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Observation of a phonon-injection-induced first-order transition in Ag-Sn proximity-effect bridges

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A steady-state heater phonon pumping into long superconducting Ag-Sn proximity-effect bridges evaporated onto thin-film underlays of germanium induces a first-order transition to the normal state at bath temperatures below T_λ. A careful consideration of various possible mechanisms reveals that the observed phenomenon could be mostly due to phonon-injection-induced nonequilibrium effects in these bridges.

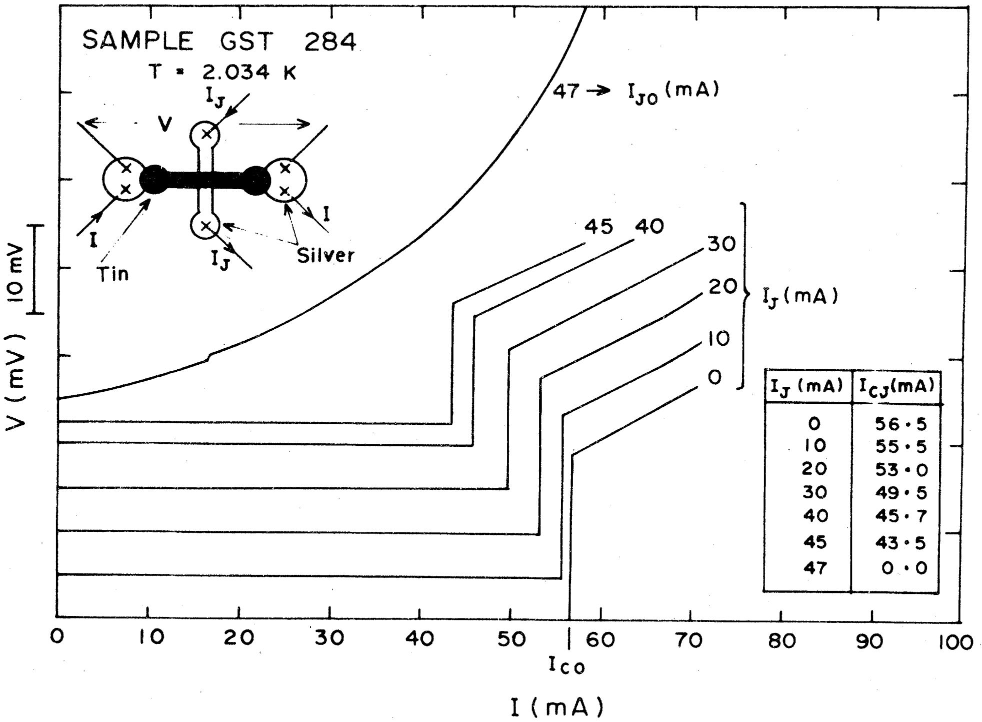
In a recent article[1] we had reported on the first experimental observation of a systematic reduction of the critical current hysteresis in long superconducting Ag-Sn proximity-effect bridges driven out of equilibrium by phonons dc injected from the bridge transverse normal-metal strip. The results showed systematic deviations from a simple heating model in a direction consistent with the Parker T^* model.[2] In a more detailed paper[3] we have shown (from experimental data obtained at bath temperatures *above* T_λ) that the critical currents observed on the returning trace of the current-voltage ($I-V$) characteristics could be satisfactorily accounted for by a simple heating model and the Skocpol-Beasley-Tinkham (SBT)[4] hot-spot-model ansatz whereas the critical currents in the forward trace show deviations in favor of the T^* model and the observed injection-induced transition to the normal state appears continuous.

In this article we report on the observation of a strikingly new phenomenon,[5] viz., an injection-induced first-order transition at bath temperatures *below* T_λ in long superconducting Ag-Sn proximity-effect bridges evaporated onto thin underlays of germanium. A careful review of various possible mechanisms indicates that the observed phenomenon could be mostly due to nonequilibrium effects[6–11] associated with heat pumping[7] into the overlay region from the heated transverse normal-metal strip. Apparently, this is the first experimental evidence of a first-order transition in a phonon-injected nonequilibrium superconductor.

In these experiments we have used conventional crossed-strip Ag-Sn proximity-effect bridges (see inset Fig. 1) on germanium-coated glass substrates. Typical dimensions of the proximity-effect-induced weak overlay region are 500 μm (width of the normal-metal strip) × 200 μm (width of the superconducting tin strip) × 0.4 μm (thickness of the overlap region) and its measured bulk transition temperature is typically around 2.5 K. The experimental $I-V$ characteristics for different injector-current values I_J are obtained using the same procedure as in Ref. 1.

The zero-injection $I-V$ characteristic (see Fig. 1) exhibits features similar to those previously reported.[1] As the injection current through the normal-metal strip of the bridge (immersed in superfluid helium) is increased, the critical current decreases continuously and eventually at a well-defined injection current I_{J0} ($I_{J0}=47$ mA in Fig. 1), the critical current abruptly falls to zero which is to be contrasted with the behavior at bath temperatures above T_λ (in normal helium) where the critical current decreases continuously over the entire range of injection currents.[1,3]

Further we have observed that if we replace the normal-metal strip by a superconducting strip and repeat the experiment no detectable change is observed in the longitudinal critical current I_c even if the transverse injection current I_J exceeds I_c which clearly indicates that the observed phenomenon is not at all due to the transverse supercurrent flowing through the superconducting region. In addition in Fig. 1 we note that the critical injector current that drives normal the overlay region I_{J0} (47 mA) is less than the longitudinal zero injection critical current I_{c0} (56.5 mA) even though the width of the normal-metal strip (through which I_J flows) is 2.5 times the width of the superconducting strip (through which I_c flows). This observation reinforces our argument that the observed effect is not caused by the increase in the transverse supercurrent density. In fact a crude estimate of the reduction in the longitudinal critical current caused by the transverse supercurrent using a steady-state solution of Eq. (3) of Ref. 10 or similar



I_J (mA)	I_{CJ}(mA)
0	56·5
10	55·5
20	53·0
30	49·5
40	45·7
45	43·5
47	0·0

FIG. 1. $I-V$ characteristics of a typical proximity-effect bridge for different injector currents.

equations from Ref. 12 also shows that the contribution of the transverse supercurrent to the observed effect is negligibly small.

We admit that the heating of the overlay region by thermal energy transported by phonons and hot electrons from the normal-metal strip Joule heated outside the overlap region could be the most probable cause of the observed phenomenon. But the question is whether it is a result of simple heating or nonequilibrium heating.[1-3,7,8] The experimental evidence for nonequilibrium heating at bath temperatures above T_λ has already been presented in Refs. 1 and 3. For the samples studied the thermal healing length[4] estimated using the values of heat-transfer coefficient (for typical values see Ref. 13) determined from the experimental critical currents observed in the returning trace of the $I-V$ characteristics[1,3] and Eq. (1) of Ref. 4 is as large as 200 μm in normal helium (T above T_λ) and larger than 50 μm in superfluid helium (T below T_λ). With an additional quasiparticle diffusion length[11] comparable with the thermal healing length one can safely assume a spatially uniform steady-state nonequilibrium phenomenon in the overlay region of width $\simeq$200 μm. With the above qualifications the experimental observations can be qualitatively interpreted as described below.

The phonons diffusing in from the heater as well as phonons emitted [by processes given in Fig. 1(a) of Ref. 7] by hot electrons excited by Joule heating in the normal strip and carrying energy into the overlap region first appear in the silver underlay region and then divide between the tin overlay (in direct contact above it) and the substrate below. The ratio depends upon the phonon-transmission properties of the relevant interfaces. Silver being a noble metal does not stick well to glass and hence the phonon transmission through the silver-glass interface is rather poor as inferred from the low values of heat-transfer coefficient in normal helium.[13] Thus most of the phonons injected into the overlap region are diverted into the helium bath through the tin overlay (which forms the major part of the proximity-effect-induced weak region) in direct contact with the silver underlay. High-energy phonons (of energy greater than 2Δ where Δ is the BCS energy-gap parameter of the superconductor) break pairs and create excess quasiparticles causing the gap supression[7] as well as a corresponding reduction of the critical current.

The resulting nonequilibrium quasiparticle distribution causing the gap supression is very sensitive to the ratio of the phonon escape time τ_{es} to the pair breaking time τ_B (see Fig. 9 of Ref. 7) which is approximately given by $\tau_{es}/\tau_B \simeq 1/\eta$ where η is an escape probability [see Eq. (5) of Ref. 7]. From the estimated heat-transfer coefficients in normal and superfluid helium[13] we infer that η increases by an order of magnitude when the sample is immersed in superfluid helium. This implies that $(\tau_{es}/\tau_B)_{T>T_\lambda}$ in normal helium is an order of magnitude larger than $(\tau_{es}/\tau_B)_{T<T_\lambda}$ in superfluid helim. In other words at bath temperatures above T_λ the overlap region is relatively weakly coupled to the temperature bath compared to bath temperatures below T_λ. Then one would expect from the most recent[8] Chang and Scalapino numerical solutions of the coupled set of nonlinear kinetic Boltzmann equations[7] that the results in this case (in normal helium) could be well approximated by an extension of the Parker T^* model.[2] This in a way qualitatively accounts for our observations at bath temperatures above T_λ.[1,3]

In Fig. 2 we have plotted $(I_{cJ}/I_{c0})^{1/3}$ against I_J/I_{J0} where I_{cJ} is the longitudinal critical current corresponding to an injection current I_J. In a crude approximation[3] this would relate the normalized effective energy gap Δ_J/Δ_0 with the strength of the driving force which is a function of the normalized excess quasiparticle density.[7] We observe that for samples without a germanium underlay the injection-induced transition is continuous both in normal and superfluid helium (see inset of Fig. 2). However we wish to mention that these samples also show large deviations from a simple heating model[5] in the opposite direction at bath temperatures *below* T_λ suggesting that the phonon-injection-induced nonequilibrium phenomenon in these bridges immersed in superfluid helium cannot be adequately described by a T^* distribution of quasiparticles. This observation does not necessarily contradict the Chang and Scalapino prediction[8] since the thermal coupling between the overlap region and the temperature bath is relatively strong for T below T_λ. Further it is rather interesting to note that samples underlaid with a thin film of germanium exhibit an injection-induced first-order transition at bath temperatures below T_λ as shown in Fig. 2 (for sample *GST* 284) reminiscent of the recent observations of Iguchi[6] under tunnel injection below T_λ.

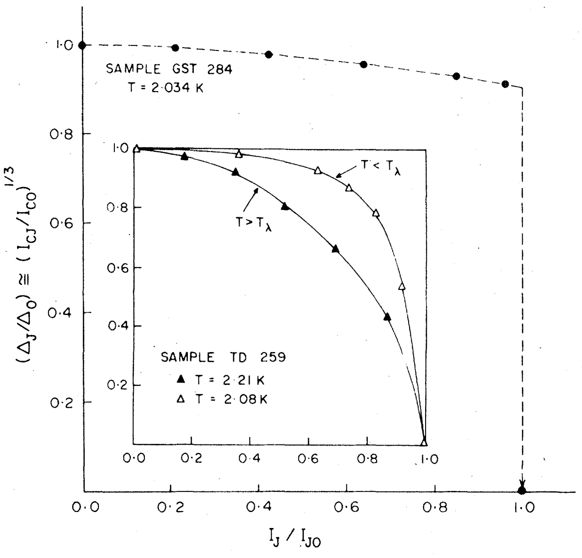


FIG. 2. Typical injector-current dependences of the normalized energy gap for a few typical bridges. Note the injection-induced first-order transition for sample *GST* 284.

Another interesting observation is that the samples with germanium underlay have lower heat-transfer coefficients than those without the germanium underlay (about a factor of 2) which suggests that these samples have considerable phonon trapping even in superfluid helium indicative of the preservation of the Owen-Scalapino condition,[6] viz., that the quasiparticle recombination time should exceed the thermalization (quasiparticle inelastic scattering) time to favor a μ^* distribution of the quasiparticles which leads to a first-order transition. The above argument is in qualitative agreement with one of the most recent experimental observations of Pals and Dobben,[9] viz., that their experimentally determined recombination time is larger than the inelastic scattering time because of phonon trapping. Thus the role of the germanium underlay in engineering the observed first-order transition is clear-cut inasmuch as the interposed layer of germanium traps a part of the fraction of the phonons which otherwise could have escaped through the metal-glass interface. If the results were entirely due to pure heating one should have observed a discontinuous transition to the normal state even at bath temperatures above T_λ because of poorer refrigeration provided by the normal helium. In addition, the fact that a sample immersed in superfluid helium when heated above T_λ does not show any discontinuity in its Kapitza resistance[14] precludes a simple heating explanation of the observed discontinuous transition.

By virtue of the complex nature of the relationship between the high-energy phonon injection rate and the excess quasiparticle density given by Eq. (13) as well as on p. 19 of Ref. 7, we find it rather difficult to make a quantitative comparison with the μ^* model.[6] However from the collective evidence given above we infer that one cannot rule out the possibility of the observed phenomenon being the first-order transition (for the phonon-injection case) predicted by Owen and Scalapino.[6] The similarity between the observation of Iguchi[6] and ours is rather striking in the sense that both have observed the injection-induced first-order transition only at bath temperatures *below* T_λ. The novel idea of interposing a thin-film layer of germanium between the superconductor and substrate to control phonon trapping might prove useful in future investigation of nonequilibrium superconductors.

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