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Low-Frequency Photon-Assisted Tunneling in Superconducting Tunnel Junctions

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ABSTRACT

The photon-assisted tunneling response of Sn-SnO-Pb and Sn-SnO-Sn superconducting junctions to a 3.9 GHZ microwave field has been measured. The experimental response of the tunneling current to the rf field agrees very closely with the response predicted by the theory of Tien and Gordon. The predictions of the Cook and Everett theory do not fit the data well.

La réponse tunnel assisté par photons des jonctions Sn-SnO-Pb et Sn-SnO-sn à un champ de microondes à 3.9 GHZ a été mesuré. La reponse expérimentale du couvant tunnel au champ de haute fréquence est en trés bon accord avec la réponse calculée à l'aide de la théorie de Tien et Gordon. Les previsions de la theorie de Cook et Everett ne correspondaient pas bien aux résultats expérimentaux.

Microwave photon-assisted quasiparticle tunneling between two superconductors has been the subject of several recent experiments designed to investigate the range of validity of the simple Tien-Gordon[1] theory of this process and to advance or examine alternate, more complex theories. We have measured the photon-assisted tunneling response of Sn-SnO-Sn and Sn-SnO-Pb thin film junctions to a 3.9 GHZ microwave electric field perpendicular to the junction plane, and compared the measured current-voltage (I-V) characteristics to the theories of both Tien and Gordon,[1] and Cook and Everett.[2] Excellent detailed agreement with the Tien-Gordon (TG) theory has been obtained for all junctions with normal state resistances greater than a few ohms. The Cook and Everett (CE) theory does not agree well with the experimental data, except at extremely low microwave (rf) power levels where both the CE and the TG theories converge to the same result.

In the TG theory the net effect of the microwave field of angular frequency ω is assumed to be the appearance of induced rf voltage, $V_{rf}\cos\omega t$, across the junction electrodes. The expression derived by TG for the dc current at a bias voltage V in the presence of a microwave field is

$$I_{TG}(V) = \sum_{n=-\infty}^{\infty} J_n^2(\alpha) I_o(V+n\hbar\omega/e), \qquad (1)$$

where $\alpha = eV_{rf}/\hbar\omega$, $I_o(V)$ is the quasiparticle tunneling current in the absence of the rf field, and the J_n are ordinary Bessel functions of the first kind of order n.

Although TG derived Eq. (1) using somewhat hueristic arguments about modulation of the densities of states, the same result can in fact be derived from more general theory.[3-6] The TG result also reduces to the correct classical expression for the average (dc) current,

$$I_{RF}(V) = \frac{\omega}{2\pi}\int_o^{2\pi/\omega} I_o(V+V_{rf}\cos\omega t)dt, \qquad (2)$$

in the limit $\hbar\omega \to 0$. If the integrand in (2) is expanded in a Taylor series about V and integrated term by term, the resultant series is exactly the same as that derived by Goldstein, Abeles, and Cohen[7] from Eq. (1) in the limit $\hbar\omega \to 0$.

In an attempt to explain their 36 GHZ photon-assisted tunneling measurements, Cook and Everett[2] proposed a modified theoretical model based on modulation of the densities of states in both the superconducting films. Their result for the current in the presence of a microwave electric field is given by

$$I_{CE}(V) = \sum_{n,m=-\infty}^{\infty} J_m^2(\alpha) J_n^2(\alpha) I_o[V+(n-m)\hbar\omega/e]. \tag{3}$$

After some manipulation, Eq. (3) may be rewritten in the form,

$$\begin{aligned} I_{CE}(V) &= J_o^2(\alpha) I_{TG}(V) + 2\sum_{m=1}^{\infty} J_m^4(\alpha) I_o(V) \\ &+ \sum_{m,n=1}^{\infty} J_m^2(\alpha)[J_{m+n}^2(\alpha) + J_{m-n}^2(\alpha)] \\ &\times [I_o(V+n\hbar\omega/e) + I_o(V-n\hbar\omega/e]. \end{aligned} \tag{4}$$

In the limit $\alpha \to 0$, $J_o^2(\alpha) \to 1$ while all other J_n approach zero, and hence $I_{CE}(V) \to I_{TG}(V)$. As α becomes appreciably greater than 1, the difference between I_{CE} and I_{TG} becomes quite large, indicating that I_{CE} does not reduce to the correct classical limit when $\hbar\omega \to 0$.

In our experiments, conventional crossed-strip tunnel junctions were placed on the sidewall of a TE 101 rectangular resonant cavity at a point where $\underset{\sim}{E}_{rf}$ was perpendicular to the plane of the junctions and $\underset{\sim}{H}_{rf} \simeq 0$. All junctions tested had areas of (0.16×0.16) mm^2, with metallic film thicknesses between 2000 Å and 6000 Å. The Sn-SnO-Sn junctions had normal state resistances of 2 - 7 Ω while Sn-SnO-Pb junctions were in the range 20 - 130 Ω. All junctions with normal state resistances less than 30 Ω had appreciable dc Josephson currents, which were quenched with a small magnetic field during our measurements. A comparison of typical experimental results for a high resistance Sn-SnO-Pb junction with theory is shown in Fig. 1. The curves marked I_{TG} and I_{CE} were calculated from Eqs. (1) and (3) respectively, using the measured $I_o(V)$. The value of α was deduced by fitting an experimental I-V curve to a theoretical TG curve at a high microwave power level (in this case, one corresponding to $\alpha=60.2$). α was then scaled as the square root of the microwave power incident on the cavity. The curve marked I_{BCS} is the bare current predicted by the BCS constant Δ model with $\Delta_{Pb} + \Delta_{Sn}=1.98$ meV at 1.1°K. Since $\hbar\omega/e=16$ μV, while the width of the current step in $I_o(V)$ at $\Delta_{Pb} + \Delta_{Sn}$ is ≃ 175 μV, we can not resolve individual microwave induced steps[2,7] in the I-V characteristics at voltages $V_n=\Delta_{Pb}+\Delta_{Sn}\pm n\hbar\omega/e$. These steps will begin to appear when the angular frequency satisfies the condition $\hbar\omega/e \gtrsim 175$ μV, corresponding to a frequency $\nu \gtrsim 40$ GHZ. In Fig. 2, the current deviation, $\Delta I=I(V)-I_o(V)$, is plotted at three different microwave power levels for the junction whose $I_o(V)$ characteristic is shown in Fig. 1. The close agreement between the experimental data and the TG theory is clear.

In Fig. 3, $\Delta I(V)$ is shown for a 6.35 Ω Sn-SnO-Sn junction at a relatively low microwave power level corresponding to $\alpha=1.8$. Even at this low value of α, the differences between the CE and TG theories are quite pronounced. It can also be seen that $I_{RF}(V)$ is very close to $I_{TG}(V)$ even at this low value of α. Numerical calculations indicate that I_{TG} and I_{RF} are approximately equal when $\alpha \gtrsim 10$ for 4 GHZ microwaves.

In view of the detailed agreement between the predictions of the TG theory and the experimental data for low-frequency photon-assisted tunneling, it would appear that recent attempts[2,7] to explain the results of higher frequency tunneling experiments with Eq. (3) are incorrect. An alternate explanation for the deviation of experimental results from Eq. (1) at high microwave frequencies has recently been proposed by Hamilton and Shapiro[8] to explain their experimental data at 70 GHZ. Their theory uses Eq. (1) but takes into account the transverse spatial variation of the rf voltage across the junction. Since the free space wavelength, λ_o, of the electromagnetic radiation is reduced by a factor of approximately 20 in the oxide barrier,[9] this variation is important only at frequencies where $\lambda_o/20 \sim$ junction width. At 4 GHZ, $\lambda_o/20 \simeq 3.7$ mm, which is much larger than the junction width used in our experiments. Thus, the basic TG result, Eq. (1), can be expected to provide a correct theoretical description of our experimental data, while for frequencies $\gtrsim 40$ GHZ, $\lambda_o/20 \lesssim 0.37$ mm and spatial variation would have to be taken into account.

To summarize, we have observed excellent agreement between our low-frequency photon-assisted tunneling observations and the basic theory of Tien and Gordon over a wide range of microwave power levels, while the agreement with the theory of Cook and Everett has been found to be quite poor. We therefore conclude that the TG formula does in fact provide the correct description of the basic photon-assisted tunneling process, and that deviations from the TG formula at high frequencies are most probably attributable to spatial variation of the rf voltage induced in the junction.

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FIGURE CAPTIONS

Fig. 1. Typical I-V characteristics for a Sn-SnO-Pb junction at voltages near $\Delta_{Pb} + \Delta_{Sn}$. $I_o(V)$ is the measured bare current. $I_{TG}(V)$ was derived from Eq. (1) using $\alpha=19$, and $I_{CE}(V)$ was derived from Eq. (3) for the same value of α. The points are experimental. $I_{BCS}(V)$ is the current predicted by the BCS constant Δ model.

Fig. 2. $\Delta I(V,\alpha) = I(V,\alpha) - I_o(V)$ derived from measured I-V graphs for the junction of Fig. 1. P_D is the average power dissipated in the microwave cavity and V_o is an arbitrary voltage near $\Delta_{Pb} + \Delta_{Sn}$ chosen for convenience in data reduction. The α values were scaled as $(P_D)^{1/2}$ after fitting a theoretical $\Delta I_{TG}(V)$ to measured data at $P_D = 19.5$ mW (not shown).

Fig. 3. $\Delta I(V,\alpha)$ for a 6.35 Ω Sn-SnO-Sn junction at $\alpha = 1.8$. $\Delta I_{RF}(V)$ has been calculated from Eq. (2), using $V_{rf} = 1.8\ \hbar\omega/e$. The points are experimental values.

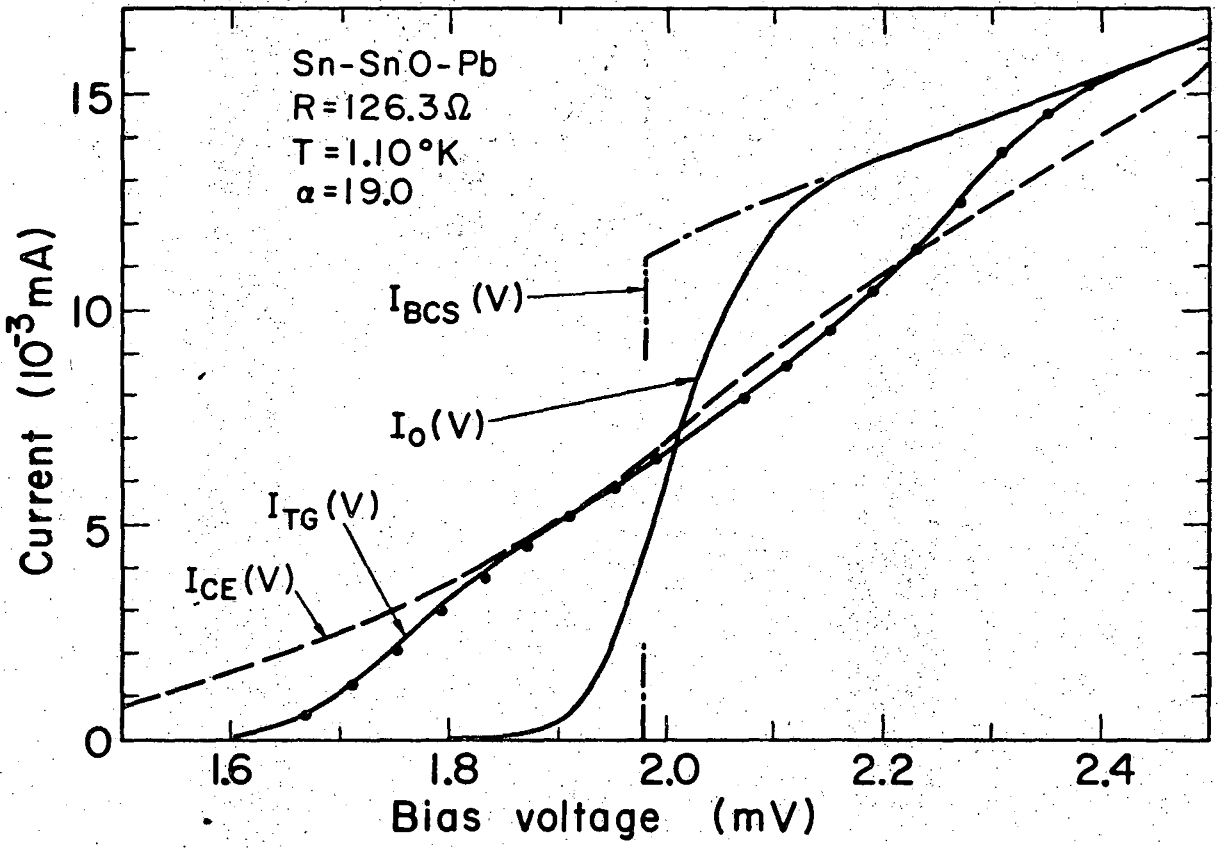

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Fig. 1

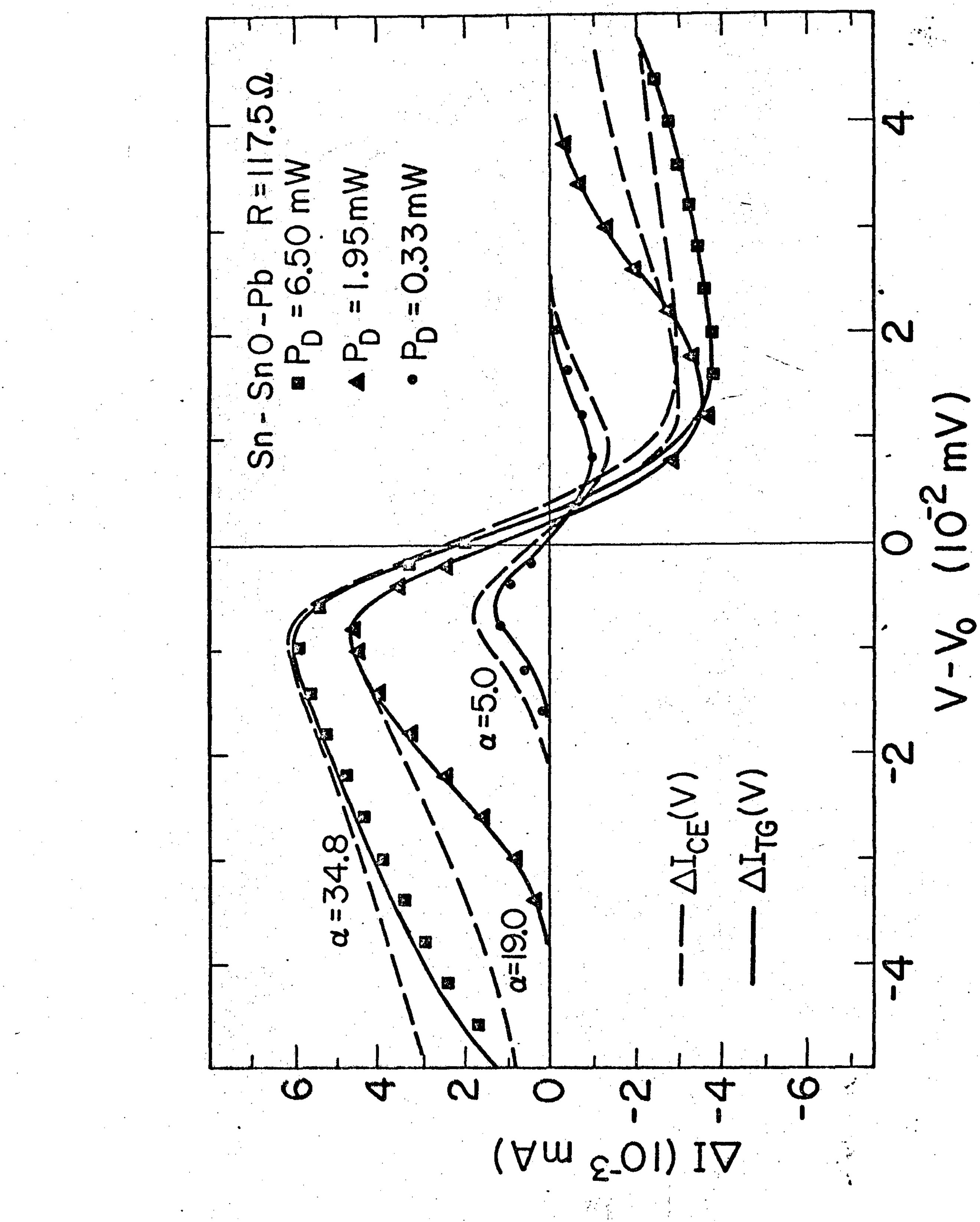

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Fig. 2

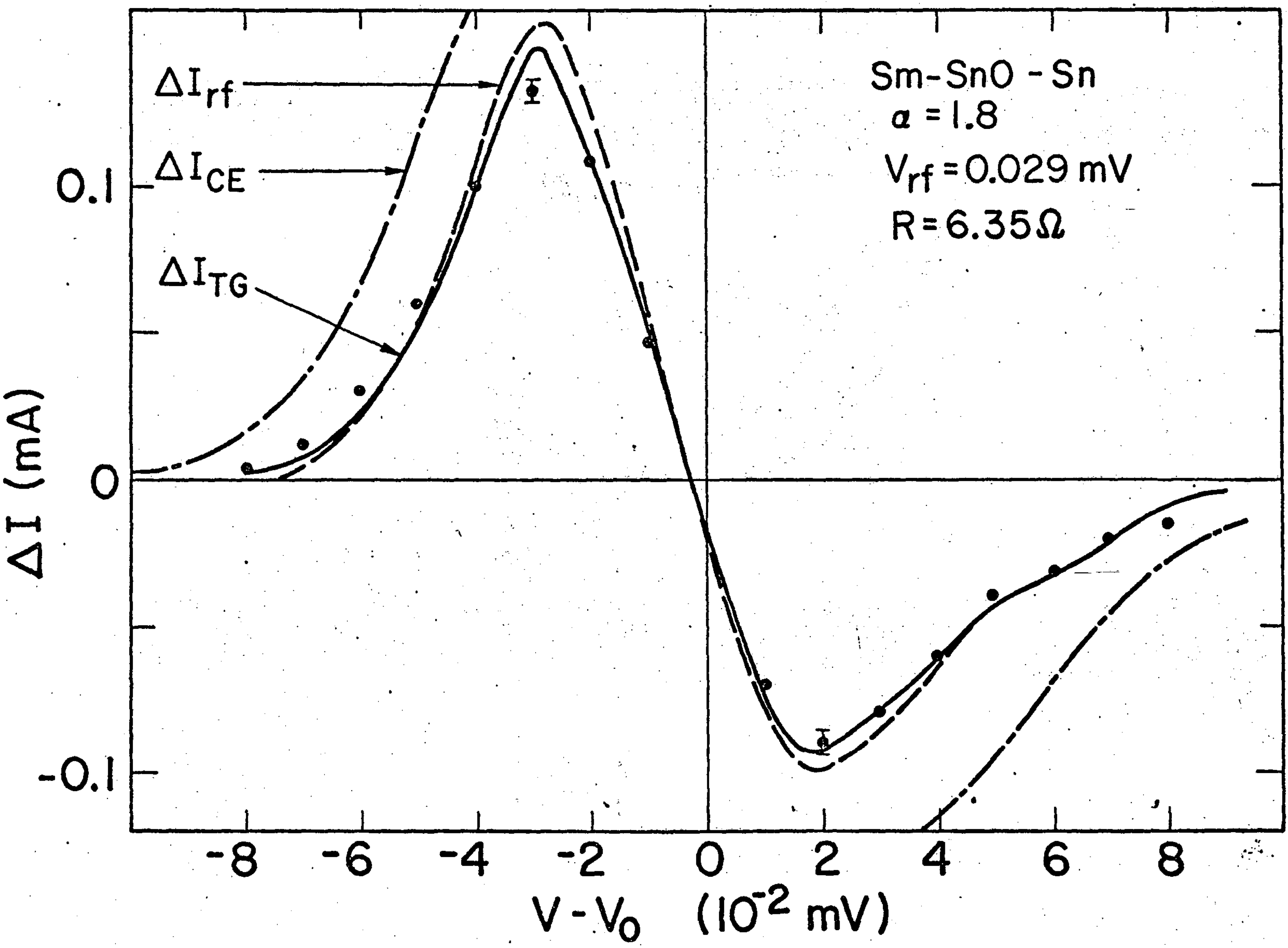

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Fig. 3

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