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PROPERTIES OF JOSEPHSON POINT-CONTACT FAR-INFRARED DETECTORS

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Abstract—The far-infrared (FIR) properties of niobium cat-whisker point contacts were studied using radiation from an optically pumped FIR laser. The reproducible behaviour of junctions with excellent high-frequency performance allowed a measurement of the FIR frequency dependence of the strength of the a.c. Josephson effect. The shape of the laser-induced steps was used to measure the effective noise temperatures, which increase with bias voltage in agreement with a heating model of metallic constrictions. The high-quality junctions were tested as frequency-selective, incoherent FIR detectors, with the d.c. bias in the vicinity of the incipient laser step. The response was found to be linear in the laser power, and the best measured responsivity at 604 GHz was $\sim 2 \times 10^5$ V/W, while the best noise equivalent power was $\sim 10^{-13}$ W/Hz$^{1/2}$, with a 450 Hz chopping frequency. The NEP is limited by the voltage noise in the junction, which was found to have an approximately $1/f^2$ frequency dependence. The detector performance is degraded considerably at higher FIR frequencies. Also studied was the low-laser-power behaviour of the I–V curves near the critical current, which may be of importance for mixing applications with external local oscillators.

INTRODUCTION

The extension of the operating range of Josephson-effect devices to far-infrared (FIR) frequencies introduces questions concerning the frequency dependence of the Josephson effect above the superconducting-energy-gap frequency and the importance of additional noise resulting from the higher levels of dissipated power. By studying the effects of radiation from an optically pumped FIR laser on the d.c. I–V characteristics of Nb cat-whisker point contacts, we have been able to examine some of these issues.

Niobium cat-whisker point contacts were used for this work because of their good performance at high frequencies. Their relatively high impedance combines with their three-dimensional geometry to minimize the effects of Joule heating,(1) and to match(2) the resistance of the antenna formed by the whisker itself. As a result of a systematic study of the junctions obtained with our point contacts, we have identified the characteristic shape of the d.c. I–V curve of those junctions with the best high-frequency performance.(3) These junctions are quite reproducible from junction to junction, both in the shape of their d.c. I–V characteristics(3) and in their high-frequency behaviour.(2) Therefore, we have been able to measure the FIR frequency dependence of the strength of the a.c. Josephson effect,(4) which should be useful in determining the high-frequency limitations of Josephson-effect devices.

In an attempt to further characterize these junctions, we have measured their characteristic noise levels both with and without incident FIR radiation, and have studied their performance as a frequency-selective incoherent detector of FIR radiation. In the next section we describe the experimental techniques and apparatus used in our work. We then summarize the properties of junctions which show strong Josephson response at FIR frequencies, and show measurements of the intrinsic rolloff of the Josephson effect above the superconducting energy gap frequency. We also analyze the noise rounding of Josephson steps at high laser power levels, which is consistent with heating-enhanced Johnson noise but not with shot noise. We examine the response of the junctions to low levels of FIR laser radiation in the vicinity of the incipient step. The minimum detectable power in this case is limited by low frequency voltage fluctuations, analyzed later in this paper. Finally, we note the peculiar behaviour of the d.c. I–V curves near the critical current when our junctions are irradiated by low levels of laser radiation, which may be of importance in mixing applications with an external local oscillator. The results of this work are summarized.

EXPERIMENTAL

The optically pumped FIR molecular laser used in these experiments had a 3 m long, 38 mm dia. dielectric waveguide cavity(5) with two flat end mirrors. One mirror was mounted on a translation stage for tuning the cavity and had a 3 mm dia. central coupling hole through which the CO_2 pump radiation was introduced. The second mirror was a capacitive mesh output coupler(6) for the FIR radiation. A grating-tuned CO_2 laser, whose output coupler was mounted on a PZT stack for fine frequency control, supplied ~20 W of pump power, which was focused into the FIR cavity by an $\sim f/50$ mirror. By changing the CO_2 pump line, lasing gas, and mesh constants of the output coupler, FIR output was obtained at wavelengths from 42 μm to 1.2 mm. Typical output powers were ~10 mW on the stronger lines with up to ~80 mW on the strongest line. The laser was always operated in the EH_{11} mode, which gave a linearly polarized output beam with a nearly Gaussian profile for good focusing. An $\sim f/4$ polyethylene lens focused the FIR radiation onto the point contact through two crystal quartz windows in the side of the Dewar.

The point contacts were formed between a polished Nb flat and a 75 μm dia. Nb wire, sharpened by standard electroetching techniques. A bend in the wire defined an antenna that was ~500 μm long which helped to couple the junction to the FIR radiation.(7) The coupling was further enhanced by using relatively high-resistance junctions that were well matched to the antenna and to free space.(2) The position of the flat could be adjusted by a differential screw, controlled from the top of the Dewar. Using a combination of mechanical adjustment and electrical burn-in, the junctions were formed and adjusted while they were immersed in liquid helium. With these techniques,(3) we were able to obtain junctions with desirable characteristics that remained stable over the few hours necessary to make the required measurements.

Low-level voltage measurements were made with a PAR 124 lock-in amplifier, using the PAR 116 plug-in preamplifier in its transformer mode. The power spectrum of the voltage fluctuations was measured using the a.c. voltmeter mode of the PAR 124 with its tuned input amplifier set for narrow bandwidth ($Q = 100$). All leads were brought through r.f. filters at the top of the metal Dewar to eliminate spurious pick-up. The frequency-dependent transfer function of the filter–transformer combination was measured and the data were corrected for it. The background noise, as measured across a 100 Ω resistor at 4.2 K, was subtracted from the data. This background noise was ~0.8 nV/Hz$^{1/2}$ at 450 Hz, but was considerably higher at odd harmonics of 60 Hz, so that we avoided these frequencies.

CHARACTERISTICS OF 'IDEAL' JUNCTIONS

The bottom curve in Fig. 1 shows the d.c. I–V curve of a typical 'high-quality' point contact.(3) This type of junction always couples very well to the laser radiation and shows a strong a.c. Josephson effect well above the energy gap. Such junctions are also quite reproducible from junction to junction both in the characteristic features on their d.c. I–V curves(3) and in their high-frequency behaviour.(4) They are characterized by an I_cR product typically within ~20% of the theoretical value of ~2.2 mV, a very steep voltage onset to a voltage $V_j \approx 0.5\, I_cR$, pronounced structure at the energy gap, and an excess current that extends to ~30–50 mV and has a value of $I_{ex} \approx 0.8\, I_c$ just above the energy gap. The gap structure always takes the form shown in Fig. 1, and is well characterized by its sharpness, S, defined as the ratio of the differential resistance just above the gap (R) to that just below the gap (r). High-quality junctions always have $S \gtrsim 2.0$, and the highest voltage still showing the a.c. Josephson effect increases roughly linearly with S. These features on the d.c. I–V curves allow identification of junctions with good high-frequency performance.

The top three curves in Fig. 1 show the fundamental laser-induced step for various FIR laser wavelengths. The maximum of the first step normalized to the zero-power critical current, I_1^{max}/I_c, is a measure of the intrinsic strength of the a.c. Josephson effect

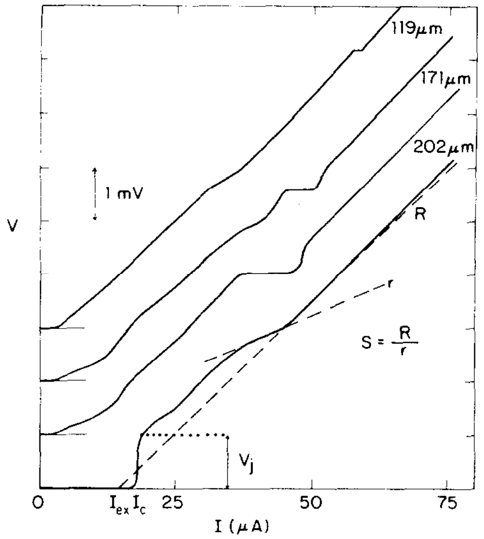

Fig. 1. Typical d.c. I–V curves of a high-quality junction. The lowest curve is with no incident radiation, while the upper three curves show the fundamental steps induced by radiation of different FIR laser wavelengths.

at the step voltage and is plotted for a number of FIR laser frequencies in Fig. 2. The solid dots represent the raw data, while the ×'s represent an estimate of the step size corrected for the effects of noise rounding(8) and heating.(1) The strength of the Josephson effect rolls off above the gap frequency, as suggested by a simple voltage-bias version of Werthamer's frequency-dependent self-coupling theory.(9) At the two lower frequencies, better agreement with the data is obtained using a more realistic *current* bias (as in the RSJ model), but the quantitative discrepancy with Werthamer's theory above the gap is not yet understood. Nevertheless, the data confirm the intrinsic rolloff of the strength of the Josephson effect above the gap frequency.

A fit of the shape of the laser-induced step to the prediction of the noise-rounded RSJ model(8) yields the effective noise temperature, T_{eff}, at the step voltage. Using the 496 μm laser-induced steps, we have measured T_{eff} as a function of bias voltage, and

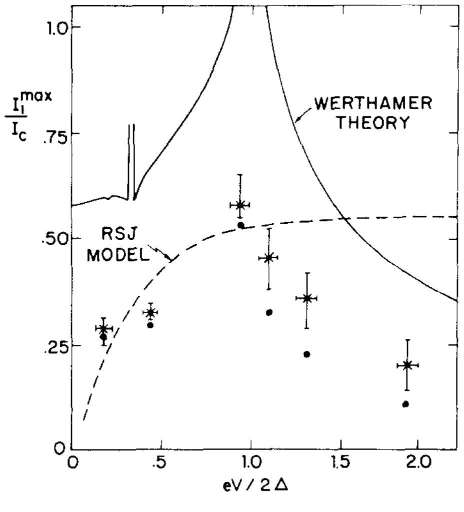

Fig. 2. Frequency dependence of the strength of the Josephson effect. The maximum current half-width of the fundamental laser-induced step, normalized to the zero-power critical current, is plotted against the step voltage, normalized to the energy gap. The solid dots represent the measured data, while the crosses with the error bars represent our best estimate for the values corrected for the effects of noise rounding and heating.

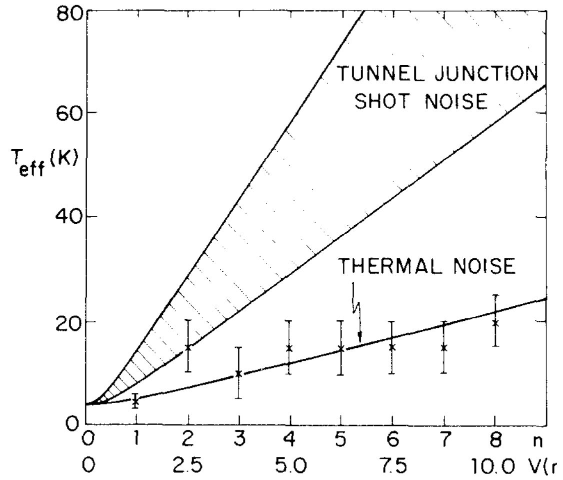

Fig. 3. The effective noise temperatures, from a fit of the shape of the 496 μm laser-induced steps. The data is in good agreement with the calculated T_{eff} due to the heating-enhanced Johnson noise of a metallic constriction, but is substantially less than the shot noise predicted for a tunnelling-type contact.

plot the results in Fig. 3. The measured values are in good agreement with the noise temperatures predicted by the heating theory of Tinkham *et al.*(1) In this theory, it is assumed that the junction is a metallic constriction, and the local temperature distribution due to power dissipation from both the d.c. and the laser-induced currents is calculated. An average of this local temperature weighted by the contribution of each element of the constriction to the resistance of the contact gives an effective Johnson noise temperature, T_{eff}. As shown in Fig. 3, the data seem inconsistent with the much higher T_{eff} due to shot noise expected for a *tunnelling* type of contact(8) at these voltage levels. The level of shot noise would depend on the relative amounts of 'pair' and quasiparticle currents, but would be expected to fall within the shaded region in Fig. 3. It is possible that a metallic constriction might also show shot noise, but only if its dimensions were much less than the electron mean free path in the vicinity of the constriction,(10) which appears not to be the case in our point contacts.(1) Nevertheless, these noise temperature data support other experimental evidence(3) which suggests that junctions like ours are modeled better as small metallic constrictions than as tunnel junctions.

The reproducibility and consistency of the high-quality junctions has prompted us to suggest that they are approaching the 'ideal', clean, low-capacitance point contact.(4) However, the primary goal of our work has been a study of the high-frequency Josephson effect, and the main criterion for classifying and optimizing our point contacts was the existence of large Josephson steps well above the energy gap. These junctions may in fact not be the optimum ones for some practical device applications, in which the Josephson effect at these very high frequencies might be less important. For example, stability requirements may favour more-oxidized junctions, even though their high-frequency performance is more limited. The difficulty in maintaining a stable d.c. bias on the very high dynamic resistance of the voltage onset of our 'ideal' junctions may also limit their use as mixers. However, in cases where excellent high-frequency performance *is* essential, junctions like these probably will be necessary.

LOW-POWER LASER MEASUREMENTS

In order to characterize further the high-frequency performance of our junctions, we have investigated their voltage response to low-level laser radiation, when the d.c. bias is in the vicinity of the incipient first step. Frequency-selective, incoherent detectors operated in this mode have been proposed,(11–13) although much better sensitivity has been attained with Josephson-effect mixers using external local oscillators.(14,15)

We have been primarily interested in the intrinsic response of the junction itself, and have not addressed the very important practical issue of optimizing the coupling efficiency of the point contact to the laser radiation. All of our measurements are referred to the power actually coupled into the junction. This was done as follows. Initial measurements on each junction were made at high enough laser powers to induce constant voltage steps on the d.c. I–V curves. We have shown(2) that the power dependence of the current half-widths of these steps are well described by the simple voltage-bias approximation of Werthamer's frequency-dependent theory.(9) By fitting the data for each junction to the theory, we were able to calibrate our external power meter in terms of $2\alpha = 2eV_{\mathrm{a.c.}}/\hbar\omega$, the normalized, laser-induced voltage in each junction. From this we calculated the induced power in the junction,

$$P = \frac{V_{\mathrm{rms}}^2}{R} = \frac{V_{\mathrm{a.c.}}^2}{2R}$$

$$= \left(\frac{\hbar\omega\alpha}{e}\right)^2 \frac{1}{2R}. \tag{1}$$

In this way, we could refer all measurements to the power actually coupled into the junction.

In the limit of very small laser power, the noise-rounded RSJ model predicts(11) the voltage response of the junction in the vicinity of the incipient step to be

$$v = \frac{-i_1}{i_1^2 + i_0^2} P \tag{2}$$

with the characteristic noise current

$$i_0 = \frac{2ek_B T_{\mathrm{eff}} R_D I}{\hbar V}. \tag{3}$$

Here, I, V and R_D are, respectively, the d.c. current, d.c. voltage and dynamic resistance at the step centre, while i_1 is the d.c. bias current measured from the step centre. Equation 2 predicts a resonant response that changes sign at the step centre and peaks at a bias current i_0 on either side. The magnitude of the peak response is also predicted to be linear in the laser power coupled into the junction.

To make these measurements, the output of the CO_2 laser was chopped at 450 Hz with a 50% duty cycle and the voltage response to the FIR laser was detected synchronously. A typical measured response is shown in the inset of Fig. 4 for $\sim 3.7 \times 10^{-11}$ W of 604 GHz (496 μm) laser radiation coupled into the junction. This particular junction had $R_D = 70\,\Omega$ and $I = 21\,\mu$A at the 1.25 mV step. The voltage separation between the two peaks implies $i_0 \approx 0.36\,\mu$A, in reasonable agreement with the 0.25 μA predicted by Eqn 3 for $T_{\mathrm{eff}} = 5$ K. In the inset of Fig. 4, the solid points show the response calculated using Eqn 2 with the height and width adjusted to fit the data. Good agreement with the theory is obtained for the *shape* of the response.

As the laser power is varied, the shape of the response and the value of i_0 remain the same, while, as shown in Fig. 4, the magnitude of the peak response, v_m, decreases linearly with decreasing laser power as predicted by the theory. However, the measured responsivity, s, is $\sim 8 \times 10^4$ V/W, which is substantially less than the value predicted by the theory,(11) $s = 1/2i_0 \approx 1.4 \times 10^6$ V/W. Our best measured responsivity at 604 GHz was $\sim 2 \times 10^5$ V/W, but was still less than the predicted value. The reason for this discrepancy is not understood. However, it is likely that the RSJ model cannot be used to make *quantitative* predictions at these high frequencies, where other frequency-dependent effects become important.

We have also tried to make these sorts of measurements at different FIR frequencies. Attempts to measure the responsivity using 246 GHz (1.2 mm) laser radiation were not

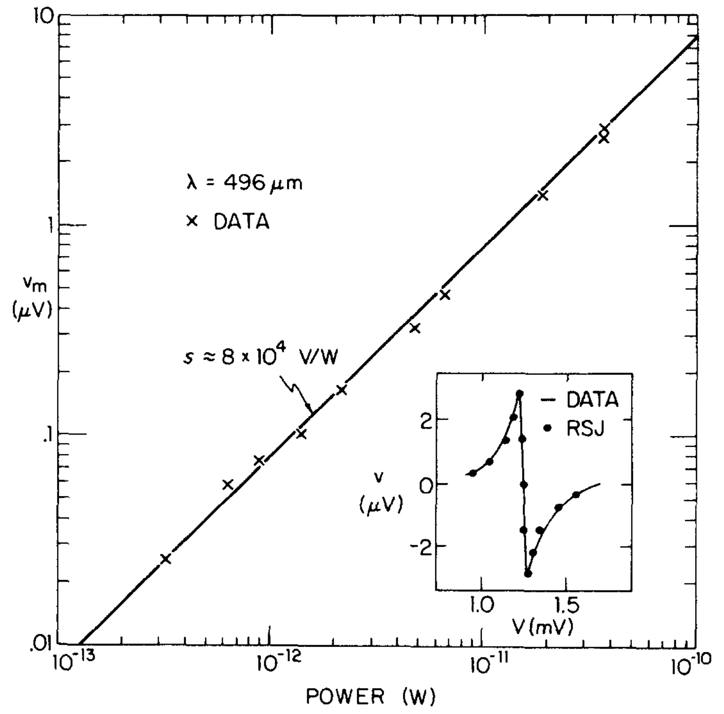

Fig. 4. The peak voltage response, measured near the first step, as a function of the 496 μm laser power coupled into the junction, for a 110 Ω high-quality point contact. The inset shows the voltage response as a function of bias voltage for $\sim 3.7 \times 10^{-11}$ W coupled power. The solid dots are the shape predicted by Eqn 2 in the text.

successful. The laser-induced step at 0.51 mV occurs at the middle of the very steep voltage onset. The dynamic resistance was too large to maintain a stable enough d.c. bias with the current-bias network used, and we were unable to measure the resonant response at low laser-power levels and small step sizes. We were able to measure the resonant response around the 5.22 mV step induced by 2.52 THz (119 μm) laser radiation. Its shape was again well described by the RSJ prediction of Eqn 2. For a junction that had $R = R_D = 60\,\Omega$ and $I = 113\,\mu$A at the step, the measured i_0 was 0.91 μA, compared to the 0.62 μA predicted by Eqn 3, using $T_{eff} = 15$ K, the noise temperature obtained from Fig. 3. The response was also linear in laser power but the measured responsivity was only $s \sim 4 \times 10^2$ V/W, far below the value predicted(11) for this i_0, which is $s \approx 6 \times 10^5$ V/W. Thus the disagreement with the RSJ model becomes even more severe as the frequency increases. With the 119 μm laser radiation, there was also a non-resonant, bolometric response whose magnitude was somewhat less than that of the resonant response. This sort of bolometric response is predicted by Tinkham *et al.*(11) to become larger than the Josephson response at high frequencies, with the crossover at

$$f_c = e/h(2RP_0)^{1/2} \tag{4}$$

where $P_0 \approx 10\,\mu$W. For this junction, $f_c \approx 6$ THz, which corresponds to $\lambda = 50\,\mu$m. Thus, even at 119 μm, observable heating effects are expected.

LOW FREQUENCY VOLTAGE FLUCTUATIONS

Our best observed noise equivalent power (NEP) at 604 GHz was $\sim 10^{-13}$ W/Hz$^{1/2}$, measured with a 1 sec time constant, and referred to laser power coupled into the junction. It was limited by voltage fluctuations in the junction at the chopping frequency (450 Hz) which obscured the laser response. Figure 5 shows the frequency dependence of the voltage noise power spectrum, $S_V(f)$, at three different bias levels, for a 92 Ω

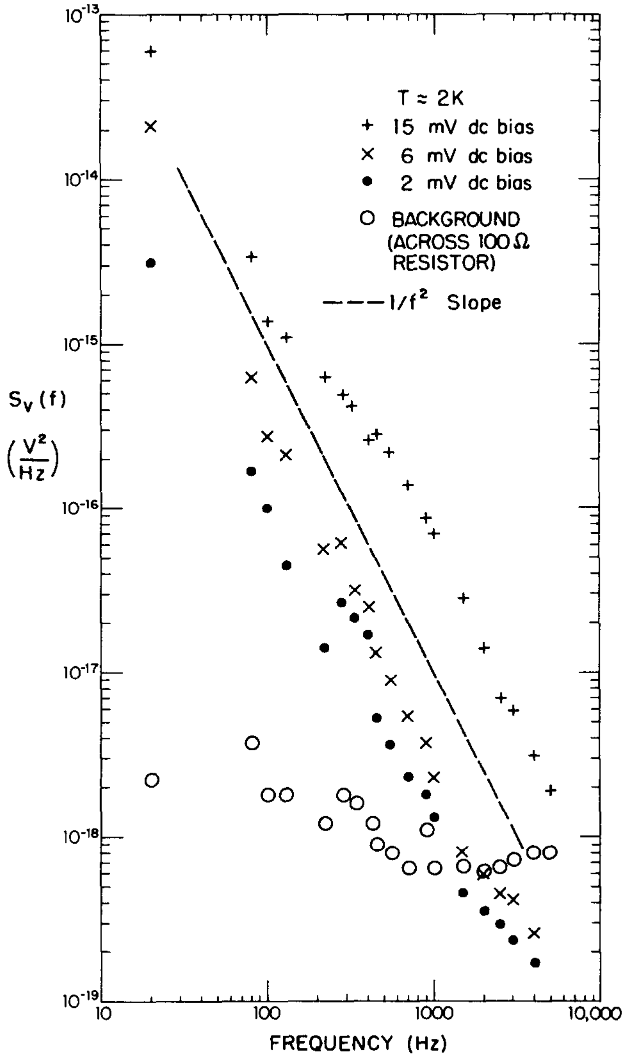

Fig. 5. The spectral density of the voltage fluctuations for a 92 Ω junction measured at three different bias-voltage levels. The data have been corrected for the background noise (circles), measured across a 100 Ω resistor. The dashed line shows a $1/f^2$ frequency dependence.

junction. Although there is considerable scattering in the data, the frequency dependence appears to be approximately $1/f^2$. Data from other junctions had similar amounts of scatter, but all seemed to have approximately the same f^{-2} frequency dependence. However, the level of $S_V(f)$ varied by as much as an order of magnitude from junction to junction. The data shown in Fig. 5 were taken at $T \sim 2$ K, below the λ-point of the liquid He bath, to ensure that the bubbling of the He bath did not contribute to the measured noise power. However, approximately the same level and frequency dependence were found at 4.2 K. At 450 Hz, we have also measured the voltage noise, V_N, as a function of bias voltage, and find that for bias voltages up to $\sim$3–5 mV, it depends on the dynamic resistance with V_N/R_D approximately constant. At higher bias voltages, V_N increases with the bias voltage. Although this high level of fluctuations severely limits our measured NEP, the $1/f^2$ dependence of $S_V(f)$ suggests that the detector performance could be improved considerably by going to higher chopping frequencies.

The origin of both the magnitude and the frequency dependence of the observed $S_V(f)$ is not understood. The $1/f^2$ frequency dependence is unlike that observed for thin metallic films(16) or resistively-shunted Josephson tunnel junctions,(17) which both show a $1/f$ behaviour of $S_V(f)$. More experimental measurements, over a wider frequency range, will probably be required for a complete understanding of the nature of these fluctuations.

Despite the large spectral density of the low-frequency voltage noise, its contribution to the linewidth of the Josephson radiation is relatively small. The linewidth, which determines the voltage separation between the two peaks of the resonant response in the RSJ model,(11) corresponds to $\sim 25\,\mu$V for the 496 μm data described earlier. According to standard FM theory,(18) narrow-band, low frequency noise contributes its full root mean square voltage deviation, $(\overline{V^2})^{1/2}$, to the linewidth, while broad-band noise contributes less than its total $(\overline{V^2})^{1/2}$ because of 'motional narrowing'. Nevertheless, the broad-band noise is still the major cause of the measured linewidth. The contribution from the low frequency noise can be estimated by assuming a $1/f^2$ frequency dependence and a typical value of $S_v(f) \approx 10^{-16}\,\mathrm{V^2/Hz}$ at 100 Hz (from Fig. 5). Integrating the spectral density, including frequencies down to 10^{-4} Hz, gives a contribution to the linewidth of less than 1 μV.

LOW POWER BEHAVIOUR OF I_c

One of the peculiar features of our high-quality junctions is the behaviour of the I–V curves in the vicinity of the critical current at low laser powers. Examples of d.c. I–V curves with no incident laser radiation, and with the critical current depressed by successively increasing powers from the 496 μm laser line, are shown in Fig. 6 for two high-quality junctions with resistances of (a) 50 Ω and (b) 100 Ω. The effect of the low level laser radiation is to considerably reduce the dynamic resistance of the lower portion of the voltage rise, so that there appears to be a gradual voltage onset rather than the very steep onset seen with no incident radiation. However, the steep upper portion of the initial voltage rise and the excess current at higher voltages are not reduced nearly as fast as the critical current. As the laser power is increased further and the critical current passes through its first zero, this effect becomes much less pronounced, with the initial voltage onset not as gradual and the dynamic resistance becoming somewhat larger again, as shown by the dotted I–V curves in Fig. 6. We see similar low-laser-power behaviour in all our high-quality junctions, and for all the laser frequencies used. Figure 7(a) shows a further example for a 80 Ω junction irradiated by successively increasing powers of 119 μm laser radiation. Similar behaviour has also been reported by others(15) using 2.3 mm (130 GHz) radiation, but only for junctions that had $R \gtrsim 60\,\Omega$. This behaviour contrasts with the RSJ prediction and with the reported behaviour of point contacts with much lower I_cR products,(19) where there is not such

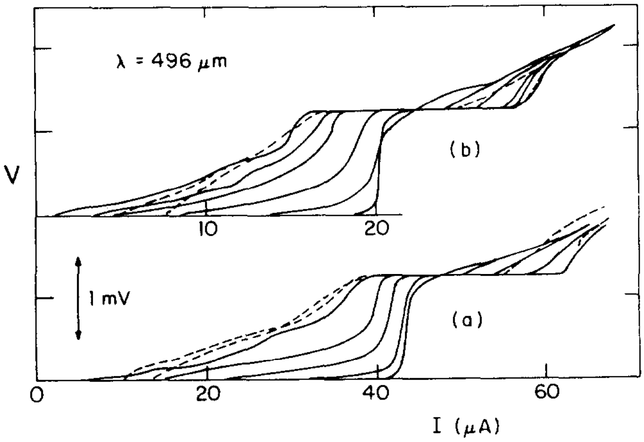

Fig. 6. A sequence of d.c. I–V curves of high-quality junctions with the critical currents successively depressed by increasing 496 μm laser power. The critical currents of the dashed curves have passed through their first zero. Note the decrease in R_D at the voltage onset as the laser power increases. The resistances of the junctions are (a) 50 Ω and (b) 100 Ω.

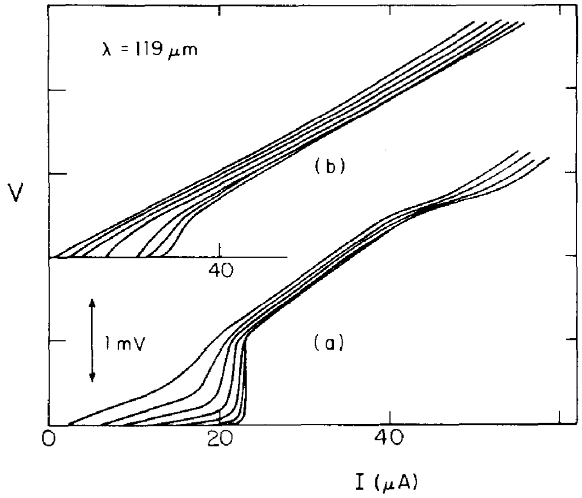

Fig. 7. A sequence of d.c. I–V curves with the critical currents successively depressed by increasing 119 μm laser power. (a) High-quality junction, showing a large decrease in the initial R_D, and (b) poor-quality junction, which does not show as large a decrease of the initial R_D.

a large decrease in the initial R_D and the whole voltage onset moves to lower current levels as I_c is decreased. The latter behaviour is observed in our poor-quality junctions, as shown by the example in Fig. 7(b) for 119 μm radiation.

The low-laser-power behaviour of our 'ideal' junctions may necessitate a re-examination of the optimum operating conditions if these junctions are used as mixers with external local oscillators (LO). Operation in this mode is usually optimized with the critical current reduced to $\sim\frac{1}{2}I_c$ by the LO power, and with the d.c. bias point set at about half the voltage of the first step.(15,20) However, good performance also requires that R_D be as high as possible. Thus if junctions like these are used as mixers, it may be necessary to operate with less LO power, to maintain a reasonably high R_D. We note that Edrich *et al.*(14) have reported excellent performance of a Josephson mixer receiver that used a point contact whose I–V curve had a very large R_D at the voltage onset similar to our high-quality junctions. They obtained the best performance when the 300 GHz LO reduced I_c by only a few percent. Further experimental testing in a mixer configuration is necessary to fully address this issue.

SUMMARY

This paper reports on the FIR properties of niobium cat-whisker point contacts, studied using radiation from an optically pumped FIR laser. We have identified the characteristic shape of the d.c. I–V curves of junctions with excellent high-frequency performance, making them potential FIR detectors or mixers. Their reproducible behaviour has allowed us to measure the intrinsic rolloff of the strength of the a.c. Josephson effect at frequencies above the superconducting energy gap frequency.

To characterize these junctions further, we have made measurements of their characteristic noise levels, both with and without incident FIR radiation. Noise temperatures obtained from a fit of the laser-induced step shape(8) increase with bias voltage in agreement with the calculated(1) increase due to the additional Johnson noise caused by Joule heating at the contact. However, they are substantially less than the predicted effective temperatures due to the shot noise expected for a tunnelling type of contact.(7)

For low laser power and a d.c. bias in the vicinity of the incipient first step, the junction operates as a frequency-selective incoherent detector. Our best observed NEP at 604 GHz was $\sim 10^{-13}\,\mathrm{W/Hz^{1/2}}$, and was limited by the voltage noise in our point contacts at the chopping frequency (450 Hz). We have measured the power spectrum of these voltage fluctuations from $\sim$ 10 Hz to 50 kHz, and find an approximately $1/f^2$

frequency dependence, so that we would expect the NEP to be considerably improved at higher chopping frequencies. Both the shape and the power dependence of the resonant response near the first step agree with calculations(11) using the resistively-shunted junction (RSJ) model when responsivity at 604 GHz is 2×10^5 V/W, but this drops considerably at higher frequencies. The responsivity predicted within the RSJ model(11) does not agree with the data, and more work is necessary to explain the measurements more fully.

Finally, we have studied the behaviour of the d.c. I–V curves near the critical current when our high-quality junctions are irradiated with low laser power. The dynamic resistance of the voltage onset is considerably reduced as the critical current is depressed. This behaviour may be important in understanding the performance of junctions like ours when used as mixers with external local oscillators.

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