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Microwave-Enhanced Critical Currents in Point Contacts of Superconducting Aluminum

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Enhancement of the critical current of clean point contacts made of bulk superconducting aluminum is measured when the contacts are in a 1–10 GHz microwave field. This enhancement interferes with the ac Josephson effect.

There has been much recent interest in the influence of microwave fields on the critical current of constricted superconductors. In particular the enhancement of the critical current, which is observed for a number of experimental arrangements, has received considerable attention. In this Letter we report the observation of a microwave-enhanced critical current (Dayem-Wyatt effect) in point-contact Josephson junctions.

The Dayem-Wyatt effect was first observed in thin-film constrictions.[1-3] It was found that very small bridges[3] of the order of the coherence length or smaller has a maximum relative enhancement of only 10% or less but in a temperature region which extends at least down to a reduced temperature $t = T/T_c = 0.5$, whereas larger bridges[1,2] sometimes have very large relative enhancements but only in a temperature region very close to T_c. The Dayem-Wyatt effect has been observed also in proximity bridges of tin with gold underlay[4] and in long thin-film strips of superconducting aluminum.[5]

It is obviously of interest to see whether the enhancement can be observed in other weak-link geometries as well. We have studied the occurrence of the Dayem-Wyatt effect in point-contact Josephson junctions. Earlier results for thin-film microbridges indicated that the enhancement was largest in films with a large residual resistivity ratio. We therefore included in our efforts also a study of clean point contact.[6] We studied tin, indium, and aluminum contacts. The microwave frequencies were in the range 1–10 GHz. Whereas we did not observe any enhancements in tin or indium, we did observe the enhancement in the aluminum point contact as evidenced in Figs. 1 and 2.[7]

In order to observe the enhancement in aluminum point contacts we indeed found that these had to be clean, i.e., with little or no oxide or dirt in the contact region. We obtained these clean contacts either by breaking a constricted wire or by passing a very large current through the constricted wire and thereby melting the constriction when immersed in the helium bath. In both cases the two halves of the wire were very accurately brought together again to form a clean contact. The point contacts were difficult to adjust and very sensitive to mechanical vibration because the clean contacts must be very small in order to have a sensible supercurrent. In order to avoid effect of Earth's magnetic field the sample holder was encased in a superconducting lead shield and the Dewar surrounded by two concentric Mumetal cans. To exclude the possibility of trapped magnetic flux the point contacts were occasionally heated for a short time to above the critical temperature, and the measurements were repeated. The microwaves were either coupled to the point contact by a loop antenna or conducted directly through the point contact, using microwave capacitors. The temperature was determined by pressure above the He bath. Thus in the case of aluminum, the temperature was not

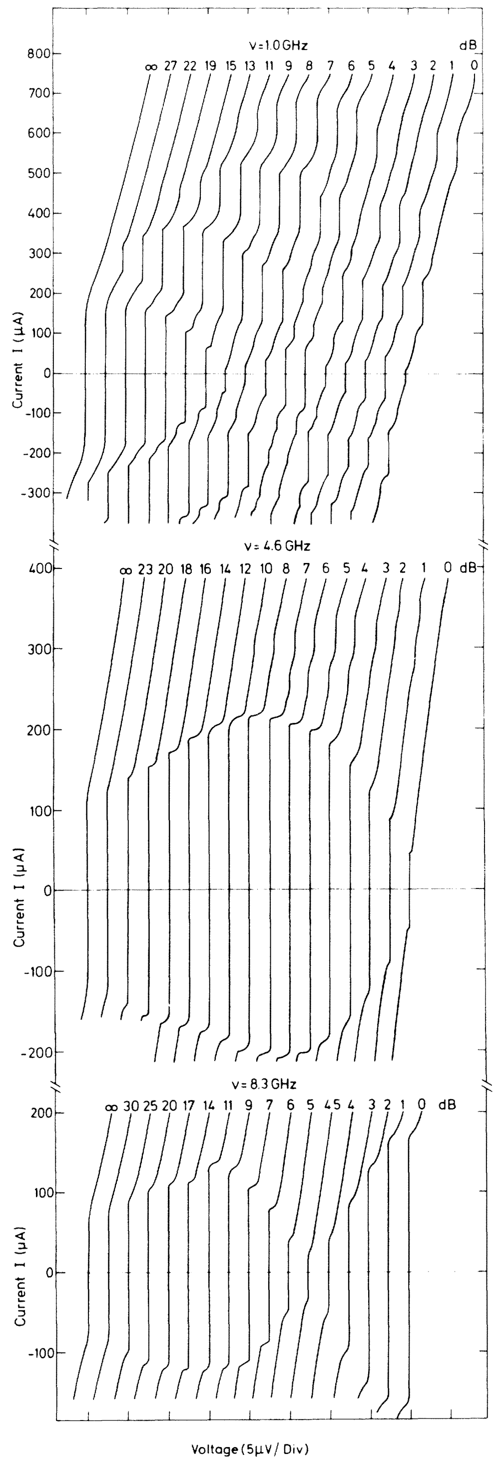

FIG. 1. A series of current-voltage characteristics of a clean aluminum point contact for various power levels of microwave irradiation at three discrete frequencies $\nu = 1.0$, 4.6, and 8.3 GHz. The temperature was very close to the critical temperature (but not directly measured).

directly available. For tin and indium, however, we found the relation

$$I_0 = \frac{\pi}{4e} \frac{\Delta^2(T)}{k_B T_c} \frac{1}{R} \tag{1}$$

to be fairly well satisfied at temperatures close to T_c; and from knowledge about the supercurrent I_0, the normal-state resistance of the contact R, and the energy gap $\Delta(T)$, we had a reasonable idea about the temperature relative to T_c for aluminum.

With the clean contacts of aluminum as described above, we generally observed a maximum enhancement at 9 GHz which was of the order 5–10%. The enhancement always appeared below T_c of the bulk aluminum and it became undetectable at the lowest temperatures ($T_c - T \approx 200$ mK). In a few cases we observed larger enhancements with contacts prepared in this way. Figure 1 shows the largest enhancement we have obtained so far with our clean aluminum point contacts. This particular contact had a normal-state resistance of 14 mΩ. A number of I-V characteristics taken at T very close to T_c are displayed for increasing microwave power at 1.0, 4.6, and 8.3 GHz. Only at 1 GHz did we have sufficient microwave power available so that it was possible to observe several periods in the quasiperiodic (Bessel-function–like) variation of the supercurrent and the microwave induced step structure versus microwave power as given by the Josephson equations. At this frequency, on the other hand, the relative enhancement was only small, as can be seen. At the higher frequencies, the enhancement is considerably larger. One interesting feature is that for 8.3 GHz the maximum enhancement occurs at power values beyond the first Bessel-function minimum in the supercurrent. This is similar to the observations on proximity bridges.[4]

In these clean contacts we often observed subharmonic-microwave-induced current steps at voltages $V = (n/m)\hbar\omega/2e$. This was particularly pronounced for the sample from which the data of Fig. 1 are taken. In Fig. 2 we have shown another series of I-V characteristics for varying microwave power at 8.3 GHz with an expanded voltage range to show the large number of subharmonic steps (up to $m = 7$). The large number of subharmonic steps is an indication that the contact had dimensions on the verge of being too large to see the Josephson effect. Contact resistances in the region 10–100 mΩ were difficult to obtain and it

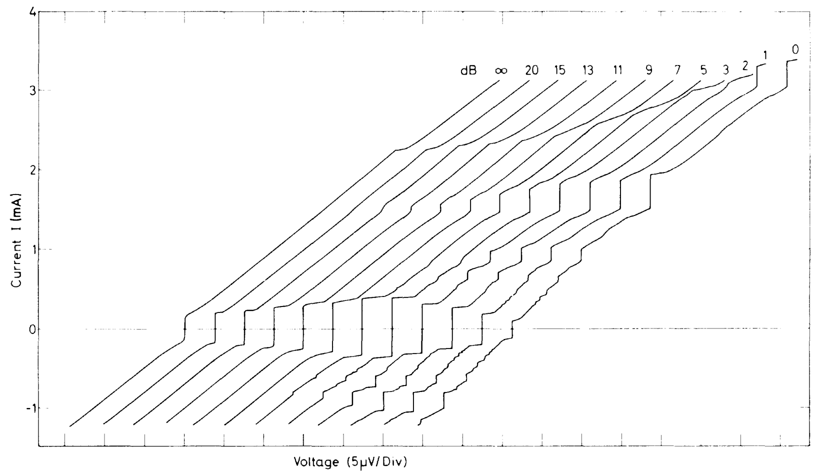

FIG. 2. Current-voltage characteristics at various levels of microwave power at $\nu = 8.3$ GHz; the same aluminum point contact as Fig. 1 but with coarser current scale.

happened to be the optimum resistances in order to see a large Dayem-Wyatt effect. For the clean contacts the resistance was often less than 1 mΩ. We believe that the crudeness of our contact adjustment was responsible for this general trend. For these low-resistance contacts we did not have enough microwave power available to make any changes in the very large critical current.

Over the last decade, a number of suggestions have been given as to the explanation of the Dayem-Wyatt effect. Recent experimental results by Klapwijk and Mooij[5] who observe the enhancement in long regular aluminum strips, and by Tredwell and Jacobsen[8] who find strong enhancement in thin film microbridges and point contacts (incorporating thin films) of aluminum when these are irradiated by high-frequency phonons, and very recently results by Clarke and Kommers[9] who directly observe an enhanced energy gap in tunnel junctions made of aluminum films, all support the predictions made by Eliashberg.[10] In our results we believe that there is also evidence in favor of the predictions in Ref. 10. In Fig. 2 for the curve without microwave power there is a voltage step at 28 μV. A closer examination of the I-V characteristic also reveals a structure at 14 μV. There is little doubt that this is the subharmonic energy-gap structure which is well known from Dayem bridges.[11] We do not know the absolute temperature of our helium bath, so we cannot make any commitment about the expected magnitude of the gap; however, $2\Delta = 28$ μV, $I_0 \approx 100$ μA, and $R = 14$ mΩ are consistent with Eq. (1). The structure at 2Δ in the I-V curves in Fig. 2 is seen to occur at higher voltages (and currents) when a 8.3-GHz microwave field is applied and this is presumably a direct observation of the microwave-enhanced energy gap close to the aluminum point contact.

Many aspects of the microwave-enhanced supercurrent in various geometries are still unsolved. One main question is to answer why the enhancement is so easily observed in constricted geometries. In a constriction we have a small superconducting volume which determines the critical current. Through this volume we can concentrate a large microwave current and at the same time have very efficient cooling through the superconductors on each side of the constriction altogether favoring the Eliashberg gap enhancement. Furthermore, the gap at the middle of the constriction is suppressed by the dc current, and the ac quasiparticle current therefore injects quasiparticle into this volume with a nonequilibrium distribution with excess population at an energy Δ above the Fermi energy which is somewhat higher than the gap edge of the constricted region; this may in itself lead to an Eliashberg-type enhancement of the gap in the constricted region. Such a mechanism can possible be phenomenological described as in Lindelof.[12] These remarks would then also explain the curious results obtained in ultrasonic attenuation measurement[13] where large ultrasonic amplitudes apparently sharpens the energy gap since the low-gap region will profit most from the enhancement effect.

We have benefitted from several discussions with George Pickett. We are indebted in particu-

lar to John Clarke for allowing us to see and refer to his recent data on gap enhancements.

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COMMENTS

Meson Electromagnetic Mass Differences

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The electromagnetic mass differences of the pseudoscalar and vector mesons are calculated in the bag model. The electromagnetic mass difference of the charmed pseudoscalar (D) is predicted to be 7.82 MeV; and that of the D^*, 6.81 MeV.

Evidence[1] now exists for both the charged and neutral pseudoscalar bosons (D^+, D^0) carrying the new quantum number charm.[2] The mass splitting between the two particles is measured at 12 ± 15 MeV. It has been emphasized[3,4] that this mass difference, and the mass difference between the corresponding vector mesons (D^{*+}, D^{*0}) is very important in determining branching ratios because the D^* and the D are expected to be different in mass by just about the mass of the pion. Two estimates of the $D^+ - D^0$ mass difference have been made, one[3] by assuming the interaction distance between the quarks to be the same for π, K, and D, and another[5] by using Dashen's theorem[6] to extract the up-down quark mass difference from the pion and kaon mass differences. Both the rough estimate of Ref. 3 (15 MeV) and the more detailed treatment of Ref. 5 (6.7 MeV) are within the framework of a field theory of colored and flavored quarks and colored gluons[7] in which it is hoped that quark confinement will result.

The purpose of this note is to present a calculation of the $D^+ - D^0$ and $D^{*+} - D^{*0}$ mass differences within the Massachusetts Institute of Technology bag model.[8] The present calculation has several distinctive features: (1) The bag model is Lorentz-invariant and the quarks are treated fully relativistically; this is especially important for electromagnetic mass differences since these are determined by the light quarks. (2) The calculation is based on explicit wave functions; this allows the interaction distance between the quarks to be different for different types of quarks as well as for different particles. (3) Mass differences of all the (low) hadrons are calculable in