Niobium point-contact Josephson-junction behavior at 604 GHz[a)]

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We have measured the ac Josephson effect in Nb point contacts at 604 GHz (496 μm). We find the coupling of the far-infrared radiation to the point contact to depend in a simple manner on the resistance of the contact. The behavior of the high-resistance point contacts ($50 \leq R \leq 200$ Ω) is very reproducible, allowing a quantitative comparison of the data to the frequency-dependent Werthamer theory. We also account for the effects of noise and heating and compare these to Tinkham's heating theory.

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Josephson-effect devices may hold great promise for use as detectors and mixers in the millimeter and submillimeter region of the spectrum. In order to fully evaluate their potential, it is essential to know the magnitude and frequency dependence of the ac Josephson effect. The best high-frequency performance is obtained with point contacts which have the reputation of being unstable and irreproducible, making quantitative measurements very difficult. This paper reports the first quantitative measurements of the ac Josephson effect at far-infrared (FIR) frequencies using a form of point contact that is reproducible and reasonably stable. By studying the power dependence of the constant-voltage steps induced on the dc *I-V* characteristics by a FIR laser, we have determined the behavior of the ac Josephson current. By studying the gap structure and step shape, we have determined the effects of heating and noise.

The optically pumped FIR laser was of the high-efficiency large-diameter ($1\frac{1}{2}$ in.) dielectric-waveguide type[1] operating on the 496-μm line of CH_3F. A grating-tuned CO_2 laser supplied about 20 W of pump power on the $P(20)$ (9.6-μm) line, and was focused by $f/50$ optics through a 3-mm-diam hole in the back mirror of the 3-m-long FIR cavity. The FIR output coupler was a 100-line/in. Al capacitive mesh on crystal quartz.[2] The laser was always operated in the EH_{11} mode, producing about 10 mW cw of linearly polarized radiation in a nearly Gaussian output beam. The intensity was controlled by attenuators and monitored by a thermal detector fed by a beam splitter. An $f/4$ polyethylene lens focused the output onto the point contact through two crystal quartz windows in the side of the Dewar.

The point contact was formed between a 75-μm-diam niobium wire sharpened by standard electroetching techniques and a polished etched 12-mm-diam Nb flat. The wire itself served as an antenna to couple to the radiation,[3] with a 90° bend defining an antenna length of somewhat less than 500 μm. The incident laser radiation was polarized with a component of its E vector along the antenna. A differential screw mechanism drove the flat and allowed the contact to be formed and adjusted in liquid helium. The desired *I-V* characteristics were normally obtained by first mechanically adjusting the flat to make a very-high-resistance ($\gtrsim 500$ Ω) contact, and then reducing the resistance with a "burn-in" process[4] using about 2 V p-p at 35 Hz. Both sides of the point contact were exposed to atmosphere for as short a time as possible after final etching to produce a "clean" contact as evidenced by a high $I_c R$ ($\gtrsim 1.8$ mV). We were able to obtain high-resistance point contacts ($10 \lesssim R \lesssim 200$ Ω) that normally remained stable over the 2–3 h necessary to perform the experiments.

Typical dc *I-V* curves are shown in Fig. 1. This type of *I-V* curve is used for high-frequency mixing[5] and is characterized by a high $I_c R$ product, a very sharp but non hysteretic voltage onset to $V \approx \frac{1}{2} I_c R$, and a current increase at the gap voltage ($2\Delta/e \approx 2.8$ mV). The constant-voltage steps occurring at 1.25 mV intervals are shown for two values of laser amplitude (2α). We have seen steps up to the 10th harmonic at 12.5 mV using only this rather insensitive dc detection technique. This is a higher voltage than any laser-induced step previously reported in the literature.

One measure of the coupling of the radiation to the point contact is the laser power required to produce the maximum current width of the first step, which ought to occur at a particular value of the induced ac voltage, independent of the junction resistance. The lower part of Fig. 2 is a plot of the square root of the required laser power as a function of junction resistance. The

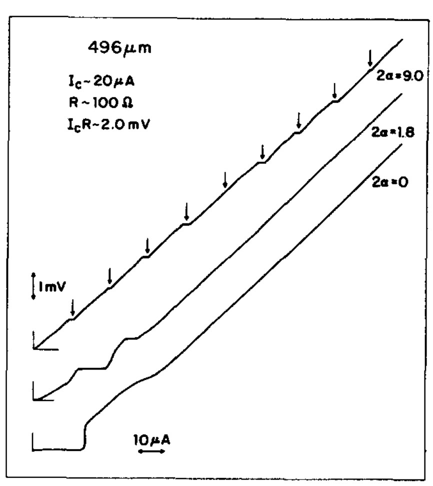

FIG. 1. Typical dc *I-V* curves at increasing laser powers.

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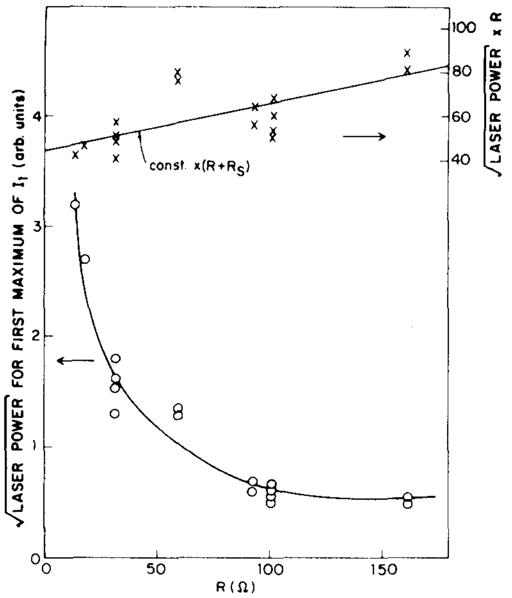

FIG. 2. Coupling effects. Lower curve is the square root of the laser power required to produce the maximum width of the first step as a function of junction resistance. Upper curve is the product of this times the resistance, with the solid line consistent with coupling from a source resistance R_s, of ~200 Ω.

large rise at low R suggests that the low-resistance junctions are effectively current biased. This is borne out by the plot in the upper half of Fig. 2 which shows the product of the square root of the required laser power times the junction resistance; the line through the points represents the coupling from an ac source resistance of ~200 Ω which, presumably, reflects the antenna resistance. Thus, the high-resistance junctions are very well matched both to the antenna and to free space.

Using the well-matched higher-resistance junctions, we are able to see seven or more steps, and we get very reproducible step-width data. A composite plot of the power dependence of the critical current and eight steps induced by 496-μm radiation is shown in Fig. 3 with data from five different point contacts having resistances between 50 and 170 Ω. The half-widths of the experimentally measured steps are normalized to the critical current at zero power and are plotted as functions of the square root of the laser power. The power measurements are scaled once for each junction to account for its coupling efficiency.

The consistency of the data from junction to junction allows a quantitative comparison to theory. The solid lines in Fig. 3 represent the fit to Werthamer's theory[6] with the approximation of purely voltage sources for both the ac and dc biases. The theory is derived for a tunnel junction (rather than a metallic constriction) and includes the frequency dependence of the supercurrent. In the low-frequency limit, the Werthamer theory reduces to the usual Bessel function theory (dashed lines in Fig. 3). The frequency-dependent theory is a better fit, particularly for the first zero of the critical current and for the second humps of the critical current and of the second and fourth steps. The improvement is due mainly to the contribution of the second harmonic frequency component at 1.21 THz (2.5 mV), where the magnitude of the supercurrent has risen as it approaches the Riedel peak at 1.35 THz (2.8 mV). Both theories predict step widths much larger than those actually

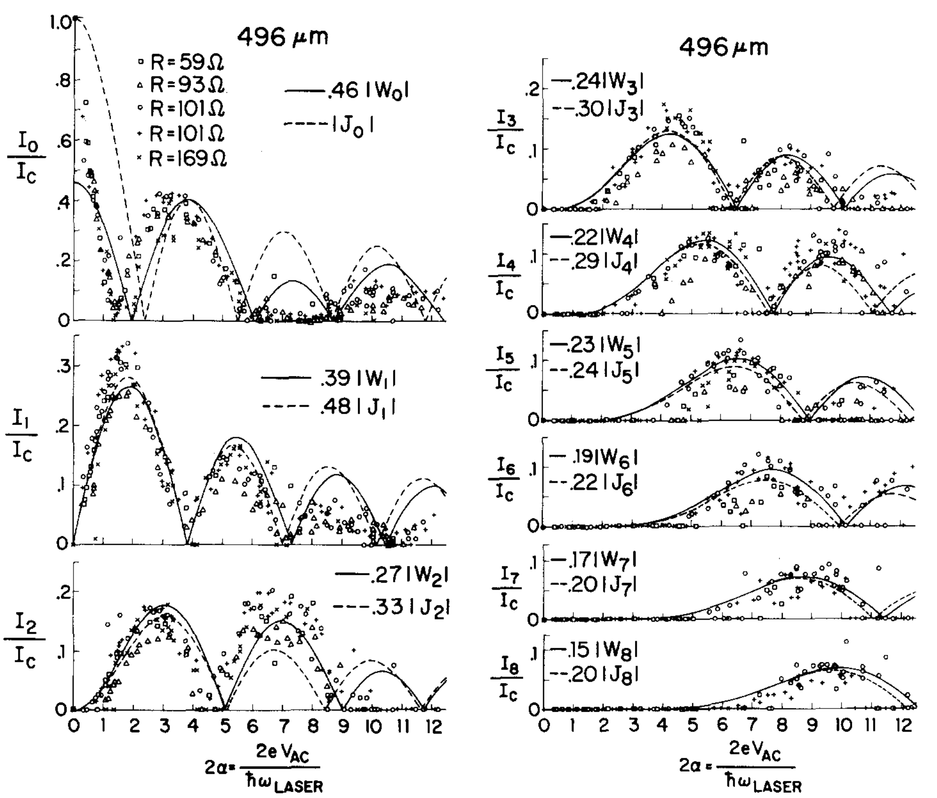

FIG. 3. Normalized step-width behavior as a function of induced laser voltage compared to the Bessel function (J) and the frequency-dependent Werthamer theory (W). This is a composite plot made from the data of five different junctions.

observed. For quantitative agreement with the data, the theoretical values must be decreased by the step-dependent scale factors indicated in Fig. 3. To account for this decrease, we have investigated the effects of capacitance, heating, and noise.

We have considered the effects of a capacitance shunting the high-frequency supercurrent oscillations by adding a capacitive rolloff to the step-width calculations using the frequency-dependent Werthamer theory. If the $(RC)^{-1}$ cutoff is below the gap frequency $(2\Delta/\hbar)$, the effect of the Riedel peak is lost and the improvements of the Werthamer theory over the Bessel functions disappear. Any smaller capacitance cannot account for the observed decrease.

A recent theory[7] has shown that heating will reduce the step widths by $\exp(-P/P_0)$, where P is the total power dissipated and P_0 is a characteristic power level predicted to be about 10 μW for typical Nb-Nb point contacts. Other measurements[8] on these point contacts, using the gap structure on the I-V curve as a local thermometer, imply heating parameters which lead to a P_0 of ~12.5 μW. Even at the highest voltages and laser powers used in this experiment, the total dissipated power in a typical 100-Ω junction is ~1.5 μW which will cause only a 10–15% reduction in the step widths. Moreover, the scale factors do not cut off exponentially as they would if heating were the cause of the observed decrease. Finally, we find no significant difference in normalized step widths for junctions with resistances varying from 50 to 170 Ω, while the dissipated powers vary as $1/R$. Thus, we conclude that though heating may cause a small reduction in step width, mainly on higher steps, it will not account for the much larger decreases actually measured.

Fluctuations in the phase due to noise can round the edges of the steps[9,10] and reduce the measured step widths. We have used a two-parameter fit to compare our step shapes to those predicted by Stephen's theory[9] and have obtained the effective noise temperatures and the unrounded step widths. We find that noise reduces the step widths we measure by nearly 50% for the higher steps. The combined effects of noise and heating do not account for the full decrease in the measured step widths, but do remove most of the step-number dependence from the scale factors. There still remains a factor of approximately 2 that must be explained.

One possible cause for this remaining discrepancy between the data and the theory is our assumption of a voltage bias. In fact, the *current*-bias frequency-independent RSJ (resistively shunted junction) model does predict a reduction in the step widths[11] which is observed for lower resistance junctions and lower frequencies.[12] However, at 604 GHz, the frequency dependence of the supercurrent becomes relevant, and ~100-Ω point contacts are comparable to the impedance of the ac source. Thus, though the qualitative ideas of the current-bias RSJ model may be valid, more detailed calculations are necessary. We are currently using a time-domain formulation[13] of the Werthamer theory to investigate effects of a more realistic external circuit.

TABLE I. Comparison of the noise temperatures (T_N) predicted by Tinkham's heating theory with those (T_{FIT}) obtained from a fit of the step shape to Stephen's theory for the first eight steps induced by 496-μm radiation.

n	T_N (°K)	T_{FIT} (°K) (± 5°K)
1	5	5
2	7	15
3	10	10
4	12	15
5	15	15
6	17	15
7	19	15
8	22	20

The fit of the step shape to Stephen's theory[9] also resulted in the determination of an effective noise temperature for each step. These temperatures are listed in the last column of Table I, and are in excellent agreement with those in the second column, the predicted values using Tinkham's heating model.[7] This demonstrates a result that could be important for practical devices: even at power-dissipation levels well below P_0, where the reduction in the supercurrent due to heating is small, the effective noise temperature can still be significantly larger than the bath temperature.

In conclusion, we have made stable reproducible point contacts with $I_c R$ products very near the theoretical value. The high-resistance contacts are well coupled to FIR radiation at 496 μm, with the step-width behavior best described by a simple voltage-bias approximation using the frequency-dependent Werthamer model. The theoretical values are about a factor of 2 larger than the experimentally observed step widths even after the data are corrected for noise rounding. This noise rounding reflects the high noise temperature due to heating in the contact, and could be a significant limitation on the performance of a practical device.

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