PHOTON-ASSISTED TUNNELING AND AC JOSEPHSON EFFECT AT 246 AND 604 GHz IN SMALL-AREA SUPERCONDUCTING TUNNEL JUNCTIONS

W. C. Danchi, F. Habbal, and M. Tinkham

Physics Department and Division of Applied Sciences
Harvard University, Cambridge, MA 02138

Abstract

We report the first observations of photon-assisted quasiparticle tunneling and AC Josephson effect in superconducting tunnel junctions irradiated with far-infrared (FIR) radiation. Radiation at 246 GHz (λ=1.22 mm) and 604 GHz (496 μm) from an optically-pumped FIR laser source was used. Tin-tin oxide-lead junctions of ~1 μm² area were fabricated on crystal quartz substrates with integral planar dipole antennas of resonant length at the frequency of the incident radiation. The observed photon-assisted tunneling features are in excellent agreement with the Tien-Gordon theory, and the inferred responsivity approaches the quantum limit at low temperatures for photon energies less than the gap. At 604 GHz, with a 176 ohm junction, we have seen 7 Josephson steps, compared to point contact performance. The variation of the step widths with laser power is found to agree quite well with both the RSJ model and the Werthamer theory. For low resistance junctions (e.g. 16 ohms), we find the Josephson steps to be flat and to agree well with the shape predicted by the RSJ model without noise rounding, while noise rounding is very evident with the higher resistance junctions. In all cases the step shape is in reasonable agreement with the theory of P. A. Lee, using a noise temperature of 10-20K with an appropriate small junction capacitance.

Introduction

Since the discovery of the Josephson effect and the photon-assisted tunneling effect in superconducting junctions, considerable effort has been expended to employ these junctions as practical devices. In particular the quasiparticle tunneling response appears attractive for detection and mixing circuitry, as well as in high-speed computing and sampling circuitry, as well as in high-frequency detector applications. Knowledge of the high-frequency roll-off of the ac Josephson effect in a tunnel junction, which has been treated theoretically, rather than in a point contact, for which the theory may not apply in detail, can provide useful information for electronic applications at both FIR frequencies and picosecond time scales.

High junction capacitance has hindered experiments in the submillimeter domain. Prior to this work, only point contacts had shown Josephson steps in the far-infrared (FIR), but these suffer mechanical instabilities which limit their potential usefulness. The advent of photolithographically-fabricated small-area tunnel junctions has made it possible to reduce junction capacitance to a tolerable level, making our FIR investigations possible.

In this paper we review our experimental results to date on the behavior of small-area tunnel junctions in the FIR frequency domain. After presenting the experimental techniques used to fabricate our samples and couple FIR radiation into them, we discuss the photon-assisted tunneling effect and the variation of the ac Josephson effect with incident power, and finally we present our preliminary analysis of the effect of noise on the width and shape of FIR-induced steps.

Experimental Techniques

Our small-area junctions were fabricated at the center of resonant dipole antenna structures designed for coupling to FIR radiation. Photoresist stencils were prepared on quartz substrates using the techniques of Dunkleberger and Dolan. A photoresist "bridge" of thickness ~1.0 μm was suspended above the surface of the substrate by 1.5 μm thick photoresist supports on either side, with a thin (~500 Å) layer of aluminum between the photoresist layers in order to separate them. The substrates were attached to a rotatable sample holder which was cooled to liquid nitrogen temperature in a cryopumped evaporator with a base pressure of ~2x10⁻⁷ torr. Thin films were thermally evaporated from tungsten boat sources to form junctions using the "resist-aligned" technique described by Howard, et al. A layer of Sn was first evaporated at an angle of ~35° to the substrate normal, followed by a layer of Ge at 42° to the substrate normal. The Sn was oxidized by a dc glow discharge in pure oxygen at 30 mtorr for 30 to 60 seconds with 12 mA of current at 1.1 KV. Finally a layer of Pb was deposited at ~50° to the substrate normal. In Figure 1(a) we display an SEM photo of the junction-antenna structure. A closeup of the junction region is shown in Figure 1(b). The area of this junction is 2.4 x 10⁻⁴ cm², and Jc is 1.1x10⁹ A/cm² at T=4.4 K. A typical junction has a small area that reduces the capacitance to the range of 0.01 to 0.05 pF, and yields a normal resistance range of 15 to 400 ohms.

![Fig. 1.](image)

(a) SEM micrograph of typical sample with ~5μm linewidth and overall length of 182 μm for the dipole antenna. At the center of the antenna is the tunnel junction. (b) Closeup of the junction region in (a).

The antennas used had lengths which were scaled to the FIR laser wavelength according to the design rules of Mizuno, et al., which take into account the substrate thickness (2.5x10⁻² cm) and index of refraction (n=2.34), so that the antenna is resonant at a given frequency. For the 496 μm laser line, we used a 182 μm antenna length, and for the 1.22 mm line a length of 431 μm was used. The source of the incident radiation is a home-made FIR laser, optically pumped by a CO₂ laser. The 496 μm laser line was produced by pumping the CH₃F gas at a pressure of ~50 mtorr, with the 9P(20) CO₂ pump line at 9.61 μm. For the 1.22 mm line, we used CH₃F at a pressure of 60 mtorr using the
9P(32) line of the pump laser. The linearly polarized radiation, E_{H}I_{2} mode, forms a Gaussian beam which is focussed through the transparent substrate onto the junction-antenna structure (which is on the back side of the substrate) by an f/4 TPX lens and an electro-formed copper cone. The antenna coupling depends strongly on polarization, being nearly zero for radiation polarized perpendicular to the antenna. The beam intensity (-10 mW) is monitored by a thermal detector fed by a beamsplitter. Unfortunately, the overall coupling efficiency is poor, and only a few tenths of a microwatt of the laser power is coupled into the junction. Nevertheless, sufficient radiation was coupled to allow us to observe as many as seven Josephson steps and six photon-assisted tunneling steps in some high resistance junctions.

Results and Discussion

FIR-induced steps, due to photon-assisted tunneling (PAT) and to the ac Josephson effect, were observed when the junction was irradiated. The number of steps observed depended on the intensity of the coupled radiation, and the shape of the steps was also affected by noise. Essentially, we can distinguish two types of responses. In the low resistance, large-area junctions (R=200, A=2x10^{-8}cm^2), we find flat steps, free of noise rounding; but the low impedance of these junctions causes a severe impedance mismatch between junction and antenna, so that only a small fraction of the FIR power is coupled into the junction and hence only a few steps are observed. The behavior of the high-resistance small-area junctions (R=176, A=0.5x10^{-8}cm^2) is quite different. More steps can be observed, but noise causes marked rounding and a slight slope in high voltage steps. In Fig. 2 (solid curves) we display the effects of the FIR radiation on two junctions, one a 176 ohm junction irradiated with 604 GHz radiation, shown in the left part of the figure, for two different laser powers; the other is a 176 ohm junction driven by 246 GHz laser radiation. Each junction was at the center of an antenna of properly scaled length.

PAT Steps

The Tien-Gordon theory8 of photon-assisted tunneling predicts that, upon irradiation of the junction, the dc I-V curve will have the form of a weighted sum of the dc I-V curves obtained without the radiation, each displaced in voltage by \( n\hbar\omega_{L}/e \), and appearing with weight \( J_{n}(a) \). That is,

\[
I_{dc}(V) = \sum_{n=-\infty}^{\infty} J_{n}(a)I_{dc}(V-n\hbar\omega_{L}/e)
\]

where \( J_{n}(a) \) is the nth-order Bessel function, and \( a \equiv eV_{l}/\hbar\omega_{L} \), with \( V_{l} \) being the (inferred) laser radiation voltage across the junction.

In order to compare our data with this theory, we fitted the I-V curves obtained at different values of \( a \), using theoretical curves calculated by digitizing the experimental dc I-V curve obtained at \( a=0 \), and then using (1) to compute the I-V curve for a given \( a \). The constant of proportionality (for a given sample and frequency) between the square root of the thermal power meter reading and the parameter \( a \) was determined both by fitting (1) and by fitting the theoretical \( a \)-dependence of the Josephson step widths. Since these two independent methods gave results consistent to 5%, we are quite confident of our internally calibrated determination of \( a \) from the power meter reading. As can be seen in Fig. 2, the Tien-Gordon theory (dashed lines) gives a good fit to the PAT steps, and, although (1) completely ignores the Josephson effect, it gives a good account of the entire I-V curve shape except for the Josephson steps themselves.

We also applied similar analysis to data obtained at \( T=4.2K \), where the Josephson effect is absent, because \( T>Tc(\text{Sn}) \). I-V curves for those S-I-N (Superconductor-Insulator-Normal metal) junctions, without and with radiation, are shown in Fig. 3. The agreement between theory and experiment is very good, so that on the scale of Fig. 3(a), one can not distinguish between the theoretical and experimental curves. To be able to discern any differences, in Fig. 3(b) we compare the experimentally determined dV/dI with the theoretical expression. For \( a=0 \), the large peak, reflecting the nonlinearity at \( V=V_{q} \), is obtained, and for \( a\neq0 \), minima and maxima occur with period \( n\hbar\omega_{L}/e \). The position and magnitude of the maxima and minima agree well with the theory. (dashed lines in Fig. 3(b)).

The theoretical current responsivity, \( R \), which determines the detection efficiency of the junction, can be calculated from the dc I-V curve using the Tucker9 result, which, in the limit of low power, is

\[
R = \frac{I_{dc}(V+\hbar\omega/e) - 2I_{dc}(V)-(\hbar\omega/e)}{I_{dc}(V+(\hbar\omega/e)) - I_{dc}(V-(\hbar\omega/e))}
\]

(2)

Here the numerator and the denominator are proportional to the quantum generalizations of \( d^{2}I/dV^{2} \) and \( dI/dV \), respectively. The responsivitiy reaches its quantum limit, \( e/\hbar\omega_{L} \), when for each photon absorbed an additional electron tunnels through the barrier. In Fig. 4, we plot \( R \) as a function of the bias voltage for a junction irradiated at 604 GHz. Using (2) with either the experimental or the theoretical \( I_{dc}(V) \) for \( T=0.2K \) (which differ hardly at all), we find that the highest...
voltage.

There is good agreement among these various experimental and theoretical results. It occurs at $V_g$, where we would expect the nonlinearity of the geometric limit to be greatest. For comparison, we show, in solid curves, data in Fig. 3(a). Inset shows computed frequency dependence of $R/e/h$ for various values of $F$.

No gross error could enter from using this result, because the theoretical ratio never differs by more than 50% from the normal state value $1/R_0$. There is good agreement among these various experimental and theoretical results. It is interesting to note that at $T=0$, $R$ is predicted to reach the full quantum limit over a small voltage range near the gap voltage.

The variation of $R$ with frequency, as predicted by (2), for a junction biased at $V_g$ is shown in the inset of Fig. 4. At $T=0$, $R$ is predicted to have the full quantum-limited value up to the gap frequency, where $h=2h$. At higher frequencies, $R$ decreases rapidly, reflecting the fact that the nonlinearity of an S-I-N junction is limited to an energy range $2h$. For $T>0$, $R$ falls below the quantum limit at all temperatures. There is good agreement between our experimentally inferred results (solid circles) and the theoretical predictions.

It is worth mentioning that the remarkable agreement between the Tien-Gordon theory, which assumes a voltage-biased junction, and our findings is presumably due to the presence of sufficient junction capacitance to cause a voltage biasing for ac, although the junction is current-biased at dc.

**Josephson steps**

Below $T_c(Sn)$, the junctions are S-I-S ones, and Josephson steps are observed in addition to the PAT steps. Some of the data taken at $1.4K$ are shown in Fig. 2. The Josephson steps occur at a dc voltage given by $n e/h$, where $n$ is an integer. The power dependence of the widths of the different steps is shown in Fig. 2(a) for the junction biased at $4.2K$, and in Fig. 2(b) for a $1.6K$ junction irradiated at 246 GHz. The solid curves are the predictions of the Werthamer theory, and the dashed curves are the RSJ model predictions, which actually are little different. The assumption of voltage bias at the laser frequency, which is common to both models, is probably justified by the high frequencies used, which heighten the effect of both capacitive and resistive shunting relative to the inductive Josephson supercurrent. Unfortunately, our experimental data are insufficient to clearly discriminate between the predictions of the two models, both of which fit the data reasonably well; on theoretical grounds the Werthamer theory is expected to be more correct. An obvious problem with these fits is that scaling factors of -2.0 are required to bring the predicted step widths up to those observed, if one normalizes them to the observed $I_p$ (zeroth step width with no radiation present). We believe this discrepancy reflects the impact of noise currents in reducing the apparent $I_p$ in these weakly coupled junctions, as discussed in the next section.

**Noise current effects on the PAT steps**

As noted earlier, noise-rounding effects are unimportant in our lower-resistance, higher-critical-current junctions. That is, the $I_p$ product computed using the nominal $I_p$ is close to the theoretical value for a Sn-Pb tunnel junction. Moreover, the Josephson steps are flat and fitted very well by the simple RSJ form without noise rounding, as is illustrated in Fig. 6, which shows a step at $2.5 mV$ in a $162K$ junction.

This situation is in clear contrast with that which prevails in the higher resistance junctions which give the best coupling to radiation. In these, the nominal $I_p R$ product falls increasingly below the theoretical value as $R$ increases, the discrepancy reaching a factor of -0.1 in a $400K$ junction. The systematic nature of the deviation suggests a fundamental origin, and we suggest that this may be the reduction of the apparent $I_p$ by noise rounding. To test this conjecture, M. Octavio has carried out computer modeling of a capacitively-shunted Josephson tunnel junction with noise current, and he finds that the sweep of the $I_p R$ data can be well fitted in this way using reasonable parameter values ($C = 0.01 pF$, $T_i = 10K$). Given such a large depression of the dc critical current by noise currents, it is obvious that they would be expected to affect the higher Josephson steps as well. For example,
if the effect of the noise in narrowing the finite voltage steps was significantly less than that on the zero-voltage step, it could account for the need to scale up the ratios $I_n/I_c$ by a factor of -2 in Fig. 5.

In addition to narrowing and rounding the steps, the noise gives them appreciable differential resistance, i.e., they are not flat. To avoid the computational effort of full computer modeling, we have attempted to fit the step shape using the analytic result of P. A. Lee. This is valid in the limit $R_c < 1$, and in the limit of zero capacitance, it reduces to the result of Ambegaokar and Halperin which was used earlier to analyze the noise rounding observed with point contacts. Since $R_c = 2$ in our junctions, the approximation for $R_c < 1$ is not strictly applicable, but we assume nonetheless that this approach will give us a reasonable indication of the effect of noise on the steps.

In fitting our data, we assumed a value for $R_0$, the dynamic resistance near the step, given by the experimental curve, and used $C$, $T_{eff}$, and $I_0$ (the width of the $n$th step in the absence of fluctuations) as parameters. For example, as shown in Fig. 7, we obtain
reasonable fits for the 4th step in a 1760 junction using various combinations of C = 0.01-0.015 pF, Teff = 20-25K, and Ic = 2.2-2.5mA, but wider excursions in these parameter values gave significantly poorer fits. This fitted value of Ic is in reasonable accordance with the value computed using the Werthamer theory and the nominal IcR(-1.2 mV) determined in low R junctions at 1.4K. The capacitance value is also consistent with estimates based on the geometry. The elevated value of Teff may reflect the effect of shot noise at this high DC current level, or perhaps black-body radiation coupled from room temperature through the window/antenna system, or pickup of extraneous noise currents. Further experimental and theoretical work to clarify the noise properties of these junctions is presently underway.

Conclusion

In summary, we have reported the first observations of photon-assisted quasiparticle tunneling and of ac Josephson effect steps in superconducting tunnel junctions irradiated by far-infrared radiation. The photon-assisted tunneling is in excellent agreement with the predictions of the Tien-Gordon theory, implying responsivities near the quantum limit. The widths of the Josephson steps also are in good agreement with theoretical predictions if one takes account of finite capacitance and noise-rounding effects for Teff - 10-20K.

Acknowledgements

The authors are pleased to thank Dr. M. Octavio for sharing the results of his noise calculations with us prior to publication, and to thank M. Iansiti for his assistance. This research was supported in part by the Joint Services Electronics Program and the Office of Naval Research.

References