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Flux nucleation in Josephson junctions formed by touching lead pieces

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Microwave-stimulated flux nucleation has been observed in an artificial superconducting loop with Josephson junctions formed by pressing lead pieces together. A regular series of microwave absorption lines similar to those seen in niobium, indium, and single crystals of Y-Ba-Cu-O is obtained. The separation of the first derivative of the absorption lines indicates a band of microwave absorption that is proportional to the square root of the microwave power and has a definite threshold power. A simple model based on that of Silver and Zimmerman is used to explain the data. A superconducting path with two weak links is assumed with flux entering the junction when microwaves drive the junction normal.

The interesting feature of the anomalous absorption of microwaves in both high- and low-temperature superconductors has received considerable attention recently.[1-17] Dulcic *et al.*[5] have shown that the absorption can be generally divided into two effects: surface absorption and absorption within Josephson junctions. The surface effects have been explained and modeled by Portis *et al.*[8] to be the results of damped fluxon motion driven by microwave currents. The pinning and depinning of the fluxons results in the hysteretic effects observed during a modulation cycle. The more fundamental problem of fluxon nucleation within a junction was recently the subject of a study by Blazey, Portis, and Holtzberg[16] (BPH) in both single crystals of $YBa_2Cu_3O_{7-\delta}$ and irregular pieces of niobium. In these experiments a band of microwave absorption is observed as the field is increased beginning with a minimum threshold power and the width of the band growing with the square root of the power. This same behavior has also been observed in indium.[17] A more recent examination of $YBa_2Cu_3O_{7-\delta}$ was done by Vichery, Beuneu, and Lejay[18] who explained their data using the earlier work of Silver and Zimmerman.[19,20]

In the present work, we have attempted to form Josephson junctions by pressing small irregular pieces of superconducting lead together. In this simple way we hoped to simulate the loops with Josephson junctions of single-crystal Y-Ba-Cu-O. We tried several sample formats but here we will report on the example of two small pieces touching each other. In a single piece, for example, no junctions were formed since lead is a type-I superconductor. Even when the sample was well oxidized, no flux nucleation spectrum appeared. In the case of the two touching samples, multiline repeated spectra similar to those observed on single crystals of $YBa_2Cu_3O_{7-\delta}$,[8] niobium,[16] and indium[17] were obtained. To explain our results we expand on the model of Silver and Zimmerman for flux nucleation in the loops containing at least two Josephson junctions.

The sample was prepared using two irregular particles of lead of purity 99.7%. The lead particles were ~200 μm in diameter. After two days, when the lead surface had oxidized, the two particles of lead were joined together to obtain a few weak Josephson junctions. In this way possible superconducting loops with a weak Josephson junction were made. An epoxy glue was used to keep the lead particles from moving relative to one another. The sample was put in a holder mounted in an Oxford Instrument flow helium cryostat at the center of the 9.3-GHz EPR resonant cavity of a Varian E 109 series spectrometer. The temperature of the sample was measured using a carbon-glass thermometer connected directly to the sample with vacuum grease.

Figure 1 shows the regular microwave absorption spec-

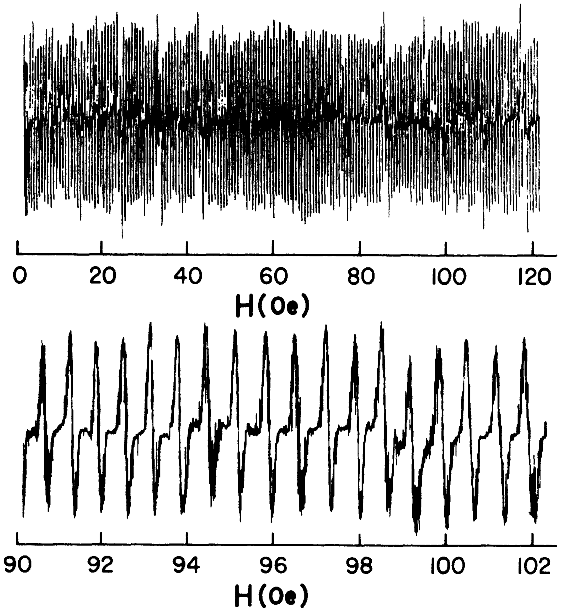

FIG. 1. Derivative of the microwave absorption in the lead sample having a weak Josephson junction at 4.2 K with 12-mW microwave power (9.3 GHz) and 100-kHz modulation of peak to peak of 1 Oe: (a) scan range 100 Oe; (b) scan range 10 Oe.

tra $[dA(H)/dH]$ at temperature 4.2 K with 12-mW microwave power and 100-kHz modulation of peak to peak of 1 Oe. These regular spectra were obtained from 0 Oe to about 600 Oe. The distance between the lines is 0.66 Oe. As the sample was rotated about the axis perpendicular to dc magnetic field, the interval $\Delta H = \Phi_0/S$, where $\Phi_0 = hc/2e$ is the quantum of flux and S is a magnetic cross-sectional area for the interception of flux, moved in field as expected because of the apparent change of the S area presented to the magnetic field. From $\Delta H = 0.66$ Oe the area of the loop is 3.1×10^{-7} cm^2. Since no microwave absorption spectrum was detected in the single piece of lead, it is clear that microwave absorption is occurring within Josephson junctions at the interface of the touching pieces.

Figure 2 shows microwave absorption lines as a function of microwave power at 4.2 K. From 2.5 mW, where the amplitude of the lines showed the largest noise, to 10 mW, the amplitude of derivative absorption increased and the width of the individual lines was practically the same. Above the 10-mW threshold, the lines split as power was increased; i.e., the magnetic field distance between peaks in the derivative absorption line increased. The magnitude of this splitting, $2\delta H$, is seen to be a linear function of the square root of the microwave power and is plotted at temperatures 4.2 and 5 K in Fig. 3. The threshold power of splitting at 5 K is 7 mW. For very high microwave power (110 mW) the spectra become irregular owing to thermal effects in the Josephson junction similar to those seen in high-T_c $YBa_2Cu_3O_{7-\delta}$.[21,22]

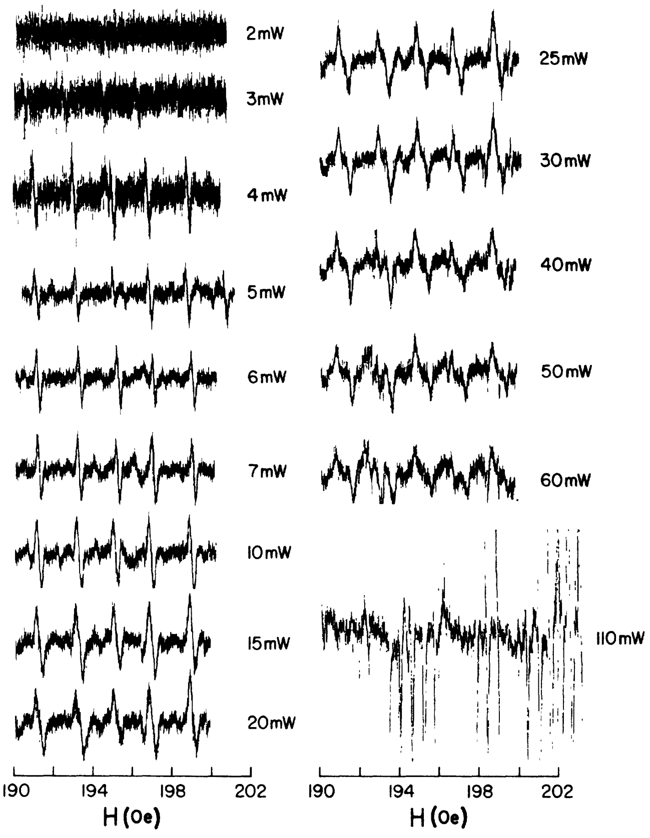

FIG. 2. Derivative of the microwave absorption in the lead sample having weak Josephson junctions in function of the microwave power at temperature 4.2 K.

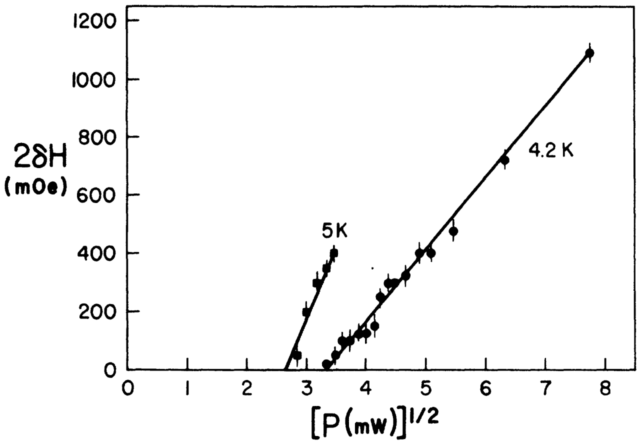

FIG. 3. Plot of the band widening $2\delta H$ above threshold of the lead sample as a function of the square root of the microwave power at temperature 4.2 and 5 K.

To explain our data we choose a model suggested by Silver and Zimmerman[19] who studied the problem of flux nucleation in a superconducting loop containing a weak link (Josephson junction). Their model includes nearly all of the experimental essentials such as slowly varying applied field and microwave field. This same model was used more recently by Vichery, Beuneu, and Lejay[18] to interpret the regularly spaced lines in Y-Ba-Cu-O. Several features of the model are salient; namely, that there is a threshold of microwave power for the appearance of absorption, the shape of the signal represents a band of microwave absorption, the separation of peaks in the spectra is proportional to the square root of the microwave power, and the energy of the fluxon behaves according to the square of the applied field. This last point was the crux of the phenomenological argument of Blazey, Portis, and Holtzberg. In that model, they used a quadratic function of field versus microwave power that was cut, or separated in energy, to explain the onset of absorption (threshold).

Silver and Zimmerman suggest that some mechanism provides a sufficient perturbation such that transitions from one energy state to another will occur when the current in the junction reaches the initial current. The transition is the formation of a fluxon in the junction. At the critical current, the junction is driven normal, the free energy is thermalized, and the ring resets itself to the lowest superconducting free-energy state. Using this idea and assuming that the superconducting loop has interference from two or more junctions, it is easy to derive the relation from a physical point of view that this separation $2\delta H$ is proportional to the square root of the microwave power.

A superconducting loop having two (or more) weak links is shown in Fig. 4(a). The interference pattern of current versus field for such a system will appear as shown in Fig. 4(b). This means that there will be current flowing in the loop until the microwave power and the applied

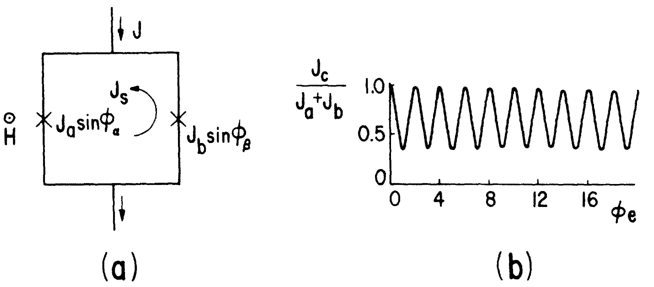

FIG. 4. Superconducting loop with two nonidentical Josephson junctions (a) and critical current versus external flux (b) for loop for negligible inductance (Ref. 20).

field reach a critical level which then drives one of the junctions normal, permitting the nucleation or entry of a fluxon from the amplified field. If the junctions are not identical, the critical current J_c in the loop exhibits a modulation by the external field H_0 according to the relation[20]

$$J_c(\phi_e) = |(J_a+J_b)\cos\pi\phi_e - j(J_a-J_b)\sin\pi\phi_e| \quad (1)$$

or

$$J_c(\phi_e) = (J_a^2+J_b^2+2J_aJ_b\cos2\pi\phi_e)^{1/2}, \quad (2)$$

where $\phi_e = \Phi_e/\Phi_0$. In this case we assume that the loop inductance can be neglected. The effective flux Φ_e within the loop is equal to the geometrical flux: $\Phi = n\Phi_0 \approx \Phi_e$. Figure 4(b) is obtained from Eq. (2) and shows the critical current versus external flux for a two-junction loop of negligible inductance. The maximum current varies between $|J_a+J_b|$ and $|J_a-J_b|$. Similar dependence of the supercurrent on the externally applied magnetic field H_e shows a double junction interferential behavior as was shown recently by Barone *et al.*[23] for $YBa_2Cu_3O_{7-\delta}$-Nb bulk junctions. When the current in the loop with superconducting weak links exceeds the junction critical value J_c, a fluctuating voltage $V(A)$ appears and can be written as[20]

$$V = R(J^2-J_c^2)^{1/2} \quad (3)$$

when $J > J_c$. By using Eq. (2) we get

$$V = R[2J_aJ_b(1-\cos2\pi\phi_e)]^{1/2} \quad (4)$$

or

$$V \approx 2\pi R(J_aJ_b\phi_e^2)^{1/2} \quad (5)$$

for small ϕ_e. Since the power absorbed by the superconducting loop can be described as $P = V^2/R$, Eq. (4) may be used to get

$$\phi_e = [2\pi(RJ_aJ_b)^{1/2}]^{-1}P^{1/2}, \quad (6)$$

so that

$$2\delta H = \phi_2 - \phi_1 = [\pi(RJ_aJ_b)^{1/2}]^{-1}P^{1/2}. \quad (7)$$

Equation (7) shows that in the region where critical current is linear in field, $2\delta H$ will be proportional to the square root of the microwave power. Figure 5 shows the dependence of the critical current versus external magnetic field ϕ_e for microwave absorption in a two-loop system. When the microwave power is small, current flow through the loop is smaller than the critical current J_c, and microwave absorption does not occur. When current reaches the critical value, the junctions, or at least the weakest junction, switches normal, the superconducting loop is interrupted, the flux goes through the loop, and microwave absorption occurs. The minimum value of the critical current corresponds to a lower value of the Gibbs free energy. The microwave absorption is caused by fluctuation of the superconducting state, and occurs near $J = J_c$.

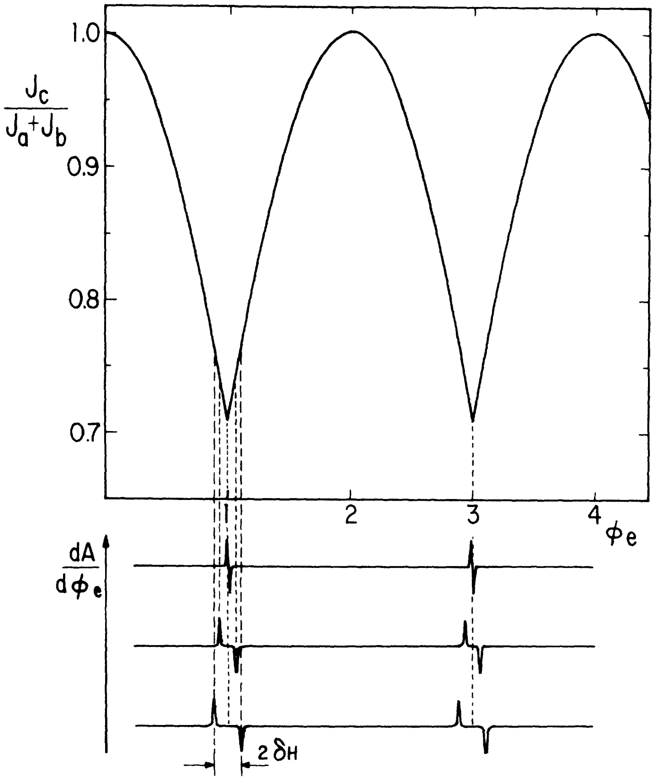

FIG. 5. Critical current and the first derivative of the microwave absorption in a superconducting loop with two weak links vs external magnetic field.

The model here differs from that of Vichery, Beuneu, and Lejay only in that it refers to a loop that specifically contains two weak links. The earlier phenomenological model of Blazey, Portis, and Holtzberg was based on the energy of a fluxon in a junction behaving as a quadratic function of the applied field which, according to Silver and Zimmerman, is correct. The two-junction model has the same behavior, namely, once the fluxon is generated in the junction, its energy will behave as a quadratic function of applied field. The threshold energy arises simply because there must be enough current generated by the microwave field to drive the weak junction normal. The model explicitly predicts the appropriate field dependence for line splitting from thermal considerations and appears valid in the linear behavior region of the critical current with field. Figure 5 shows that for larger field sweeps the critical current is not linear. However, we are unable to follow the line separation $2\delta H$ beyond about half of the Φ_0, i.e., to about half of the maximum critical current shown in Fig. 5. The linear approximation is still reasonable in this range. The explicit dependence of the critical current on applied field for lead junctions has not been measured to our knowledge. Since it is known that in Y-Ba-Cu-O single crystals the separation of the resonance lines spans and overlaps the field corresponding to Φ_0,[24] the physical model of two junctions outlined here may not be fully valid for that case.

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