon monoxide and Dr. R. D. Parks for useful discussion.

*Work supported in part by the Army Research Office (Durham).

[1]I. Giaever, Phys. Rev. Letters 15, 825 (1966), and 16, 460 (1966).

[2]One should point out that a voltage across a superconductor need not necessarily imply vortex motion. For example, G. J. VanGurp, Phys. Letters 24A, 528 (1967), shows the existence of at least two dissipative mechanisms present in type-I superconductors. Thus one is led naturally to suppose that the dc transformer enables one to isolate the effect of viscous motion from other possible voltage-producing mechanisms which may be present in, say, single films. As can be seen in Fig. 1 no "linear" regions are present in the I-V characteristic; however, vortex motion is deduced owing to the existence of the secondary voltage in this regime.

[3]R. Deltour and M. Tinkham, Phys. Rev. Letters 19, 125 (1967).

[4]K. Maki, in "Superconductivity," edited by R. Parks (Marcel Dekker, Inc., New York, to be published).

[5]M. D. Reeber, J. Appl. Phys. 34, 481 (1963).

[6]P. R. Solomon, to be published.

[7]P. W. Anderson and Y. B. Kim, Rev. Mod. Phys. 36, 39 (1964).

SIMPLE INTERPRETATION OF THE JOSEPHSON EFFECT*

F. Bloch
Department of Physics, Stanford University, Stanford, California
(Received 26 August 1968)

The effect of a dc voltage to cause an alternating current through the barrier between two superconducting regions was predicted on theoretical grounds by Josephson. It is shown for the simplified geometry of a thin ring, interrupted by a single barrier, that this effect can be interpreted as a direct consequence of general principles which are closely related to those previously employed to explain the quantization of trapped flux.

It was predicted by Josephson[1] and has been confirmed by experiment that a dc voltage V across the partitioning barrier of a superconductor gives rise to an alternating current of frequency

$$\nu = 2eV/h. \tag{1}$$

This important result was originally derived as a consequence of the BCS theory of superconductivity. An alternate formulation was based upon the theory of Ginzburg and Landau with particular significance attributed to the phase of the order parameter. The following observations indicate that it is possible, irrespective of the underlying detailed theory, to interpret the Josephson effect as a direct consequence of general principles. They will here be limited to the discussion of conditions chosen for the sake of simplicity and yet compatible with the essential features.

In particular, the considerations shall be restricted to the case of a thin superconducting ring (see Fig. 1) which contains a single barrier B. Although the short circuit around the ring prohibits in this case the application of a voltage across B by means of a battery, one deals with an equivalent induced voltage

$$V = \frac{1}{c}\frac{d\Phi}{dt} \tag{2}$$

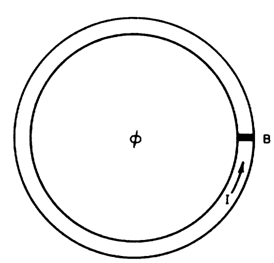

FIG. 1. Superconducting ring containing a barrier B with flux Φ through the interior and circulating current I.