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A STUDY OF APPLIED MICROWAVES AND QUASIPARTICLE INJECTION ON THE DYNAMICALLY ENHANCED SUPERCURRENT OF A MICROBRIDGE

H.J.T.Smith and M.Dion
Guelph-Waterloo Program for Graduate Work in Physics
University of Waterloo, Waterloo, Ont, Canada, N2L 3G1
R.Escudero
Instituto de Investigaciones en Materiales
Universidad Nacional Autonoma de Mexico, Mexico, D.F., Mexico

ABSTRACT

We have measured the influence of external excitations on the dynamically enhanced critical current of a superconducting microbridge. In one experiment microwaves were applied to a microbridge and the dynamically enhanced critical current was monitored. In a second experiment, two superconducting microbridges were fabricated closer together than a coherence length. The dynamically enhanced critical current of one microbridge was measured as a function of the current through the second microbridge. In each experiment the dynamically enhanced critical current was found to be changed. A qualitative explanation of this effect is discussed.

INTRODUCTION

In this paper we present data and discussion of the non-equilibrium behaviour of superconducting microbridges. Microbridges exhibit a great many phenomena which have been studied extensively. Pair coupling exists across these contacts in a similar way to that across a Josephson junction but with the exception that a large quasiparticle current exists through the contact. The resistively shunted junction (RSJ) model has been used to explain many of the properties of these microbridges. When the slope of the I-V curve in the range $0<V<10$ μV was found to be larger than predicted by the RSJ model it was suggested that non-equilibrium states of the pairs and quasiparticles were occuring within the microbridge. This region of the I-V characteristic is termed the dynamically enhanced critical current by some authors and termed the `foot' by others. Theoretical models of Aslamazov and Larkin[1] and Golub[2], which use Ginzburg-Landau theory, were introduced to analyse these non-equilibrium properties. The dynamically enhanced critical current is readily observed in the current-voltage characteristic of a microbridge and it has been attributed to the presence of self induced non-equilibrium quasiparticles. A qualitative description of this effect was given by Tinkham[3] and a theoretical discussion has been given by Schmid et al[4].

In the present work the I-V characteristic of a single microbridge, in the region of the dynamical enhanced critical current, was measured as a function of the applied microwave power. The microwave frequency was 23.12 GHz. In a second experiment two closely coupled microbridges were fabricated with the separation between the microbridges being less than a coherence length. The I-V characteristic of one microbridge in the region of the dynamically enhanced critical current was measured as a function of the bias current through the second microbridge.

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MICROWAVE EXPERIMENT

In the first experiment a tin microbridge was fabricated by a previously described technique[5] that enabled the length of the microbridge to be accurately known and readily duplicated. The length of the microbridge was 0.2 micron, the the thickness of the banks was 0.3 micron and the diameter was approximately 1 micron. These variable thickness microbridges have the advantage that they are able to sustain higher levels of dissipation than planar microbridges. The microbridge was mounted at the lower end of a glass dewar. A K band waveguide was terminated with a horn 40 cm from the microbridge. The microwave power at the microbridge was less than the microwave power which was measured in the waveguide due to the mismatch between the waveguide and the microbridge. However, there is a linear relation between the microwave power in the wave guide and microwave power at the microbridge. Fig.1. is a series of current-voltage characteristics at 3.635 K for various applied microwave powers from 0 to 50 mW in the waveguide. At zero microwave power the critical current is 1.8 mA and as the microwave power is increased to 50 mW the critical current is enhanced to 2.2 mA. Further increasing the microwave power did not further enhance the critical current. The region of the dynamically enhanced critical current between 0 and 10 μV is visible at zero and low microwave power but it disappears as the critical current is enhanced to its maximum value by the applied microwaves. The enhancement of the critical current by microwaves has been discussed[6].

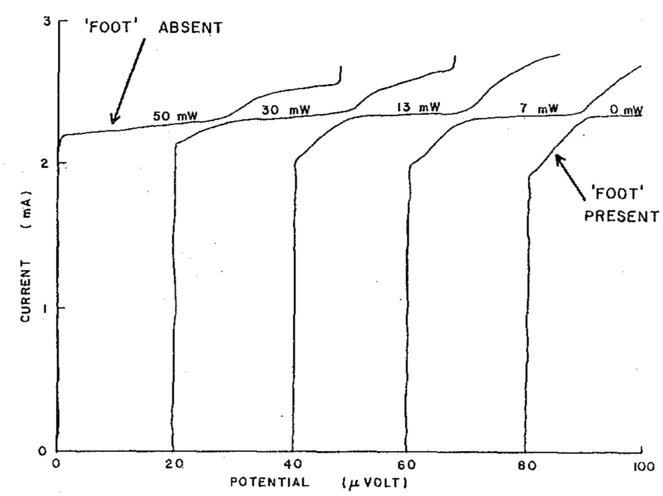

Fig.1. The current-voltage characteristic of a tin microbridge at T=3.635 K for various applied microwave powers. The curves have been displaced horizontally from each other by 20 μV for clarity. Note that at microwave power of 50 mW. the dynamically enhanced critical current has disappeared.

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Tinkham[3] has presented a simplified qualitative picture of the dynamically enhanced critical current which does much to reveal the underlying physics. We shall first follow the qualitative arguments of Tinkham and then modify them to take into account the effect on the dynamically enhanced critical current of an external excitation which could be either microwaves or injected non equilibrium quasiparticles. With a potential across a microbridge the gap oscillates at the Josephson frequency and the quasiparticle energy will also attempt to oscillate at the same frequency. However, the quasiparticles must lose or gain energy to the lattice or another quasiparticle in order to remain in thermal equilibrium during this cyclic process. There are two main mechanisms for this energy exchange, i) inelastic electron phonon scattering and ii) diffusion. The inelastic scattering process takes place in a finite time which is categorised by the time constant, τ_e. On the other hand diffusion can occur when there is a vacant energy level at some distance away from the present position of a quasiparticle to which it may diffuse. Diffusion can occur between states in the banks and states in the microbridge whose energies are greater than the energy gap in the banks, Δ_b, because there are always available states in this energy range in the banks. However, as the gap, $\Delta(t)$, (t is time) in the microbridge decreases below, Δ_b, diffusion between states in the energies range $\Delta_b-\Delta(t)$ from within the microbridge to the banks cannot take place as there are no available states in the banks in this energy range. Thus the occupation number of the states below $\Delta(t)$ within the microbridge will remain at whatever value the states had as they decreased below Δ_b. The occupation numbers of the states below, Δ_b, and within the microbridge are not at their thermal equilibrium values. This non-equilibrium situation has been interpreted as a temperature change[3] which in this case is cooling, and it takes place at the Josephson frequencies. In turn this cooling gives rise to an enhanced critical current. The measured microbridge current is the sum of the pair and the quasiparticle currents. Hence, when the critical current is enhanced at potentials greater than $h/2e\tau_e$ the measured current is enhanced.

When a bulk superconducting region is irradiated with microwaves, absorption by the quasiparticles can occur and their energy is raised to a higher state. Subsequently, this state will decay by inelastic electron phonon scattering to a lower energy state. Thus a continuous absorption of microwave energy can take place in a bulk superconductor.

When a microbridge has a potential greater than $h/2e\tau_e$ there are many non-equilbrium quasiparticle states. Irradiation by microwaves will attempt to increase the level of non-equilibrium quasiparticles but appears to have a limited effect. Thus at potentials that are greater than $h/2e\tau_e$ the I-V characteristic of a microbridge is not significantly changed by the applied microwaves. When the Josephson frequency is a harmonic of the microwave frequency, the usual step structure will be present in the I-V characteristic. However, the potential at which these steps occur is usually greater than the region of the dynamically enhanced critical current and consequently the steps do not interfere with this experiment. In Fig. 1. the first step at 47 μV is just visible in the I-V curves.

We must now turn our attention to the case of a microbridge whose potential is less than $h/2e\tau_e$. First consider the case V=0 where the critical current is enhanced by the presence of microwaves. This enhancement is most prominent near the critical temperature. Eliashberg[6] has developed a theory that explains this enhancement. When a quasiparticle close to the gap edge is raised to a higher energy state by an applied microwave energy source, $h\nu$, with $h\nu<2\Delta$ so that pair breaking does not occur directly, then the population of quasiparticles at low energy will decrease. For this reason the energy gap will increase which causes the critical current and the critical temperature to increase. The total number of quasiparticles remains constant.

The region of the I-V characteristic that lies between $0<V<h/2e\tau_e$ is intermediate to the case at V=0 where enhancement by microwaves occurs and $V>h/2e\tau_e$ where the microwaves have no effect on the I-V characteristic.

We should once again turn to the qualitative model of Tinkham and initially look at the situation in the absence of microwaves. Inelastic scattering now has sufficient time to take place but not long enough for complete equilibrium to be reached. The result is an enhanced I_c on the forward half of the Josephson current and a reduced I_c on the reverse half cycle. The net effect is an algebraic increase in the forward current in both half cycles, the increase being proportional to the voltage.

When microwaves are applied further, enhancement of the critical current occurs. However, the degree of enhancement will decrease as the voltage and hence the Josephson frequency is increased because the rate of inelastic scattering will decrease and thus the ability to absorb microwaves is also decreased. The overall effect of the microwaves on the dynamically enhanced critical current can be summarised; for $0<V<h/2e\tau_e$ the current is enhanced by the microwaves and for $V>h/2e\tau_e$ the microwaves have negligible influence. In fig.1., as the microwave power is increased, the dynamically enhanced critical current increases at the same time as the critical current until at a waveguide power of 50 mW. the dynamically enhanced critical current is no longer visible. Little change of the I-V characteristic occurs above 10μV. A reasonable[3] value for τ_e in tin is 2.8×10^{-10} sec which gives $h/2e\tau_e$ = 8 μV.

COUPLED MICROBRIDGES

In our second experiment, two tin microbridges were fabricated in close proximity by a technique[7] that is similar to that used for making our single microbridges (Fig.2.). The length of the microbridges and the thickness of the outside banks were 0.3 micron. The separation of the microbridges was 0.2 micron and the diameter of the microbridges was approximately 1 micron. The I-V characteristic of microbridge 1 was monitored whilst the current through microbridge 2 was held constant. Fig.3. is a series of current-voltage characteristics of microbridge 1 at T/T_c=0.978 for various constant values of the current, I_2, through microbridge 2. In the range -1.2mA.$<I_2<1.2$ mA. the dynamically enhanced critical current is visible. But for $I_2 >1.2$ mA. and the larger value of the critical current the dynamically enhanced critical current is absent. For $I_2 >1.2$ mA. and the lower value of the critical current the dynamically enhanced critical current is present. For $I_2<-1.2$ mA. and the lower value of the critical current the dynamically enhanced critical current is absent and for the upper value of the critical current the dynamically enhanced critical is observable. A potential was present across microbridge 2 for -1.2 mA. $>I_2>$ 1.2 mA.

The data (fig.3.) shows that the dynamically enhanced critical current is unchanged when there is not a potential across microbridge 2. Whenever a potential exists across microbridge 2 the dynamically enhanced critical current of microbridge 1 is modified

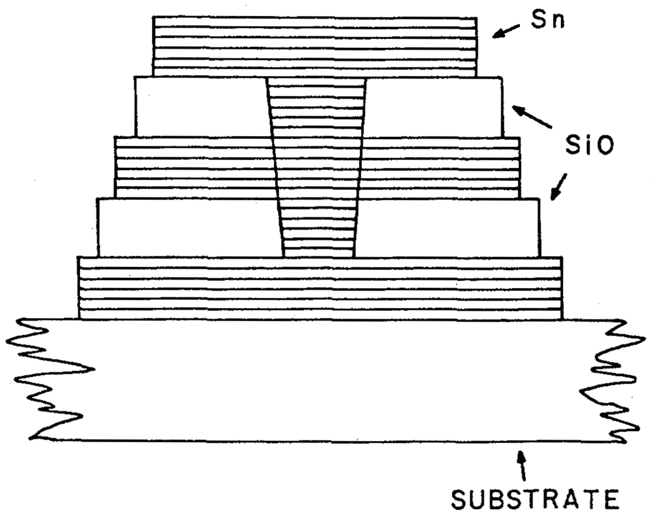

Fig.2. A transverse schematic view of the coupled microbridges.

and may no longer be visible if the potential of microbridge is sufficiently large. This suggests that non-equilibrium quasiparticles from microbridge 2 are diffusing to microbridge 1 and lower energy quasiparticles are diffusing to microbridge 1 which results in a net increase in the excitation level of the quasiparticles of microbridge 1. This injection of non-equilibrium quasiparticles modifies the dynamically enhanced critical current in a similar way to the excitation of the quasiparticle spectrum by the application of microwaves to a single microbridge.

A quite separate phenomena is also present in the data of Fig.3. The critical current of microbridge 1, irregardless of the current direction, is depressed as I_2 increases, even when the potential across microbridge 2 is zero. This effect is associated with the energy of the superconducting region between the two microbridges and it is discussed in ref. 9.

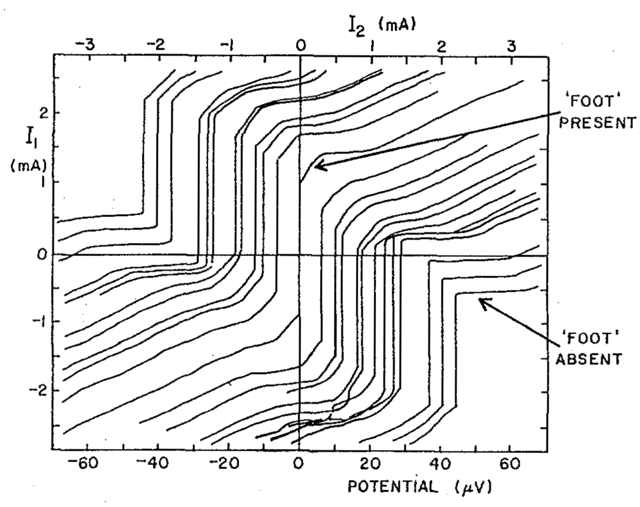

Fig.3. The current-voltage characteristic of microbridge 1 at T/T_c=0.978 of a pair of coupled microbridges. The curves are shifted horizontally by the value of I_2.

SUMMARY

Two separate experiments have been described which show how the dynamically enhanced critical current is modified by the application of either microwaves or injected quasiparticles. We have argued qualitatively that the non-equilibrium distribution of quasiparticles of the microbridge is changed by either the applied microwaves or the quasiparticles and this modification causes changes in the dynamically enhanced critical current.

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