ac Josephson effect in small-area superconducting tunnel junctions at 604 GHz

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We have measured the ac Josephson effect in small-area superconducting tunnel junctions at 604 GHz ($\lambda = 496 \mu m$) using a resonant planar dipole antenna to couple the radiation into the junction. In a 176-$\Omega$ junction, we have observed up to the 7th Josephson step (at 8.75 mV), a performance comparable to that seen in point contacts. We also compare our data with the results of the RSJ model and of the Werthamer theory.

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Superconducting tunnel junctions have demonstrated great sensitivity as detectors of radiation in the millimeter wavelength range, especially using the nonlinearity of quasiparticle tunneling rather than the more complex nonlinearity of the Josephson effect. Junction capacitance has prevented their use in the submillimeter domain, however; only point contacts have shown Josephson effect steps in the far-infrared (FIR) spectral region, but these suffer mechanical instabilities which limit their potential usefulness.

The advent of photolithographically fabricated small-area ($\sim 1 \mu m^2$) high-current-density tunnel junctions has made it possible to reduce capacitance to a tolerable level. In this letter we report the first observation of Josephson steps and photon-assisted quasiparticle tunneling in such junctions excited with FIR laser radiation. Our measurements provide the first data on the Josephson effect at FIR frequencies in a tunnel junction, as treated theoretically, rather than in a point contact, for which the theory may not apply in detail. In addition, they provide information which may help evaluate the potential usefulness of such junctions for electronic applications at FIR frequencies or picosecond time scales.

To be able to couple FIR radiation into the junctions, we developed the following technique to fabricate a small-area tunnel junction at the center of a resonant dipole antenna structure. First, a suitable “suspension bridge” stencil of photoresist was prepared by the trilevel scheme of Dolan and Dunkelberger. Second, the thin-film evaporation/oxidation sequence of the resist-aligned technique of Howard et al. was used. Specifically, a base electrode of tin was thermally evaporated followed by a Ge layer which leaves only a small window of the Sn layer uncovered, the Sn base electrode was oxidized by a dc glow discharge in pure oxygen, and the Pb counter electrode was deposited. Figure 1(a) shows a scanning electron microscopy (SEM) picture of the junction-antenna structure. Figure 1(b) is a closeup of the junction region. The area of this junction is about $2.4 \times 10^{-8}$ cm$^2$ and $J_c = 1.1 \times 10^3$ A/cm$^2$ at $T = 1.4$ K.

The source of the incident radiation is a home-made FIR laser, optically pumped by a CO$_2$ laser. In this letter we report on the response of the junctions to 496-$\mu m$ (604 GHz) radiation obtained when using CH$_3$F gas as the lasing medium. Similar results were obtained when we used the 1222-$\mu m$ line of C$_3$H$_4$F. The linearly polarized radiation, EH$_{11}$ mode, forms a Gaussian beam which is focused onto the junction-antenna structure by an f/4 TPX lens and an electroformed copper cone. The antenna coupling depends strongly on polarization, being nearly zero for radiation polarized perpendicular to the antenna. The beam intensity ($\sim 10$ mW) is monitored by a thermal detector fed by a beam splitter.

Good coupling of the FIR radiation to the junction re-
The behavior of a high-resistance, small-area junction requires scaling the antenna length with the wavelength, which is done by modifying the mask used to pattern the photosresist. For the 496-μm radiation, we used an antenna of overall length 182 μm, which is estimated to be the proper length for a half-wave dipole on our crystal quartz substrate with \( \epsilon = 2.34 \) and thickness of \( 2.54 \times 10^{-7} \) cm.

We have studied the response of junctions of different resistances and areas. In the low resistance, large-area junctions (\( R \sim 20 \Omega, A \sim 2 \times 10^{-8} \) cm\(^2\)), we find flat steps, free of noise rounding, which fit the simple RSJ step shape very well. Unfortunately, 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 only a few steps are observed. In the particular junction shown in Fig. 2(a), where normalized voltage \( 2\alpha = 2eV_s/\hbar\omega_l = 1.6 \) is coupled, we observe four Josephson steps and one photon-assisted tunneling step.

The behavior of a high-resistance, small-area junction (\( R = 176 \Omega, A \sim 0.5 \times 10^{-8} \) cm\(^2\)) shown in Fig. 2(b), is quite different. Here \( 2\alpha \) as high as 8.4 was observed from the same laser power, and seven Josephson steps and six photon-assisted steps were observed. Notice that in this case, the steps are affected by the noise, which causes marked rounding and also a slight tilt (i.e., observable differential resistance) in the steps. The coupling of the radiation to the high resistance junction is very good; it produces steps at voltages as high as 8.75 mV, which is comparable to the performance (12.5 mV) obtained by Weitz et al.,\(^2\) using point contacts with long-wire antenna structures and the same laser source. However, unlike point contacts, which are mechanically unstable and have a variety of \( I-V \) curves depending on the nature of the contact,\(^6,7\) our junctions show excellent tunneling \( I-V \) curves. As a consequence of these well-characterized properties, it is possible to identify other features, such as the photon-assisted tunneling steps, not reported previously in the FIR spectral range. We find six steps originating from the gap structures at \( V_g = (\Delta_{SN} + \Delta_{po})/e \) and at \( -V_g \); they occur at voltages \( V = \pm V_g + N\hbar\omega_l/e \). We have not yet analyzed the structure of these photon-assisted steps in any detail; it may be necessary to suppress the ac Josephson steps to permit a quantitative fitting. However, we have studied the response of the junction at 4.2 K, where the Josephson effect is absent because it is an SIN junction, and followed the variation of the photon-assisted steps with power. Results of this work will be published later, when more detailed analysis is complete.

The variation of the Josephson step widths with power is shown in Fig. 3, where we plot the observed step half-width (normalized by the critical current in the absence of radiation) versus normalized laser radiation voltage \( 2\alpha \). To obtain \( 2\alpha \) from the square root of the power level measured on the reference thermal detector, we have chosen a single scaling factor for all steps for a given junction to take account of the coupling efficiency to that junction.

In the low-resistance samples, shown in Fig. 3(a), we obtain good agreement between theory and experiment for the \( n = 0 \) and \( n = 2 \) steps, but the predictions of the microscopic Werthamer theory and of the RSJ model are indistinguishable for the low values of \( 2\alpha \) which were attainable. For the \( n = 1 \) step, the Werthamer theory predicts an appreciably larger step than the RSJ model, but the data fall somewhat below both predictions. This discrepancy may be related to the apparent need to exceed a threshold power level before the \( n = 1 \) step appears, whereas the theoretical dependence is simply linear in \( 2\alpha \). Similar effects had been seen earlier in some point-contact data.\(^7\) It presumably is related to the fact that the voltage on the \( n = 1 \) step falls in the hysteretic part of the \( I-V \) curve below the energy gap voltage. (Our convention is to define the full width of a hysteretic step as the current separation between the jump up from the step in increasing current and the jump down from the step in decreasing current. Premature jumps, triggered by noise, could cause the measured width to underestimate the intrinsic width of these hysteretic steps.)

With the high-impedance junctions, such as the one shown in Fig. 3(b), larger values of \( 2\alpha \) were obtained, allowing more steps to be seen. This permitted a more complete test of the comparative quality of the fit to the Werthamer theory and to the Bessel function dependence of the RSJ model. However, the predictions of the two models actually differ rather little, because neither the signal frequency nor its harmonics are very near the Riedel peak frequency for a Sn-Pb junction, and the scatter of the data in these preliminary measurements limits our ability to discriminate between the two. Still the Werthamer theory appears to give

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**FIG. 2.** (a) Typical \( I-V \) curves of a low-resistance sample for increasing laser powers. Here, \( V_g = (\Delta_{pm} + \Delta_{so})/e \). (b) Typical \( I-V \) curves of a high-resistance junction for increasing laser powers. Note the decrease in the critical current and its subsequent increase. The voltage of the first Josephson step is indicated by a dashed line; the \( I-V \) curves were taken at power levels giving the first maximum of this step width and at subsequent zeroes. The current step at the gap is also identified by dashed lines.
a slightly better fit to the observed positions of the zeroes of the step size. Neither theory fits the zeroth step very well. This step goes to zero more quickly than predicted by either theory; the same was true of the point-contact data of Weitz et al.\textsuperscript{21} It may be due to the fact that the zeroth step width is reduced by square-law detection of noise at all frequencies in addition to the effect of the laser radiation. In making the fits of the absolute step widths to both models, a scaling factor of 2.0 was required. At present we attribute the need for this scaling factor to a possible underestimate of the normalizing denominator $I_e$, because of the above-mentioned noise and fluctuation effects in these high-resistance junctions, in which the nominal $I_e R$ product is well below the theoretical value. This constant scale factor, exceeding unity, contrasts with the observations of Weitz et al.\textsuperscript{9} on point contacts, in which the corresponding scale factors were less than unity, becoming more so with the higher steps, presumably due to increasing heating effects at the higher voltages. Moreover, even with all known corrections, the magnitude observed in point contacts was about a factor of 2 smaller than predicted by the theory. It is satisfying that our tunnel junctions give step widths which fit the theory with less need for corrections. This might be expected both because the theory was derived for a tunnel junction, not a point contact, and because heating effects are reduced in the tunnel case because the voltage drop occurs across a high-resistance barrier rather than in a metallic constriction with high-conductivity.

In summary, we have made the first observations of ac Josephson effect steps and of photon-assisted tunneling in small-area tunnel junctions at FIR frequencies. The dependence of the step widths on laser power is close to the predictions of both the Werthamer theory and the RSJ model. In general, the performance of the small-area tunnel junctions is similar to that of point contacts, but it is less affected by heating effects at high voltages.

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\textsuperscript{8}N. R. Werthamer, Phys. Rev. 147, 255 (1966).