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Microwave-Enhanced Proximity Effect in Superconductor–Normal-Metal–Superconductor Microjunctions

J. M. Warlaumont,[a] J. C. Brown, T. Foxe, and R. A. Buhrman
School of Applied and Engineering Physics, Cornell University, Ithaca, New York, 14853
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Very large microwave enhancements of the critical current of small superconductor–normal-metal–superconductor junctions have been observed to temperatures as low as $0.2T_c$ of the superconductor. The experimental results indicate that this enhancement is due to a strengthening of the proximity effect at the center of the normal-metal layer by the time-varying field.

Microwave-induced enhancement of the critical current (I_c) of superconducting microbridges has been studied in great detail,[1,2] and it is widely believed that the physical mechanism underlying this enhancement is an increase in the superconducting energy gap due to a change in the quasiparticle energy distribution by the applied microwave field.[3,4] But all previous experiments have used microbridges in which all of the components are either below[1] or near[2] their superconducting transition temperature.

In this Letter we report the first observations of very large microwave-induced increases in the zero-voltage current through superconductor–normal-metal–superconductor (SNS) microjunctions, that is, microbridges in which the bridge is of a metal (copper) which is not superconducting at temperatures as low as 0.001 K. For an appropriate sample this enhancement can be seen at all accessible temperatures below the transition temperature of the superconducting electrodes (1.5 K$<T<$7.26 K), and over much of this temperature range the increase can be several orders of magnitude. We have examined this effect over nearly two decades in microwave frequency and over a decade in bridge length. Criteria for the minimum microwave frequency necessary for enhancement have been determined, as has the dependence of the degree of enhancement on the bridge length. Our experimental results strongly indicate that the critical-current enhancement is due to a strengthening of the superconducting proximity effect at the center of the normal-metal bridge by the time-varying electric field.

The SNS junctions were prepared in the variable-thickness microbridge geometry using electron and photon lithography; the fabrication details have been presented elsewhere.[5] The bank electrodes were of lead, the bridges of copper. The bridge thickness D ranged from 60 to 150 nm, the width W from 0.2 to 1.0 μm, the length L from 0.2 to 2.0 μm; low-temperature bridge resistances ranged from 0.1 to 1 Ω.

In the absence of applied microwaves I_c was found to have the quasiexponential temperature dependence expected of SNS tunnel junctions. The zero-voltage tunnel current first became observable at a temperature somewhere below T_c of the lead electrodes (7.26 K); this onset temperature was progressively lower the longer the junction. For T well below T_c the temperature dependence of I_c was found to be well described, both in functional form and in amplitude, by calculations based on the microscopic equations of Usadel.[6] This is illustrated in Figs. 1 and 2, where the temperature dependence of I_cR for two different samples is compared with theoretical predictions obtained in a manner similar to that employed by

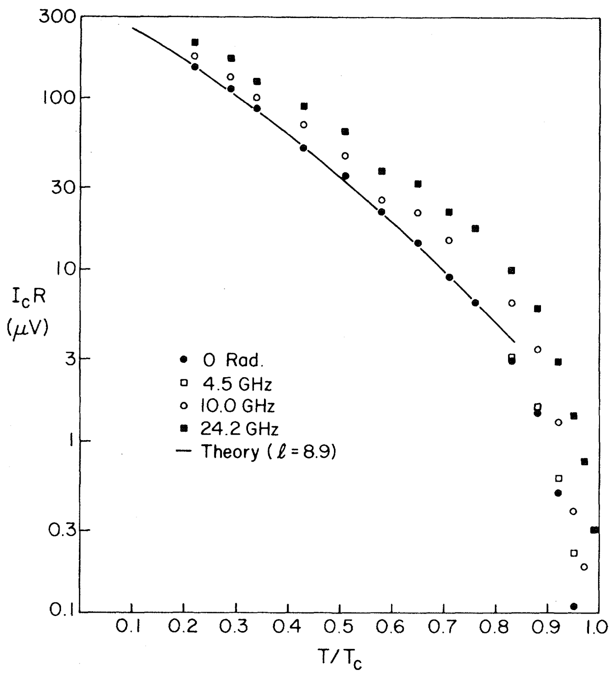

FIG. 1. The temperature dependence of I_cR of a Pb-Cu-Pb microjunction. In each instance the data were taken at the constant source level which maximized I_cR at low T. The solid line is the calculated value of I_cR for a junction with reduced length $l = 8.9$. The theory values have been reduced by a factor of 0.7 to obtain best agreement with experiment. The dimensions of the junction are thickness $T \approx 60$ nm, width $W \approx 0.2$ μm, and length $L \approx 0.2$ μm. For this junction $R = 0.35$ Ω and $(2\pi\tau^*)^{-1} \approx 5$ GHz.

Likharev.[7] The details of this comparison of theory to data have been presented elsewhere[5]; the result which is relevant here is that this fitting procedure provides a means of characterizing each junction with a temperature-independent reduced length l which is the physical length L of the bridge in units of the normal-metal coherence length at the transition temperature of the electrodes, $l = L/\xi(T_c) = L/(\hbar v_F \Lambda / 6\pi k T_c)^{1/2}$ (v_F is the Fermi velocity of the normal metal; Λ is the electron mean free path in the bridge.) For the junctions studied l has been found to range from 8.2 to greater than 30. This method of determining l is much preferable to estimating the effective junction length from normal-metal parameters and geometrical measurements.

Whenever a dc supercurrent was observable and microwave radiation applied, the bridges were found to exhibit ac Josephson steps, sometimes to quite high voltage levels, $V > 2$ mV. The amplitudes of the constant-voltage steps were periodically modulated by the microwave power in a manner at least reminiscent of that predicted for an ideal, resistively shunted Josephson junction.[8] But whenever the microwave frequency (ω_{rf}) was high enough the maximum value of I_c was found to occur not at zero power but somewhere during the first, second, or subsequent modulation period. In general, the larger the l, the higher the modulation period where the maximum in I_c was found. The periodicity (with microwave power) of the critical-current modulation was fairly independent of temperature.

Figures 1–3 show I_cR vs T data for three different junctions as measured in the presence of microwave radiation of various frequencies. Data are shown only for the temperature region over which I_c was enhanced for a given ω_{rf}. These data were obtained by determining the power level at a given ω_{rf} which maximized the zero-voltage critical current at low temperatures and then maintaining that power level while varying T. (As a function of T, the maximum I_c was usually found to occur at nearly the same microwave power level, so long as T was not too close to T_c.)

It was found that the largest absolute increases in I_cR occurred in the shortest junctions, but the percentage enhancements increased very strongly with l. The most spectacular results were obtained with the sample shown in Fig. 3. This junction was estimated to have a reduced length $l = 30$, and in the absence of microwaves it had no measurable supercurrent for $T > 0.2T_c$.

Two empirical criteria have been established for the minimum frequency necessary to observe an enhanced I_c; it was necessary to satisfy only one of the criteria to observe an enhancement. The first criterion was that ω_{rf} be greater than the Josephson frequency $\omega_J = 2\pi R I_0/\varphi_0$, where I_0 was the critical current in the absence of applied microwaves. For a given microwave frequency this determined a temperature above which an enhancement could be seen, provided that the enhanced I_c was large enough to be observable above the noise.

If $\omega_{rf} < \omega_J$ an enhancement was still observed if the second criterion was satisfied, which was that $\omega_{rf} > A/\tau^*$, where τ^* is the effective time-dependent Ginzburg-Landau relaxation time for a normal metal[9-11] $\tau^* = \tau_{GL} L^2/\xi(T)^2 = (h/16kT_c) l^2$. (We found A to be about 2.) It is important to note that τ^* is independent of temperature; thus when ω_{rf} was significantly greater than A/τ^*, I_c enhancement would occur at all temperatures regardless of whether or not $\omega_{rf} > \omega_J$.

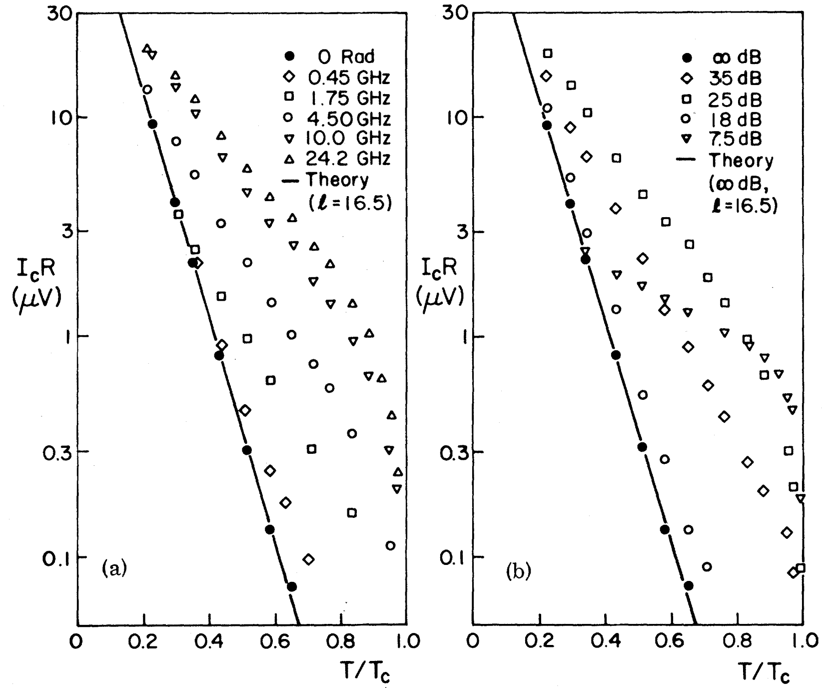

FIG. 2. (a) I_cR of a larger junction for constant power levels of various microwave frequencies. $T \approx 0.15$ μm, $W \approx 1$ μm, and $L \approx 1$ μm. The solid line is the theoretical prediction, reduced by a factor of 0.7, for $l = 16.5$. Here $R = 0.075$ Ω and $(2\pi\tau^*)^{-1} \approx 1.5$ GHz. (b) I_cR of the same junction measured at different levels of 10-GHz radiation. 18 dB is the power level that produces the first maximum in I_cR; 7.5 dB produces the second maximum.

Figure 2(b) illustrates the effect that different power levels of a constant microwave frequency had on the critical current. It can be seen that effect of the microwave field can be interpreted as changing the temperature dependence of I_cR. As the power is increased, the I_cR vs T curves take on shapes appropriate for smaller values of l. This shape-changing effect can also be seen in Figs. 1 and 3. The longer the l, or the higher the frequency, the more pronounced is the change. However, while the microwave radiation radically changes the shape of the I_cR vs T curves, the low-temperature values of I_cR remains at low levels. At no time did we observe an enhanced I_cR larger than the $T = 0$ value predicted for a given junction by the Usadel equations.

The proximity effect[12-14] near superconductor–normal-metal interfaces is as yet incompletely understood and additional theoretical efforts will be necessary to fully account for the results reported here. However, an eventual explanation in terms of an increase by the microwave radiation of the energy gap $\Delta_{\rm Pb}$ in the Pb electrodes is very unlikely.[3,4] Even near T_c, I_c varies only as $\Delta_{\rm Pb}^2$ and it depends even less strongly on $\Delta_{\rm Pb}$ as $T \to 0$.[12,15] Orders of magnitude increase in $\Delta_{\rm Pb}$ at temperatures far below T_c would be necessary to explain the data. Therefore the enhancement effect must be in the normal-metal bridge.

The basis of one possible explanation of the enhancement effect may be found in the work of Lindelof[16] and Aslamazov and Larkin[17] which deals with enhanced I_c in superconducting weak links resulting from microwave-induced changes in the occupation of states. This work may apply to our samples as follows: In a normal-metal junction the proximity of the superconducting banks alters the density of states. This alteration gives rise to a correlation between electrons in the normal metal; i.e., there is a nonzero pair density (order parameter). The amplitude of this correlation varies spatially, decreasing to a minimum value at the center of the bridge which determines the critical current I_c.[6,7,9] The effect of the applied microwave field is to modify the kinematics of the normal electrons; this changes the occupation of states in the normal metal, thereby changing the spatial dependence of the electron correlations. This can occur since the inelastic scattering time for Cu is much longer than any other time in the experiment, those normal electrons with energy less

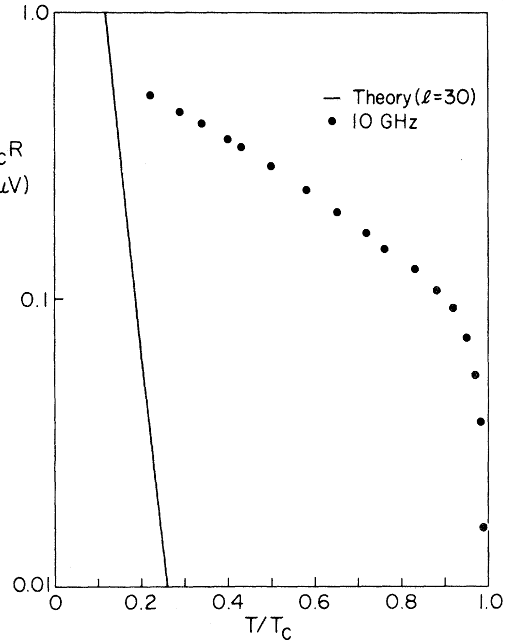

FIG. 3. $I_c R$ of the longest junction studied measured at a constant level of 10-GHz radiation. $T \approx 0.15$ μm, $W \approx 1$ μm, and $L \approx 2$ μm. No critical current could be observed in the absence of microwaves. The solid line is the calculation for the case $l = 30$ which is the estimated value for this junction. Here $R = 0.13$ Ω and $(2\pi\tau^*)^{-1} \approx 0.45$ GHz.

than Δ_{Pb} are trapped in the junction. The time-varying field then can act to average the electron distribution over the length of the junction,[16,17] thus increasing the pair density at the center of the junction and hence increasing I_c. The fact that for junctions with $l \gg 1$ only a small spatial change in the normal electron distribution would give a large increase in I_c supports the proposal. Further support is found in that increases in I_c occur only when ω_J or $1/\tau^*$ which are the conditions necessary for the microwave field to couple most strongly to the unpaired normal electrons.

We are continuing our investigation of this SNS critical-current enhancement to further test the proposed explanation. Experimental details and additional data will be presented elsewhere.

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[a] Current address: IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598.

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