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Energy Gap, Microwave-Assisted Tunneling, and Josephson Steps in Thin-Film Weak Links at 63 and 302 GHz

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We present experimental evidence for the occurrence of energy-gap structure and microwave-assisted tunneling in the *IV* curves for superconducting thin-film weak links. From measurements of the power and the temperature dependence of the Josephson steps we argue that also the Riedel peak is observable in weak links.

The occurrence of structure caused by the superconducting energy gap, subharmonics of the energy gap, microwave-assisted tunneling including the satellite structure connected with the subharmonics of the gap,[1-3] and the Josephson effect[4] in tunnel junctions and point contacts is by now a well-established fact. Also the quasiparticle-pair interference $\cos\varphi$ term has been observed in tunnel junctions.[5] In thin-film weak links, on the other hand, only the Josephson steps appear to be well established through the observations of Gregers-Hansen *et al.*[6] at 3 and 9 GHz close to T_c and through the Dayem effect.[7] Recently the $\cos\varphi$ term may have been observed.[8] The thin-film weak links used by Dayem were prepared by an evaporation technique, whereas Gregers-Hansen *et al.* used a razor-blade technique. In the latter case the dimensions are of the order 0.5 μm wide by 0.2 μm long.

In the present note we report on measurements on thin-film weak links fabricated in a novel way which will be described in detail elsewhere. The shape of our weak links may be seen in the inset in Fig. 1. The resistance of a weak link is of the order 300–600 Ω at room temperature, and below T_c the normal resistance is of the order of 50–100 Ω. The thickness of the film is about 1000 Å. During the measurements the weak link is mounted outside, but very close to, the end of a 70-GHz wave guide in a glass cryostat equipped with magnetic shielding. The 70V10 OKI klystron and the 300-GHz Carcinotron used deliver 25 and 50 mW, respectively. The electronic equipment measures the *IV* characteristic and the dynamic resistance dV/dI or the dynamic conductance dI/dV as function of the bias voltage.

Although our measurements include several weak links of In and Sn, and some of Pb, we here discuss mainly the results obtained using In, as the results for Sn and Pb are qualitatively similar. The structures in the *IV* characteristics reported in this Letter have always been seen when looked for. Briefly, we have observed a gap structure, microwave-assisted tunneling, and Josephson steps, and we have examined in some cases the power and temperature dependences of these effects.

(1) Gap structure.—In Fig. 1 the topmost trace shows the *IV* characteristic for a thin-film In weak link without incident microwaves and at a temperature of 1.58 K, i.e., $t = 0.466$. The bump on the curve, indicated by the arrow *a*, occurs at a voltage which corresponds well with the energy gap value $2\Delta/e = 1.02$ mV for In at this temperature. The same bump occurs also on both the middle and the bottom traces which are for incident microwave frequencies of 63 and 302 GHz, respectively. In order to substantiate this interpretation of the bump, we have examined its voltage position as a function of temperature.

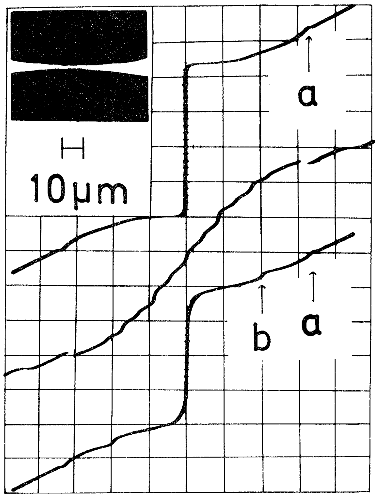

FIG. 1. *IV* characteristic for an In weak link at 1.58 K. Top curve, without applied microwaves; middle curve, exposed to 63-GHz microwaves; bottom curve, exposed to 302-GHz microwaves. Vertical scale 10 μA/div; horizontal scale 300 μV/div. Inset, a photo of a typical weak link.

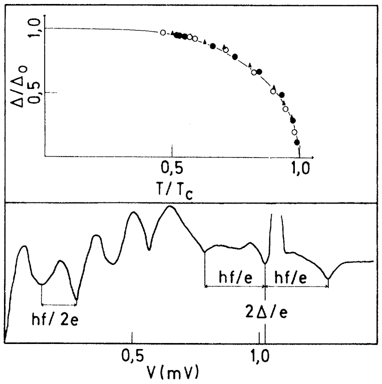

FIG. 2. Dynamic resistance as a function of the bias for an In weak link at 1.58 K exposed to 63-GHz microwaves. The inset shows the measured energy gap versus the reduced temperature compared with the BCS theory for two In weak links (circles) and one Sn weak link (triangles).

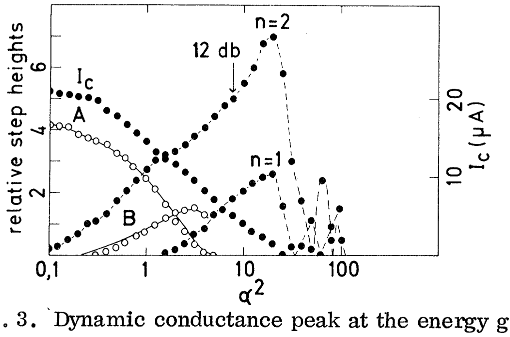

FIG. 3. Dynamic conductance peak at the energy gap (*A*) and the first microwave-assisted step (*B*) versus microwave power (open circles), compared with Tien-Gordon expression. Also shown: I_c (right-hand scale) and dynamic conductance peak for Josephson steps $n = 1, 2$ (left-hand scale) versus microwave power (closed circles). $f = 63$ GHz, $T = 1.58$ K.

Thus in Fig. 2 the dynamic resistance for the same weak link is shown for a microwave frequency of 63 GHz. The energy-gap structure is seen here more clearly. From a series of measurements of this type we are able to plot the variation of the energy gap with temperature as shown in the inset in Fig. 2. The points plotted refer to two In and one Sn weak links. For clarity some of our data have been omitted from the figure. The energy-gap structure has been observed in all our weak links. In plotting the points we have used only measured values, i.e., the measured temperature and voltage and the measured transition temperatures $T_c = 3.40$ K (In weak links) and $T_c = 3.86$ (Sn weak link). The curve drawn in the inset is the BCS curve. The measured points follow this curve very closely, indicating the correctness of our interpretation of the bump.

(2) Microwave-assisted tunneling.—On the curve showing the dynamic resistance in Fig. 2, one notes (besides the Josephson step structure discussed below) an additional structure on either side of the gap. As the separation of the additional structure from the gap in both cases is very close to hf/e, it is tempting to interpret this structure in terms of microwave-assisted tunneling. For this reason we have examined the variation of the structure as a function of the incident microwave power and performed a comparison with the Tien-Gordon theory.[9] Thus, in Fig. 3 we have plotted the variation of the dynamic conductance at the energy gap and at the additional structure as functions of the applied microwave power at 63 GHz. The values of conductance were obtained by inverting the measured resistance values and subtracting a constant background term. For comparison we have also plotted the fully drawn curves, i.e., $J_0^2(\alpha)$ and $J_1^2(\alpha)$, based on the Tien-Gordon expression, for the gap and the first microwave-assisted peak, respectively. As is well known,[10-12] the Tien-Gordon expression is valid for a tunnel junction whenever the spatial variation of the microwave field across the junction can be neglected. J_n is the usual Bessel function and $\alpha = eV_{\mathrm{rf}}/hf$, where V_{rf} is interpreted as the rf voltage set up in the junction by the microwave field. It is apparent from Fig. 3 that the measured power dependence of the dynamic conductance at the gap and at the additional structure on either side of the gap very closely follows the Tien-Gordon expression for microwave-assisted tunneling. For this reason we interpret the additional structure to be the first microwave-assisted step. This kind of structure has only been distinctly observed when we measure the dynamic resistance. We have no clear evidence of higher-order microwave-assisted steps.

(3) Josephson steps.—Observations on Josephson steps in weak links have been reported earlier, notably by Gregers-Hansen *et al.*,[6] at 3 and 9 GHz and at temperatures close to T_c. With the present weak links we easily observe the steps at 63 and 302 GHz at low reduced temperature as shown by the characteristics reproduced in Fig. 1. Here the middle trace shows a series of 63-GHz steps, while the lowest trace at the arrow *b* shows a single Josephson step at 302 GHz. In both cases the steps occur at the right

positions according to the relation $eV=hf/2$, as shown in more detail in Fig. 2 which refers to the same weak link. We have further measured the power dependence of the Josephson dc current and the first six Josephson steps. However, for clarity we show in Fig. 3 only the measured power dependence for the dc current I_c and for the first two steps $n=1$ and $n=2$. The points shown are the dynamic conductance taken from the dynamic resistance in the same way as was done for the microwave-assisted tunneling data in Sec. (2) and plotted on the same relative step-height scale. From the fit between the microwave-assisted tunneling data and the Tien-Gordon expression the conversion from a decibel scale to an α scale is obtained. From Fig. 3 one notes that the zero for I_c falls at an α^2 value which is 4 times the α^2 value for the zero for the microwave-assisted tunneling at the gap (curve A). This is in agreement with the 2α and the α appearing in the Bessel functions in the theoretical expressions for the microwave power dependence of, respectively, I_c and the microwave-assisted tunneling in tunnel junctions and point contacts. Further, one notes that the power level at which the maximum for the first and second Josephson steps occurs corresponds to $\alpha=4.5$, which again corresponds to a microwave electric field of the order of 0.55 mV in the thin-film weak link, indicating a good microwave coupling to the weak link. This is probably due to the shape of our weak links and their high resistance. Detailed measurements of this type have been performed on two In and one Sn weak link. The effect has been seen in most of our weak links.

One more feature of the Josephson-step data should be noted. As seen in Fig. 3, the Josephson step $n=2$ appears before and is larger than the step $n=1$. On account of this behavior we performed a series of measurements of the temperature dependence of the Josephson steps at a constant microwave power level, taken to be the one marked 12 dB in Fig. 3. From the measurements it follows that the magnitude of the steps shows an oscillating behavior, decreases with increasing temperature, and ultimately disappears just below the transition temperature. An analysis of our present data seems to indicate that if an even-numbered step occurs nearer to the energy gap than an odd-numbered step, then the even-numbered steps are enhanced. Conversely, if an odd-numbered step occurs nearer to the energy gap than an even-numbered step, then the odd-numbered steps are enhanced. This situation is in many respects similar to the one described by Hamilton and Shapiro[13] and by Buckner *et al.*[14] which indicates that an experimental verification of the Riedel peak is possible also for a thin-film weak link. However our present data do not warrant a quantitative, detailed analysis.

In summary, we have made thin-film weak links which have a very good coupling to the microwave field because of their shape and high resistance. We have presented experimental evidence for the occurrence of an energy-gap structure and for microwave-assisted tunneling in thin-film weak links. Josephson steps have been observed at the high microwave frequencies 63 and 302 GHz. Further, from measurements of the power and temperature dependence of the Josephson steps it was also argued that the Riedel peak is observable in a thin-film weak link. Taken together with the recent[8] observation of the quasiparticle-pair interference term, the $\cos\varphi$ term, in weak links it may be concluded that basically the thin-film weak links and the tunnel junctions show the same behavior.

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