Planar SNS microbridges have been fabricated in the variable thickness geometry with all dimensions as small as 200 nm. The behavior of these microbridges, including I-V characteristics and response to microwave radiation, is described.

Thin film planar superconducting microbridges have been the subject of much theoretical and experimental investigation for the last several years, but the physical mechanisms underlying their behavior are still poorly understood. In an effort to contribute to the understanding of these structures, as well as to produce useful elements for superconducting devices, we have produced very small microbridges in which the bridge is made from a normal metal. These structures have the inherent property that the weakening of the order parameter is confined almost exclusively to the bridge region; this feature is advantageous for theoretical calculations and for the production of high quality devices. In this paper we briefly discuss the behavior of these SNS microbridges.

These microbridges have been made in a variable thickness geometry, with copper as the bridge material and both lead and niobium have been used as bank materials. The very small geometry of these microbridges was obtained with electron-beam lithography. Pb-Cu-Pb structures were made using the lift-off method; first the copper bridge was laid down, and then the resist pattern for the banks was stenciled over the top. A neutralized argon ion beam was used to clean the copper immediately before the lead was deposited. The bridge films for these structures were 60 nm thick, and the banks had thicknesses of 150 nm or more; bridge widths ranged from 1000 nm down to 200 nm, and the bridge lengths were from 2000 nm to 200 nm. Nb-Cu-Nb microbridges were fabricated in a slightly different fashion; in this case the niobium was sputtered directly onto the copper bridge line, and the gap between the banks was formed by sputter etching. The lateral dimensions of the Nb-Cu-Nb structures were similar to those of the Pb-Cu-Pb structures, but the banks were 60 nm thick and the bridges were 20 nm thick. The resistance of these microbridges ranged between 0.3 ohms and 1.0 ohm.

As judged by the maximum achieved I_R product and by the microwave response, the Pb-Cu-Pb microbridges had a much better performance than the Nb-Cu-Nb microbridges. This is probably because the electron mean free path was much shorter in the Nb-Cu-Nb structures, resulting in a longer effective bridge (in terms of the coherence length) and hence in a reduced value for I_R.

Figure 1 shows the critical current-resistance (I_R) product versus reduced temperature for one of the shorter microbridges (T_c = 7.26 K) for all of the Pb-Cu-Pb microbridges. The current is plotted on a logarithmic scale, and while I_R is somewhat exponential in T, the data cannot be fit to a straight line at low temperatures; the shape and amplitude of this curve and those of other samples are consistent with microscopic calculations for SNS junctions.

Figure 2 shows current-voltage (I-V) characteristics at temperatures above about 0.5 T_c, for the same sample as in Fig. 1. These curves leave the zero-voltage axis with an upward curvature and have an inflection point at about 20 microvolts (V_{inflation}). At about 40 microvolts (V_{lower}) the curves become straight lines; this straight line portion continues up to a voltage of about 200 microvolts (V_{upper}). We have used the slope of this straight line as the resistance R of this microbridge. Note that except at temperatures close to the critical temperature all of the curves lie on top of each other for voltages above V_{lower}. This feature of these I-V curves persists down to the lowest temperature achieved (about 0.1 K). Figure 3 shows the temperature dependence of the voltages V_{inflation} and V_{lower}; the important thing to notice is that within the scatter in the data both of these voltages are independent of temperature. Figure 4 shows the temperature dependence of the currents at which the inflection point and the onset of the flat region occur. In contrast to the voltage at the inflection point, the current at the inflection

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**ABSTRACT**

Planar SNS microbridges have been fabricated in the variable thickness geometry with all dimensions as small as 200 nm. The behavior of these microbridges, including I-V characteristics and response to microwave radiation, is described.
Fig. 2. I-V characteristics of a Pb-Cu-Pb microbridge taken at eight different temperatures. In descending order the temperatures are: 6.63, 6.34, 5.96, 5.44, 4.76, 4.34, 4.04, and 3.69 K.

Fig. 3. Temperature dependence of the characterizing voltages $V_{\text{inflection}} (\triangle)$ and $V_{\text{lower}} (\circ)$.

Fig. 4. Temperature dependence of the microbridge currents, $R_{\text{inflection}} (\triangle)$ and $R_{\text{lower}} (\circ)$, at which the I-V characteristic exhibits an inflection point and the onset of a constant resistance, respectively. $R = 0.3 \Omega$.

Fig. 5. Low temperature I-V characteristic of a typical Pb-Cu-Pb microbridge.

Point seems to be decreasing nearly linearly with temperature; to a lesser extent the same is true for the current at the onset of the straight line portion of the I-V curve.

For temperatures below about 0.5 $T/T_c$, the I-V curves become hysteretic; the I-V for one such
The temperature is shown in Fig. 5. We have characterized this hysteresis by a voltage \( V_{\text{return}} \) and a current \( I_{\text{return}} \) at which the I-V returns to the zero-voltage axis. A significant feature of these parameters is that below about 0.8 \( T_c \), both the return current \( I_{\text{return}} \) and the return voltage \( V_{\text{return}} \) are independent of temperature. This behavior is typical of all of the SNS microbridges which we have investigated. The only distinction between samples is that the values of the characteristic voltages \( V_{\text{peak}} \), \( V_{\text{lower}} \), \( V_{\text{upper}} \), etc., decrease in a regular manner with increasing bridge length.

As we have mentioned above, the I-V curves all have a region of constant slope between about 40 microvolts and 200 microvolts. In Fig. 6 we have plotted the temperature dependence of this slope; it is temperature independent except for close to \( T_c \), where it rises very sharply with increasing temperature. This behavior is consistent with the mechanism originally proposed by Pippard et al. and developed in detail by others for the resistance of superconducting-normal metal interfaces.

![Fig. 6. Temperature dependence of the resistance R of a microbridge as measured in the constant resistance region between \( V_{\text{lower}} \) and \( V_{\text{upper}} \).

At voltages above \( V_{\text{upper}} \), about 200 microvolts for Fig. 1 - 6, the I-V curve is no longer flat; i.e., the dynamic resistance \( \frac{dV}{dI} \) of the microbridge is no longer constant as a function of voltage. A plot of \( \frac{dV}{dI} \) versus \( V \), taken at \( T = 5.44 \) K, for this sample is given in Fig. 7. The dynamic resistance is found to rise more or less linearly with voltage up to a voltage \( V_{\text{peak}} \) where it then decreases by about 15 percent and then becomes essentially constant. The value of \( \frac{dV}{dI} \) at this point is significantly less than the resistance of the microbridge for \( T > T_c \) and is also found to be essentially temperature independent. At still higher voltage levels (not shown) \( \frac{dV}{dI} \) begins to increase again, but this time much more slowly with voltage. This latter increase appears to be a consequence of ohmic heating in the bridge region. The temperature dependence of \( V_{\text{peak}} \) is found to be close to the temperature dependence of the energy gap and \( V_{\text{peak}} \) has a maximum value of about 3.2 millivolts at low temperature.

We have also observed the behavior of these microbridges under the application of a microwave field.

![Fig. 7. Voltage dependence of the dynamic resistance \( \frac{dV}{dI} \) of a Pb-Cu-Pb microbridge taken at \( T = 5.44 \) K. The constant resistance region seen at low voltages is clearly seen. The maximum resistance occurs at \( V_{\text{peak}} \) = 2.4 millivolts.

In all cases ac Josephson effects are found at all temperatures below \( T_c \) for which a measurable supercurrent exists. For the smaller microbridges Josephson steps have been obtained at voltages in excess of 2 mV under 10 GHz microwave radiation. However, we also find that if the frequency of the applied is higher than the Josephson frequency corresponding to \( V_{\text{peak}} \), there is an enhancement of the critical current [Bakem effect] and there are constant voltage steps in the I-V at submultiples of the Josephson voltage. If the microwaves have a frequency lower than the Josephson frequency corresponding to \( V_{\text{peak}} \), there is no enhancement of the critical current and there are no subharmonic steps.

This phenomena indicates the existence of a relaxation time effect with a limiting response time of about \( \frac{\hbar}{2eV_{\text{lower}}} \). This conclusion is compatible with the observation of steps at voltages much greater than \( V_{\text{lower}} \) since all that is required for a microbridge to exhibit steps at any multiple of the voltage corresponding to an applied frequency \( f \) is that the relaxation time of the microbridge be shorter than \( \frac{1}{2\pi f} \). Computer simulations of the shunted junction model readily show that without relaxation time restrictions a weak link biased on a high order constant voltage step has a supercurrent which oscillates part of the time at frequencies well above the applied microwave frequency and part of the time oscillating at frequencies at or below the applied microwave frequency. If a relaxation time equal to the applied microwave period is imposed, the high frequency oscillations are damped out but the low frequency oscillations can remain, and the constant voltage step can still be present, only partially attenuated. Now if the applied microwave period is reduced so that the step voltage of interest is now the first order step (a period much shorter than the relaxation time), there is no observed step. In
other words, the fact that we see steps at 2 mV with 10 GHz microwaves in no way implies that the bridge will mix at 1000 GHz.

Although we have presented data for only one microbridge, as mentioned above the experimental results for all of our bridges have the same features as those discussed. We are currently pursuing physical interpretations of these phenomena.

REFERENCES