# PROPERTIES OF HIGH-RESISTANCE SUPERCONDUCTING MICROBRIDGES BASED ON LEAD ALLOY FILMS*

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ABSTRACT

We have fabricated high-resistance, type-II microbridges with submicron dimensions and well-characterized lead alloy films, and studied their Josephson-effect properties. Bridge resistances of 2-18 Ω have been achieved in uniform-thickness structures which are 2000-20,000 Å wide. Critical currents of narrow bridges near $T_c$ are found to agree with theory for uniform depairing. The microwave response of the bridges agrees with theory at low power levels, but self-heating limits microwave steps to voltages < 375 μV. Specific predictions for heating limits of alloy microbridges in the variable thickness geometry are presented.

## I. INTRODUCTION

To achieve the best performance in Josephson-effect high-frequency detectors and SQUID magnetometers non-hysteretic Josephson elements with resistances ≥ 10 Ω are needed[1] to give efficient, broadband coupling and low noise. We have made such devices using high-resistivity lead alloy films in uniform-thickness microbridges. We have studied the V-I curves of these bridges as a function of applied microwave power, and at various temperatures. In this paper, critical current data are compared to theoretical predictions based on flux flow and uniform depairing mechanisms, and the microwave response is evaluated in terms of the resistively-shunted-junction (RSJ) model. Finally, the limitations due to heating are evaluated theoretically for future high-resistance bridges in the variable-thickness configuration (banks thicker than bridge).

## II. EXPERIMENTAL TECHNIQUES

The short mean free path ($\ell$=30-120 Å) in the Pb alloys implies a small effective coherence length ($\xi(0)$=125-250 Å), which in turn requires sub-micron bridge dimensions (L,w<<5000 Å). This small size has been achieved by projection photolithography and lift-off techniques, using through-the-substrate exposure to obtain the extremely sharp photoresist edge profiles necessary for good liftoff.

The fabrication procedure, described in detail elsewhere,[2] comprises three steps:
(1) Photolithography--A layer of photoresist is applied to a substrate, then exposed and removed in areas which are to be metallized in the final device.
(2) Film Deposition--A uniform superconducting film is deposited by vacuum evaporation, overlying both bare areas and photoresist-covered areas of the substrate.
(3) Liftoff--The photoresist is dissolved away, removing the metal which overlies it, while the metal in direct contact with the substrate remains.

For successful liftoff, it is important that the photoresist edges be square or undercut. We obtain such profiles by projecting the mask image through the substrate. Optical absorption within the photoresist reduces the intensity as the light passes through, so that the fully exposed region is widest at the substrate-photoresist interface. This gives the desired undercut profiles. The functional result of through-the-substrate exposure is a liftoff yield of > 90% on devices which are 3000 Å wide. The scanning electron micrograph, Fig. 1, shows a typical bridge which is 2000 Å wide and has a resistance of 5.5 Ω.

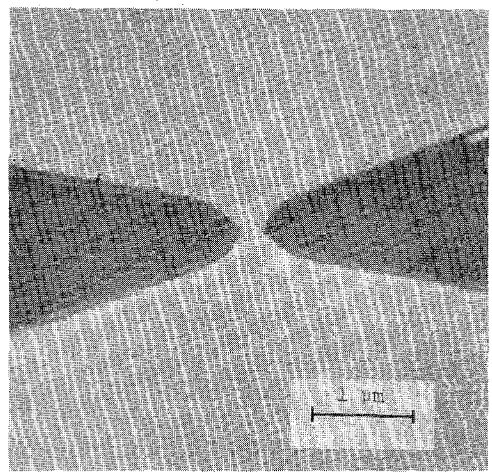


Fig. 1. Scanning electron micrograph of Bridge I-7.

For measurement of V-I curves, the bridges were current-biased with a battery-operated supply with an electrically isolated current monitor circuit. Voltages were measured with a Keithley Model 148 nanovoltmeter, also battery-powered. A buffer amplifier was used to convert the differential nanovoltmeter output to a single-ended signal which was fed to an X-Y recorder. Microwaves from 4 to 25 GHz were introduced into the cryostat via a broadband coaxial line and coupled to the bridge by a terminated section of parallel-wire transmission line.

## III. RESULTS AND DISCUSSION

Experimental results show that the properties of our thin films are very close to those of the bulk material, allowing ready comparison with theory. This contrasts with results on most hard superconductors in films a few hundred Ångstroms thick. In our devices, the combined resistive transition of bridge and banks is ≲15 mK wide, and both $T_c$ and $\rho$ of the thin films are near the bulk-material values.[3,4]

Table I presents the width (w), film thickness (d), minimum differential resistance ($R_{MIN}$), critical current ($I_c$) and voltage of the highest microwave step ($V_{MAX}$) for several bridges.

Data for the critical current, $I_c(T)$, show a temperature dependence close to that expected for these uniform-thickness bridges. $I_c$ is roughly proportional to $(T_c-T)^{1.3-1.5}$, but this result does not distinguish between the flux flow theory of Aslamazov and Larkin (1975),[5] for wide, hyperbolic bridges, and the depairing calculation of Mooij and Dekker,[6] for narrow, hyperbolic bridges. From the parameters given in Table I, we find that bridge I-7 should be in the narrow limit at $T_c$-100 mK, since

$$w = 2000 \text{ Å} < \xi(T_c - 100 \text{ mK}) = 2300 \text{ Å} . \quad (1)$$

Thus it should fall into the regime of uniform depairing, first treated by Aslamazov and Larkin in 1969,[7] and the calculation of Mooij and Dekker should be applicable. For bridge B, on the other hand, we find

$$w = 10{,}000 \text{ Å} >> \xi(T_c - 100 \text{ mK}) = 1100 \text{ Å} . \quad (2)$$

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TABLE I
Parameters of Representative Microbridges

| Bridge | Material[a] | w(μm) | d(Å) | $R_{MIN}(\Omega)$[b] | $\frac{\Delta I_c}{\Delta T}(\frac{mA}{K})$[b] | $V_{MAX}(\mu V)$[c] |
|---|---|---|---|---|---|---|
| B | Pb-Bi | ∿1.0 | 630 | --- | 0.8 | 0 |
| E | Pb-Bi | 0.6 | 610 | 7.3 | 0.48 | 150 |
| I-1 | Pb-In | ∿0.5 | 660 | 1.3 | 0.80 | 120 |
| I-4 | Pb-In | 0.35 | 440 | 2.8 | 0.21 | 180 |
| I-5 | Pb-In | ∿0.25 | 250 | 5.9 | 0.17 | 170 |
| I-6 | Pb-In | ∿0.25 | 440 | 2.9 | 0.20 | 180 |
| I-7 | Pb-In | 0.20 | 250 | 5.5 | 0.15 | 190 |

[a]The compositions of the evaporation charges were $Pb_{.70}Bi_{.30}$ and $Pb_{.86}In_{.14}$. For Pb-Bi films, the measured $T_c$ (8.5 K) and $\rho$(30 μΩ-cm) agree with measurements on bulk $Pb_{.7}Bi_{.3}$,[3] so we use the bulk parameters for this composition: $\xi(0)$=120 Å and $\lambda_{GL}(0)$=1200 Å. For Pb-In films of moderate thickness (d > 400 Å), the observed $T_c$ (7.06 K) and $\rho$(6 μΩ-cm) match the values found for $Pb_{.90}In_{.10}$,[4] and we use the bulk parameters $\xi(0)$=250 Å and $\lambda_{GL}(0)$=550 Å. For Pb-In films with d=250 Å, we find $T_c$=7.11 K and $\rho$=5 μΩ-cm, so we use the bulk parameters for $Pb_{.92}In_{.08}$: $\xi(0)$=275 Å and $\lambda_{GL}(0)$=500 Å. Since the alloy oxide is indium-enriched, indium scavenging at the film surface or oxide undercoat may affect the net composition.

[b]Measured at t=.995. Note that $I_c(T)$ is not linear (see text).

[c]Measured at t=.986. The highest value observed was $V_{MAX}$=375 μV at t=.934.

Bridge B, as all of our bridges, is narrower than the thin-film penetration depth $\lambda_\perp$, so it should be in the flux flow regime treated by Aslamazov and Larkin (1975) for uniform-thickness bridges (UTBs).

Figure 2 compares the experimental results obtained for bridge I-7 with the theoretical values calculated for each regime. The only parameters are the critical temperature $T_c$, the coherence length $\xi(0)$, assumed to be the bulk value, and the thin-film penetration depth $\lambda_\perp(0)$, which is determined from the measured values of R and $T_c$. Clearly, the Mooij result is a good fit for this narrow bridge. This supports our use of the bulk value of $\xi(0)$ and indicates that our bridges are free of complicating

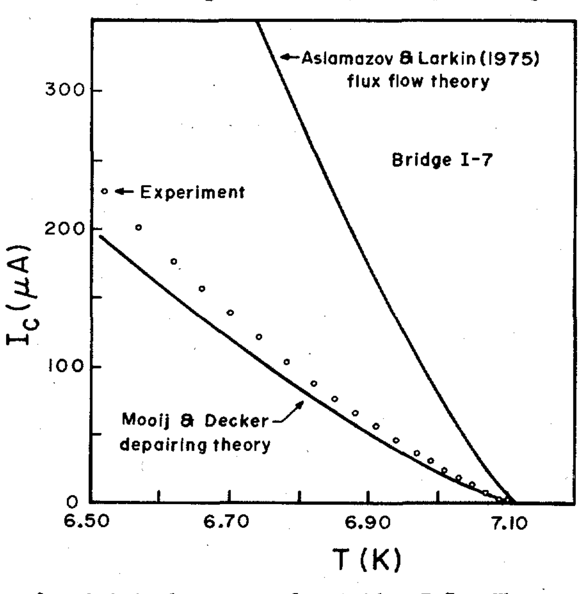


Fig. 2. Critical current for Bridge I-7. Theoretical curves are computed from the results of Ref. 7 and Ref. 8, using the parameters given in Table I.

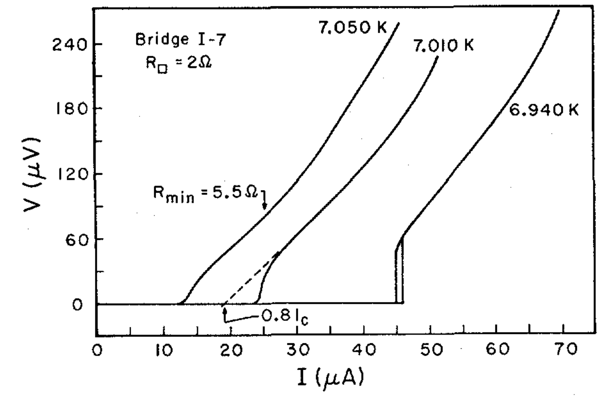


Fig. 3. I-V curves for Bridge I-7. The rounded voltage onset near $T_c$ gives way to hysteresis at lower temperatures. Positive curvature at high voltages is another sign of heating.

material defects.

For wider bridges, the data fall between the two theoretical curves, but there is no simple crossover behavior.

The V-I curves for a typical bridge are shown in Fig. 3; they are smooth and well-behaved. The rounding of the voltage onset may be due to intrinsic thermal noise. The minimum differential resistance in the finite-voltage-region is about 2-3 times the resistance per square in the normal state. If this minimum differential resistance is taken to be the effective device resistance, $R dI_c/dT$ products near $T_c$ for our Pb-In bridges range from 0.6 to 1.0 mV/K. This is in reasonable agreement with calculations for small bridges which predict 0.635 mV/K.[7] Linear extrapolation of the minimum-slope region of the curve yields an "excess supercurrent" of ∿ 0.8 $I_c$. There is positive curvature at high voltages probably due to self-heating, and as the temperature is reduced, hysteresis appears in the voltage onset, due to the same cause. The hysteretic region increases smoothly as the temperature drops, but hysteresis never appears at higher voltages, probably because the bridge is too short to support more than one normal hot-spot. No gap-related structure is observed at any voltage.

When microwave radiation is applied, constant-voltage steps are observed in the V-I characteristics of all microbridges which are 5000 Å wide or narrower. Figure 4 shows a representative set of microwave-induced V-I curves. Dependence of step width on microwave amplitude is initially according to the resistively-shunted-junction (RSJ) model, but the steps fade out at high power levels, another effect of bridge heating.

In order to confirm quantitatively that heating effects limit the performance of these bridges, and to assess the absolute microwave sensitivity of the bridges, we have used a self-heating model to calculate the microwave power coupling constants for several of our bridges. Studies of low-resistance Sn bridges have shown[8] that dissipation of microwave or d.c. power raises the temperature of the bridge region, reducing the effective critical current of the bridge. When the dissipation is large enough, the maximum temperature will exceed $T_c$, and a normal hot-spot will be created. Initially, if the hot-spot is small, the device may function as an S-N-S bridge, but further increases in power dissipation must lead to the destruction of phase coherence. As shown by Tinkham et al.,[9] this loss of phase coherence may take place over a narrow range of power dissipation.

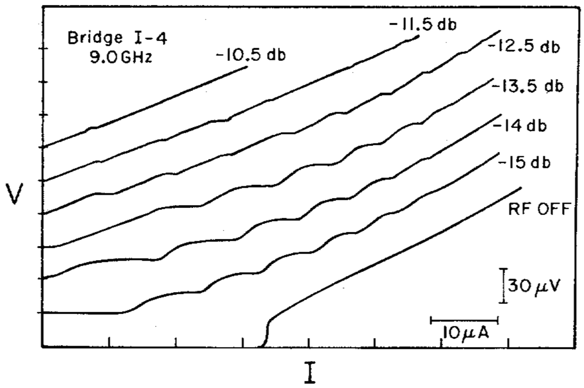


Fig. 4. Microwave-induced steps as a function of microwave power. Successive curves are offset one vertical division. $T_c$-T=100 mK. Note reappearance of zero-voltage step at -13.5 db and at -11.5 db.

To maintain a hot-spot of constant size and temperature, any increase in the microwave power delivered to the bridge must be compensated by a decrease in the d.c. power dissipation, VxI. Specifically, $V_{MAX} \times I_{MAX}$, the d.c. power dissipated by the bridge at the highest microwave step, should decrease linearly with the incident microwave power. The rate of decrease corresponds to the coupling constant for microwave power, so it should be independent of temperature. Plots of the experimental data for several bridges all show the expected linearity and temperature independent slope, confirming the diagnosis of heating limitation. Coupling constants for different bridges at 12 GHz range from $2.4 \times 10^{-4}$ to $1.2 \times 10^{-3}$, with 20% uncertainty in the value for any particular bridge.

These coupling constants can be used to apply theoretical calculations of microwave response in Josephson devices; in effect, the bridge can be used as a bolometer (d.c. substitution method) to calibrate its own Josephson effect response. This method has been used to calibrate the experimental values of microwave current at the first zero of $I_c$ for several bridges in the range .969 < t < .987. At this operating point, d.c. power dissipation is zero and microwave power is fairly low, so heating is minimized. Table II presents the experimental values and compares them to the results of the calculation by Russer,[10] using the current-biased RSJ model.

TABLE II

Microwave Response of High-Resistance Microbridges

$I_1$ is the amplitude of the microwave current at the first zero of $I_c$, and $\nu = f\phi_o/I_{co}R$ is the normalized frequency. Bridge parameters are given in Table I, and f = 12.0 GHz.

| BRIDGE | $\nu$ | t | $(I_1/I_{co})^{exp}$ | $(I_1/I_{co})^{th}$ |
|---|---|---|---|---|
| I-6 | .080 | .969 | 1.4 | 1.05 |
| I-4 | .081 | .972 | 1.2 | 1.05 |
| I-5 | .111 | .979 | 1.4 | 1.08 |
| I-6 | .171 | .982 | 1.6 | 1.11 |
| I-5 | .183 | .986 | 1.6 | 1.12 |
| I-4 | .269 | .987 | 2.6 | 1.25 |

The experimental and theoretical values agree within a factor of two, so calculations of absolute microwave sensitivity based on the current-biased RSJ model are well-justified for these bridges, at least near $T_c$.

Rounding of the steps may be due to thermal noise, since it is less severe at high frequencies and low device resistances. For bridge E, with R=7.3 Ω, the steps are much less distinct at 6 GHz than they are at 12 GHz, and they are indistinguishable at 4 GHz. In the simplest model, one may treat the device resistance as a source of Johnson noise which frequency-modulates the Josephson oscillation. For a 7 Ω bridge like this one, the linewidth would be 2.5 GHz, in reasonable agreement with the observed cutoff frequency for the observation of steps.

Finally, we note that there are no subharmonic steps and no Dayem effect was observed in any bridge. The absence of the Dayem effect is probably related to the small value of the inelastic electron scattering time, which reduces non-equilibrium effects. This is consistent with the results of Octavio,[11] who found enhancements of $I_c$ due to 10 GHz and 32 GHz radiation in Sn VTBs, but not in Pb VTBs with similar device parameters.

The general trends of our microwave data indicate that for bridges which are narrower than the coherence length, behavior is in semi-quantitative agreement with the RSJ model.

In contrast to the data for narrow bridges, bridges wider than 5000 Å do not show microwave steps, a finding which seems to conflict with the theoretical predictions of Aslamazov and Larkin.[5] At least three explanations may be advanced:

(1) It may be that the steps appear in narrow bridges and in very wide bridges, but not in bridges of intermediate width. This would be somewhat surprising in view of Likharev's work for VTBs,[12] which indicates a smooth transition from Abrikosov to Josephson vortices as a function of bridge length. Still, for uniform-thickness bridges, no theory is available which describes the transition from narrow to wide bridges.

(2) Alternatively, it is possible that steps due to flux flow require VTB geometry, in which the thick banks define a single narrow channel for vortices. Gubankov et al.[13] have found microwave steps in Sn VTBs which are as wide as 30 μm.

(3) A final possibility is that the production of significant steps in wide bridges may require levels of microwave power which exceed the self-heating threshold. If this is the case, the variable-thickness geometry should again be preferable because of its superior cooling of the active region.

## IV. CONCLUSIONS FOR UTBs

From this study of uniform-thickness lead-alloy microbridges, we conclude that one can realize device resistances an order of magnitude higher than those achieved with conventional clean materials, with no obvious degradation of other device parameters, if the devices are sufficiently small. Self-heating limitations similar to those encountered using conventional materials restrict operation to voltages < 300 μV and temperatures near $T_c$. These bridges should thus be applicable in the microwave region.

## V. PREDICTED PERFORMANCE OF HIGH-RESISTANCE VTBs

To assess the theoretically expected performance limits of a high-resistance variable-thickness bridge with superior cooling, we have computed the depression of the critical current due to Joule heating for some specific bridge configurations and material parameters which appear to be promising. In all cases the bridge resistance has been fixed at 5 ohms, to allow quantitative conclusions to be drawn. These results are presented below, and provide some guidance as to the lithographic requirements to be met.

To compute the heating effects in alloy VTBs, we have used the results of Tinkham, Octavio and Skocpol,[9] who calculated the depression of $I_c$ due to power dissipation in the bridge. The critical current is determined from a WKB calculation of the penetration of the superconducting wavefunction through the normal central region of the bridge. In the limit of large heating, Tinkham et al. find that the critical current is reduced by power (P) dissipated in the bridge as

$$I_c(P) = I_c(P{=}0)\ e^{-2W_{bridge}}\ e^{-2W_{radial}} \quad . \qquad (3)$$

The result applies for a bath temperature $T_b=0$, and for $eV >> kT_c$, so that the temperature at the midpoint of the bridge $T_m >> T_c$. For $T_c \sim 7$ K, $kT_c=0.6$ meV.

We have considered two different bridge sizes. The first is a "conventional" size bridge of 2000 Å x 1000 Å x 200 Å (length (L) x width (W) x thickness (d)). The banks are assumed to be very thick and to form a solid angle of $\pi$ at each side. Such a structure is not far beyond present capabilities. The second is a hypothetical very small bridge, 500 Å x 250 Å x 200 Å (L x W x d), again with thick banks. Fabricating such a bridge, with thick banks, may be possible with the most advanced techniques of contamination e-beam lithography, although it certainly will not be easy.

The alloy material used for these comparisons is the Pb-In alloy with properties listed in Table I. The choice of material for a microbridge VTB has different constraints than the choice of material for a point contact. For point contacts there are essentially no lithographic constraints, and clean materials are favored. For microbridges, however, use of clean materials leads to low device resistances.

For conventional-sized bridges, Eq. (3) predicts that for V = 1mV, $I_c(P) = 3 \times 10^{-3} I_c(0)$. The critical current is strongly reduced at this voltage, which corresponds to a Josephson frequency of 0.5 THz. Since Eq. (3) is in fact applicable only for V >> 0.6 mV, the reduction of the critical current will not be as severe as suggested by the above result. Still, an upper voltage limit of 1-2 mV is expected. This should be adequate for many mm-wave applications.

For the very small bridge, we find that for V=3mV, $I_c(P)=10^{-3}I_c(0)$. Josephson effects should thus be observable at 3 mV, corresponding to a wavelength of 200 μm.

We thus find that by fabricating a very small device, it should be possible to achieve excellent Josephson-effect performance and a desirable device resistance, roughly 10x larger than that of current best devices made with films of elemental superconductors. Similar performance should be obtainable with Nb films, although the smaller value of $\xi_o$ for Nb makes the lithographic requirements more severe. Even better performance than that computed above could be achieved with the use of banks which are cleaner than the bridge, $\ell_{banks} >> \ell_{bridge}$. The temperature rise in the banks would cause less reduction of $I_c$, because it would occur over a smaller length, and also because $\xi(0)_{banks} >> \xi(0)_{bridge}$.

We conclude that it should be possible in the future to fabricate high-resistance microbridges suitable for mm-wave and FIR detector applications, whose performance will approach the fundamental limits set by the superconducting bank material. Extrinsic limits due to heating [and order parameter relaxation in the bridge] can be minimized with advanced lithographic techniques. These high-resistance microbridges should be useful in many of the applications where to date only point contacts have been used successfully. The realization of such microcircuit-compatible devices should also allow the full utilization of other superconducting microcircuit components, both active and passive, allowing integrated fabrication of high-frequency superconducting receivers with improved system performance.

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