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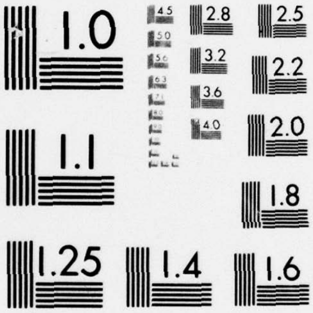

MICROCOPY RESOLUTION TEST CHART
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ABSTRACT

The final report includes ~~First~~ measurements of the time for the recovery of the critical current at a phase slip site They have been made by studying the frequency dependence of the hysteretic rf current-voltage characteristics in the low power limit. The data are explicable by a simple quasiparticle diffusion model and are incompatible with recent hot spot models.

The production and decay of non-equilibrium states in superconductors is currently of great interest. In recent studies, non-equilibrium states have been produced by tunneling[1], laser excitation[2], thermal phonon injection[3], ultrasonic phonons[4], conversion of normal to supercurrents at superconducting boundaries[5], rapid variation of the supercurrent[6], etc. In this paper we report the first determination of the temporal response of the non-equilibrium state generated by the phase slip process at a site in an ultra-thin-film superconducting microbridge in a rf SQUID configuration. The results are inconsistent with the hot spot model[7] but agree well with a modified quasiparticle diffusion model[8].

Our data were obtained using a broadband continuously variable nonresonant mutual inductance bridge (10MHz - 1.8GHz), a conventional 20MHz tuned SQUID biasing circuit, and a 9.2 GHz spectrometer employing a resonant cavity.

In order to minimize heating effects, we investigated numerous thin film cylindrical SQUIDs at 20 MHz and 9.2 GHz and selected a very low critical current, nearly granular niobium sample. This sample allowed us to study the hysteretic response over a wide temperature range with minimal heating. The physical dimensions of this niobium weak link are as follows: 3 micrometers in the direction of current flow, by 40 micrometers wide, by 35 Angstroms thick, totally covered by a 600 Angstrom insulating oxide layer. This sample has a superconducting critical temperature of 2.8 K.

No changes in the rf response were observed with the sample emersed in liquid helium just above or below the helium λ point or in a vacuum can.

Insert (a) of Fig. 1 illustrates the detected rf I-V characteristics of the sample for various frequencies at 2.167 K as observed with the broadband system. The temperature dependence of the critical current can be described in terms of a mean field behavior. This behavior is indicative of a current distribution which is relatively uniform over the width of the microbridge. Above a frequency of 120 MHz hysteresis develops in the critical currents. That is, dissipation persists in the weak link below the mean field critical current until a sudden return occurs (down arrows) to the uniform superconducting state. Note that the mean field critical current (up arrows) is independent of frequency.

This critical current hysteresis is similar to that observed by SBT[8] in the dc I-V characteristics of tin microbridges and by Rachford et al.[9] in the 9.2 GHz microwave response of weak links of various geometries and materials. This type of behavior follows[10] from the assumption that $I_{\uparrow}$ and $I_{\downarrow}$ are given by:

$$I_{\uparrow} \propto |\Psi|^2/(\xi(T)/3), \qquad (1a)$$

$$I_{\downarrow} \propto |\Psi|^2\, \pi/2\Lambda, \qquad (1b)$$

where $I_{\uparrow}$ is the mean field critical current of the microbridge, Ψ is the superconducting orderparameter, $\xi(T)$ is the coherence length, and $I_{\downarrow}$ is the minimum current necessary to support Josephson oscillations across a distance comparable to the inelastic scattering length Λ. The length Λ is given by the equation, $\Lambda = (\ell v_F \tau/3)^{1/2}$ where ℓ is the elastic length, v_F is the Fermi velocity, and τ is the appropriate inelastic scattering time. The ratio of the squares of the critical currents is proportional to temperature;

$$(I_\uparrow/I_\downarrow)^2 = [2\Lambda/(\pi\xi(0)\sqrt{3})]^2(T-T_c)/T_c. \qquad (2)$$

To explain the frequency dependence of the hysteresis [illustrated in Fig. 1, insert (a)], consider an increasing instantaneous rf current through the weak link. As the magnitude of the rf current exceeds the mean field critical current, a phase slip site is rapidly established producing non-equilibrium quasiparticles and, hence, dissipation in the sample. The quasiparticles depress the critical current so that at some point in the decreasing current part of the rf cycle (determined by Λ) the current becomes less than this new cricital value. When the magnitude of the current is less than the depressed critical current, the voltage across the site vanishes, the excess quasiparticle population is no longer sustained by the current and begins to decay. The critical current recovers towards its mean field value. On the next half cycle this time dependent critical current is exceeded, phase slip occurs, and the non-equilibrium state is regenerated. If the rf period is long compared to the decay time [see Fig. 2, insert (a)], the critical current will recover to the mean field value and no time average lowering of the critical current (no hysteresis) will be observed.

However, if the rf period is short compared to the decay time, the excess quasiparticles will not decay sufficiently between half cycles. In this case, the critical current will not have time to recover to the mean field value, and there will be a net lowering of the detected critical current as long as the non-equilibrium state is cyclically sustained. This condition will be maintained until the rf current is reduced below $I_{\downarrow}(f)$ [see Fig.2 insert (b)]. Thus the hysteresis depends on the relative values of the rf period and the decay time for the excess quasiparticle distribution.

In figure 1, the measured values of $[I_{\downarrow}/I_{\downarrow}(f)]^2$ are plotted as a function of temperature at various frequencies. Note: (1) that at each frequency the current ratio can be represented by straight lines extrapolating to a single (critical) temperature; (2) there is a temperature dependent frequency for the onset of the hysteresis; and (3) that the linear slopes approach a constant limiting value at higher frequencies. According to Eq. 2, the linear behavior implies that all the temperature dependence is contained in the coherence length and that Λ is <u>temperature independent</u> over the range studied. The variation of the slopes follows from the frequency dependence of $I_{\downarrow}(f)$ described above.

In order to account for the frequency dependence of $I_{\downarrow}(f)$, it is sufficient to make a simple extension of the quasiparticle diffusion model. Assume that the depressed critical current recovers as $\exp(+t/\tau_d)$ or, equivalently, that the quasiparticle diffusion distance Λ decays in time as $\Lambda = \Lambda_0 \exp(-t/\tau_d)$, where τ_d is a temperature independent time constant. Also assume that the phase slip center is established in a time short in comparison to the decay time. The minimum rf amplitude, $[I_{\downarrow}(f)]$, necessary to cyclically sustain the dissipative state at the phase slip site occurs when the critical current (growing in time as Λ relaxes) tangentially meets the instantaneous rf current [see Fig. 2, insert (b).] Using this condition and the above assumptions, t_2 [see Fig.2, inserts (a) and (b)] can be iteratively computed using $t_2 = t_1 - \tau_d \ln(\sin\omega t_1/\sin\omega t_2)$, where t_1 is given by $t_1 = (\tan^{-1}\omega\tau_d)/\omega$. Having found t_2, the value of $I_{\downarrow}(f)/I_{\downarrow}$ can easily be obtained, where $I_{\downarrow}$ is now taken to represent the saturated, high frequency value of the reduced critical current. Using this result and $(I_{\uparrow}/I_{\downarrow})^2$, the ratio $[I_{\uparrow}/I_{\downarrow}(f)]^2$ is obtained.

The solid curve in Fig. 2 represents a fit of this model to the experimental frequency variation of $[I_{\uparrow}/I_{\downarrow}(f)]^2$ (solid circles) as determined by the slopes of the lines shown in Fig.2. Two parameters were used in obtaining the solid curve: the ratio $[I_{\uparrow}/I_{\downarrow}]^2$ and the constant τ_d. The shape of the curve is determined from the model itself and the assumption of exponential decay of the non-equilibrium state. We find a saturated value $[I_{\uparrow}/I_{\downarrow}]^2 = 3.87$, and a temperature independent time constant $\tau_d = 5.5$ nanoseconds, and, therefore, by equation (2), $\Lambda_o/\xi_o = 9.0$.

Estimating $\xi(0)$ from the bulk ξ_o by the formula $\xi(0) = (\xi_o \ell)^{1/2}$, we find $\Lambda_o = 2590$ Angstroms, and from $\Lambda = (\ell v_F \tau/3)^{1/2}$ we find a quasiparticle inelastic scattering time $t = 8.5 \times 10^{-11}$ sec. We expect that τ sets the time scale for the establishment of the quasiparticle distribution, whereas τ_d is the time for the relaxation of the non-equilibrium state involving the interaction of quasiparticles, 2Δ phonons, and pairs[11].

From the dissipation observed in the sample at 9 GHz we can estimate the resistive length in the sample independent of the hysteresis. Previously it has been observed that the resistive length is approximately twice the quasiparticle diffusion length Λ.[9] In insert (b) of Fig. 1 we plot the quasiparticle diffusion length, Λ^R, obtained from dissipation measurements. Note that Λ^R is independent of temperature and is in excellent agreement with the value of Λ obtained from the development of hysteresis.

Recently, hysteresis in the dc I-V characteristics of weak links has been explained in terms of a simple hot spot model[7,12]. A straightforward application of this model predicts that the temperature difference ΔT between the bath and the hotspot should decay as $1 - e^{-t/\tau}$. A more detailed analysis of the heat balance equation, where there is heating only if the instantaneous temperature exceeds T_c or if the rf current exceeds the temperature dependent critical current, still results in an asymptotic relaxation of ΔT. Any asymptotic relaxation of ΔT and, hence, the local critical current to the mean field value, will require that the temperature at which hysteresis is first observed is independent of frequency. This result is inconsistent with our observations (see Fig.1.).

In the low power regime, we may expect that quasiparticles will be trapped by Andreev-like[13] scattering in the vicinity of a phase slip site due to a local reduction of the average superconducting gap in this region. The scale of the region of trapping will be set by inelastic scattering processes of the quasiparticles and will shrink to zero as the excess local excitations relax. If this is true, then Λ can be identified with the width of the quasiparticle trapping region which relaxes in a characteristic time τ_d.

In our experiments, the phase slip process is synchronized with the rf cycle; whereas, in dc I-V experiments, phase slip proceeds at the Josephson frequency. In most cases the Josephson period is fast with respect τ_d and the observed hysteresis is consistent with the usual analysis with a temperature independent Λ. However, if the critical current is small and if the voltage across the site produces Josephson oscillations with a period of the order of τ_d, then a voltage dependence of Λ will be seen. This effect simply reflects the frequency (time) dependence of Λ discussed above.

In summary, we have presented the first measurement of the broadband temporal response of a "weak link". Our results have been interpreted over the entire temperature range by a simple extension of the quasiparticle diffusion model. The data are inconsistent with simple hotspot theory or any model which predicts an asymptotic recovery of the critical current to the mean field value. From our measurements we have determined times characteristic of the dynamics of the non-equilibrium state produced by the phase slip process.

REFERENCES

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1. See S. B. Kaplan, J. R. Kirtley and D. N. Langenberg, Phys Rev. Lett. 39, 291 (1977) for references.

2. G. A. Sai-Halasz, C. C. Chi, A. Denenstein and D. N. Langenberg, Phys. Rev. Lett. 33, 215 (1974); P. Hu, R. C. Dynes, V. Narayanamurti, H. Smith and W. F. Brinkman, Phys. Rev. Lett. 38, 361 (1977); I. Schuller and K. E. Gray, Phys. Rev. Lett. 36, 429 (1976).

3. T. Wong, J. T. C. Yeh and D. N. Langenberg, IEEE Trans. Mag. 13, 743 (1977).

4. J. R. Leibowitz and M. C. Wilt, Phys. Rev. Lett. 38 1167 (1977); T. R. Tredwell and E. H. Jacobsen, Phys, Rev. B13, 2931 (1976).

5. M. L. Yu and J. E. Mercereau, Phys. Rev. B12, 4909 (1975).

6. R. A. Peters and H. Meisner, Phys. Rev. Lett. 30, 965 (1973); T. Kommers and J. Clarke, Phys. Rev. Lett. 38, 1091 (1977); J. C. Amato and W. L. McLean, Phys. Rev. Lett. 37, 930 (1976).

REFERENCES cont'd

7. W. J. Skocpol, M. R. Beasley and M. Tinkham, J. Appl. Phys. 45, 4054 (1974).

8. W. J. Skocpol, M. R. Beasley and M. Tinkham, J. of Low Temp. Phys. 16, 145 (1974).

9. F. J. Rachford, S. A. Wolf, J. K. Hirvonen and J. Kennedy and M. Nisenoff, IEEE Trans. Mag. 13, 875 (1977); F. J. Rachford, C. Y. Huang, S. A. Wolf and M. Nisenoff, Solid State Comm., 17, 1493 (1975); F. J. Rachford, PhD thesis, Case Western Reserve University, Cleveland Ohio 1975 (unpublished).

10. M. Tinkham, private communication.

11. L. N. Smith and J. Mochel, Phys. Rev. Lett. 35, 1597 (1975); J. J. Chang and D. J. Scalapino, Phys. Rev. B15, 265 (1977).

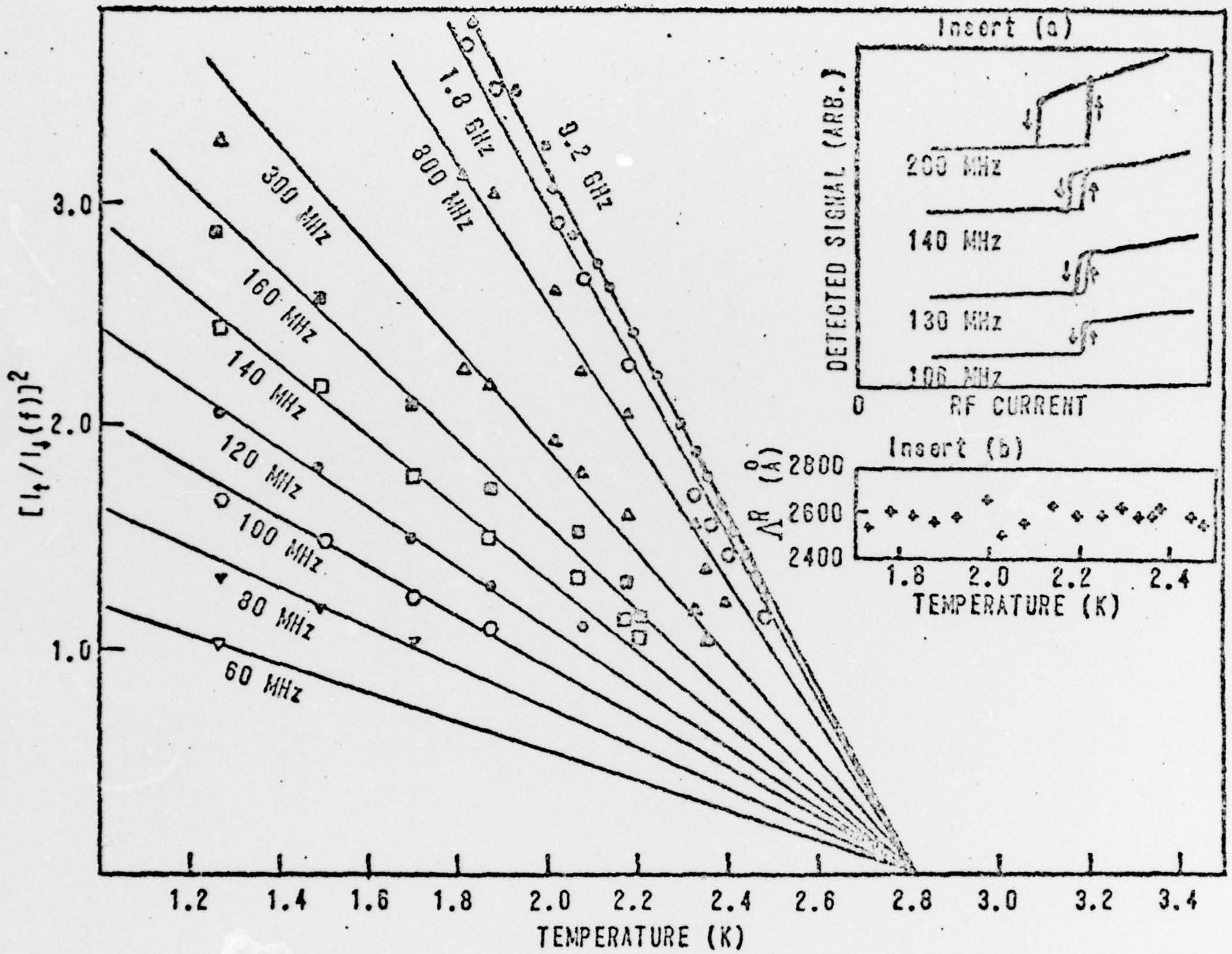
12. S. K. Decker and D. W. Palmer, J. Appl. Phys., 48, 2043 (1977); T. M. Klapwijk, M. Sepers and J. E. Mooij, J. Low Temp. Phys., 27, 801 (1977); R. P. Heubener, J. Appl. Phys. 46, 4982 (1975).

13. A. F. Andreev, ZH. Eksp. Teor. Fiz. 46, 1823 (1964) [Sov. Phys. -JETP, 19, 1228 (1964)].

FIGURE CAPTIONS

Fig. 1. $[I_{\uparrow}/I_{\downarrow}(f)]^2$ obtained from data such as shown in insert (a) is plotted as a function of temperature. Insert (a) shows the observed development of hysteresis in the detected I–V curves as frequency is increased. Insert (b) shows the temperature independence of the half-length, Λ^R, of the dissipative region as infered from the 9.2 GHz dissipation measurements.

Fig. 2. The slopes, $d[I_{\uparrow}/I_{\downarrow}(f)]^2/dT$, from the previous figure are plotted as a function of frequency (solid circles). The solid curve is calculated from the model described in the text with $\tau_d = 5.5$ nsec. and $(I_{\uparrow}/I_{\downarrow})^2 = 3.87$. In inserts (a) and (b), t_1 is the time at which the magnitude of the rf current (solid line) exceeds the time dependent critical current (dashed line) and t_2 is the time at which the rf current is less than $I_{\downarrow}$ *and* $I_{\downarrow}(f)$ is the lowest (frequency dependent) current that will cyclically sustain the dissipative state shown in (b).


[I↑/I↓(f)]²
3.0
2.0
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
TEMPERATURE (K)
9.2 GHz
1.8 GHz
800 MHz
300 MHz
160 MHz
140 MHz
120 MHz
100 MHz
80 MHz
60 MHz
Insert (a)
DETECTED SIGNAL (ARB.)
200 MHz
140 MHz
130 MHz
106 MHz
0
RF CURRENT
Insert (b)
Λ^R (Å)
2800
2600
2400
1.8
2.0
2.2
2.4
TEMPERATURE (K)