Characterization of niobium point contacts showing Josephson effects in the far infrared

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The high-frequency behavior of niobium cat-whisker point contacts has been studied using radiation from an optically pumped far-infrared laser. When the point contacts are classified on the basis of their high-frequency performance, their dc I-V curves fall into recognizable groups. We find that the ac Josephson effect has a strong correlation with the gap-related structure on the I-V curve, but none at all with the apparent excess current observed in all the contacts. For high-performance junctions, these and other features of the I-V curves are very reproducible from contact to contact, allowing a comparison with the available theories. The experimental evidence seems to suggest that our point contacts are best modeled as extremely small metallic constrictions.

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I. INTRODUCTION

The performance and fabrication of Josephson-effect devices has attracted considerable attention in recent years. One problem of particular interest has been the determination of both the intrinsic fundamental limitations of the high-frequency behavior of the Josephson effect and the practical limitations imposed by geometry, material, and other experimental parameters. Josephson-effect devices can be loosely classed into three broad categories: tunnel junctions, microbridges, and point contacts. The high-frequency performance of tunnel junctions is generally limited by shunt capacitance. There have been recent advances in fabricating small-area low-capacitance high-current-density tunnel junctions,[1] but the high-frequency Josephson behavior of these has not yet been reported. The major limitation in the high-frequency performance of microbridges is Joule heating.[2] Even the best-quality variable-thickness bridges (VTB's),[3] whose geometry optimizes the removal of the Joule heat, are still limited at higher voltages by power dissipation because of their characteristically low impedance. Point contacts, in particular the niobium "cat-whisker"type, avoid both these problems. Because of their very small area, their capacitance can be extremely small,[4] and because of their higher impedance and favorable three-dimensional geometry, the effects of heating can be minimized.[5] In fact, cat-whisker point contacts have demonstrated the best high-frequency performance of all to date, showing direct evidence of the ac Josephson effect at $\sim$8 THz (17 mV).[6] Thus they are the best device for the study of the *intrinsic* limitations in the high-frequency behavior of the Josephson effect.

Even considering only cat-whisker point contacts, both the shape of the dc I-V curve and the high-frequency performance vary considerably from junction to junction. The purpose of this paper is to present the results of a systematic study of the high-frequency behavior of contacts with various types of dc characteristics. We show that there is a strong correlation between the high-frequency ac Josephson effect and certain features on the dc I-V curves. In particular, we find that the sharpness of the structure at the energy gap correlates strongly with the existence of the ac Josephson effect at high voltages. We test the junctions using two different far-infrared (FIR) frequencies, looking either for the fundamental Josephson step induced by 119-μm (2.52-THz) laser radiation at 5.22 mV, or, for a finer voltage grid, the harmonics of the 1.25-mV step induced by 496-μm (604-GHz) radiation. The existence of a constant-voltage step is direct evidence of the ac Josephson effect at the frequency $f=2eV/h$.

In sec. II of the paper, we present the experimental details with a description of the apparatus and the procedure used to fabricate our high-quality junctions. Section III is a presentation of our results in which we classify our junctions on the basis of their high-frequency performance and show the correlation of their behavior with the features on the dc I-V curve characteristic of each class. In Sec. IV, we compare the features characteristic of our I-V curves with the predictions of various theories, in an attempt to determine how best to model our point contacts. Finally, Sec. V is a brief summary of our results.

II. EXPERIMENTAL

A. Apparatus

The point contacts used in these experiments were formed between a sharpened Nb wire and a polished Nb flat. A schematic diagram of the arrangement inside the helium

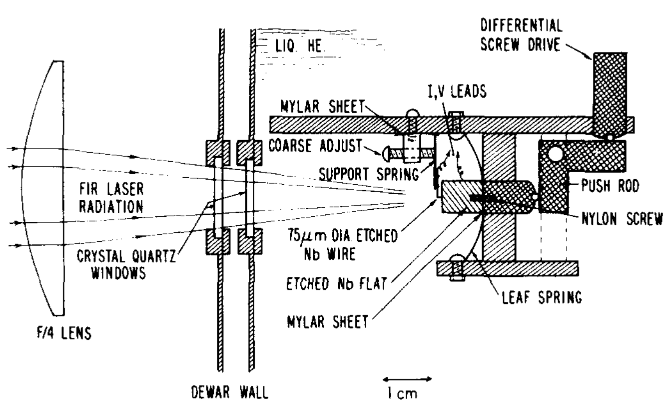

FIG. 1. Schematic of Dewar insert showing the point-contact arrangement.

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Dewar is shown in Fig. 1. The 75-μm-diam wire was bent in an L shape and glued to a phosphor-bronze spring whose position could be fixed by a small set screw to allow a coarse adjustment of the contact setting to be made at room temperature. The flat was adjusted by a differential screw and lever system driven by a set of reducing gears at the top of the rig. A complete turn of the control rod at the top of the Dewar corresponded to about 0.6 μm movement of the flat. This very fine adjustment was used to make and adjust the point contact while cold. Both the flat and the wire were electrically isolated from the rest of the rig. All leads were brought through rf filters at the top of the metal Dewar to shield the point contact from spurious pickup.

The portion of the L-shaped wire which was in contact with the flat was typically $\sim 500\ \mu$m long and served as an antenna to couple the laser radiation into the junction.[7] The whole lower structure of the Dewar insert could be rotated to change the angle between the antenna and the laser beam to improve the coupling efficiency to the antenna. The laser radiation was linearly polarized with a component of its **E** vector along the antenna and was focused through room-temperature and helium-temperature crystal-quartz windows in the side of the Dewar by an $\sim f/4$ polyethylene lens. The cooled crystal-quartz window helped filter out much of the room-temperature background radiation.

The optically pumped FIR laser was operated on either the 118.8-μm line of CH_3OH or the 496.1-μm line of CH_3F for these experiments. The CO_2 pump laser was grating tuned with its output mirror mounted on a PZT stack for fine adjustments of the frequency. It was tuned to the $P(36)$ line in the 9.5-μm band to pump the CH_3OH, while the CH_3F was pumped by the $P(20)$ line in the same band. The ~ 20 W of output power was focused with an $\sim f/50$ mirror through a 3-mm-diam hole in the back mirror of the FIR laser. The FIR cavity was a 3-m-long 38-mm-diam dielectric waveguide[8] with a capacitive mesh output coupler[9] of Al evaporated on crystal quartz. Operation in the EH_{11} mode gave a nearly Gaussian output beam with ~ 80 mW on the 119-μm line using a mesh constant of 333 lines/in. and ~ 10 mW on the 496-μm line using a mesh constant of 100 lines/in.

B. Procedure

The method of preparation of the point contacts was found to be quite critical in obtaining I-V curves that had high-I_cR products and showed strong Josephson effects at high frequencies. The Nb wire was sharpened with standard electroetching techniques[10] using about 4–6 V dc in a 5 : 4 : 1 solution of HNO_3, HF, and CH_3COOH. The radius of curvature of the points used was always less than $\sim 1\ \mu$m as observed with an optical microscope. The flat was polished to an optical finish using 0.3 μm alumina powder on a wax lap, and was etched slightly with HF, then rinsed with CH_3OH. Both sides of the junction were exposed to atmosphere for as short a time as possible after the final etching, to produce as "clean" a point contact as possible.

Contact was always made in liquid He. The position of the flat was first adjusted to make a very high-resistance wholly Ohmic contact, then the resistance was lowered and the desired IV curve produced with a "burn-in"[11] process using about 2 V_{p-p} at 35 Hz. During the course of a run, it was possible to make a wide variety of I-V curves using a combination of mechanical adjustment and burn-in. The adjustment became more difficult and the I-V curves were more likely to be hysteretic as the run progressed and the point became blunted. The blunting was visible with an optical microscope following the run if the point had undergone numerous adjustments.

Some sort of mechanical "scratching" seemed to be necessary in order to break through the surface oxide and produce high-quality high-I_cR point contacts. Attempts to make high-quality junctions with different diameter wires were less successful: thinner, 50-μm-diam, wire seemed too pliable and appeared to bend back when pushed by the flat, making it extremely difficult to produce high-quality point contacts; thicker, 175-μm-diam, wire had no give at all and became blunted too easily. However, using the 75-μm-diam wire, it was usually possible during the course of a run to make a number of high-quality junctions that remained stable for as long as was necessary to do the experiments. All the point contacts used were of reasonably high resistance ($10 \lesssim R \lesssim 200\ \Omega$) and thus were well coupled to the laser radiation.[12]

III. RESULTS

A. Classification

Our high-quality point contacts have a number of distinguishing features on their dc I-V curves that are surprisingly reproducible from junction to junction. Figure 2 shows a schematic dc I-V curve of a typical "high"-quality nonhysteretic point contact, as well as the parameters we have used to characterize the junctions. All our nonhysteretic I-V curves show a small amount of noise rounding at the voltage onset, so that the critical current, I_c, is defined by extrapolating the sharp voltage rise back to zero. In the case of a hysteretic junction, I_c is taken as the highest critical current measured, although this may not be well defined because any extraneous mechanical or electrical noise can cause premature switching into the voltage state. The resistance of the point contact, R, is taken as the differential resistance just above the gap, which we find to be the same as the resistance measured when we can couple in enough laser power to drive the junction Ohmic. The extrapolation of this differential resistance line back to the current axis defines the excess current, I_{ex}. The height of the voltage jump, V_j, is taken as the voltage at which the I-V curve bends over after the first steep straight rise. The gap-related structure is quite pronounced and always has the form of a decrease in the differential resistance below the gap voltage followed by an increase just above, as shown in Fig. 2. The identification of an appropriate feature for defining the gap voltage, V_{gap}, is somewhat arbitrary. We have consistently used the intersection of lines extrapolated from the differential resistance, R, above the gap structure and the minimum differential resistance, r, along the gap structure, as shown in Fig. 2. This corresponds closely to the voltage of maximum curvature on the I-V curve. The ratio $R/r \equiv S$ serves as a useful parameter to char-

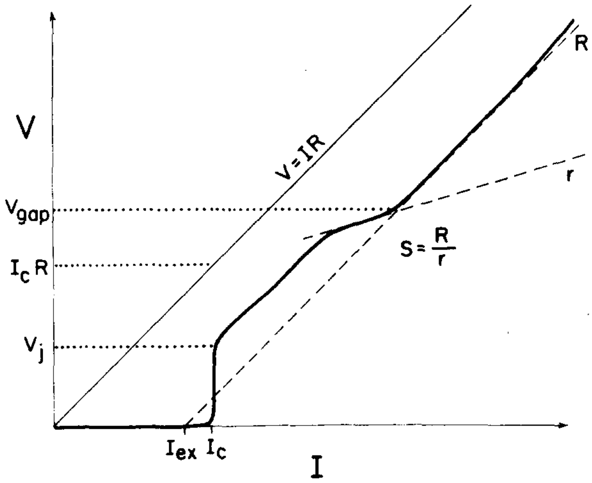

FIG. 2. Schematic of a high-quality dc I-V curve showing the parameters used for characterization.

TABLE I. Class I nonhysteretic contacts.

$R(\Omega)$	$I_c(\mu A)$	I_cR(mV)	V_j/I_cR	I_{ex}/I_c	V_{gap}(mV)	S
161	11.2	1.8	0.50	0.75	3.0	3.1
136	11.8	1.6	0.57	0.82	3.0	2.2
110	18.2	2.0	0.47	0.84	3.0	2.5
101	20.1	2.0	0.50	0.73	2.9	3.1
93	22.5	2.1	0.48	0.84	2.9	2.5
91	21.2	1.9	0.49	0.83	2.7	2.2
80	22.5	1.8	0.57	0.74	2.9	2.5
77	28.6	2.2	0.43	0.78	2.8	2.5
71	26.9	1.9	0.47	0.87	2.7	2.1
60	42.0	2.5	0.47	0.82	3.0	2.4
49	38.8	1.9	0.55	0.83	3.0	2.6
43	53.3	2.3	0.43	0.70	2.8	3.2
43	51.2	2.2	0.45	0.76	2.8	2.7
28	60.7	1.7	0.54	0.78	3.0	2.3
23	95.7	2.2	0.46	0.75	3.0	2.6

acterize the sharpness of the gap structure. Although only our high-quality point contacts have dc I-V curves closely resembling that shown in Fig. 2, we find it useful to characterize all our junctions in terms of these features.

Based on the strength of the high-frequency ac Josephson effect, we can group our point contacts into three classes. In the first of these are our high-quality junctions, which show a strong ac Josephson effect well above the gap, as evidenced by a readily visible first step induced by 119-μm radiation at 5.22 mV, or seven or more harmonics of the 1.25-mV step induced by 496-μm radiation. The second class contains our "marginal" junctions, which show no evidence of a first step with 119-μm radiation. However, their dc I-V curves have many qualitative similarities to those of class I, and this type of junction usually shows two or three steps when irradiated with 496-μm radiation. Finally, those junctions showing no steps with either FIR wavelength are grouped in the third class. We now discuss these classes in more detail.

1. Class I

An example of a high-quality nonhysteretic I-V curve is shown in Fig. 3(a). Such I-V curves are distinguished by the following features: (a) an I_cR product that is always very close to the theoretical value of $\sim$2.2 mV—typically within 20%, (b) a very steep but nonhysteretic voltage onset, with $V_j \sim 0.5 I_cR$, (c) V_{gap} between $\sim$2.8 and 3.1 mV, (d) very pronounced gap-related structure with $S \gtrsim 2.0$, and (e) an excess current that extends to bias voltages far above the gap (to $\sim$30–50 mV) and has a value of $I_{ex} \sim 0.8 I_c$ just above the gap. These features are quite reproducible in point contacts of this type, as shown in Table I, which lists data for a number of these junctions of varying resistances. As in Fig. 3(b), the first step was always easily visible with the 119-μm radi-

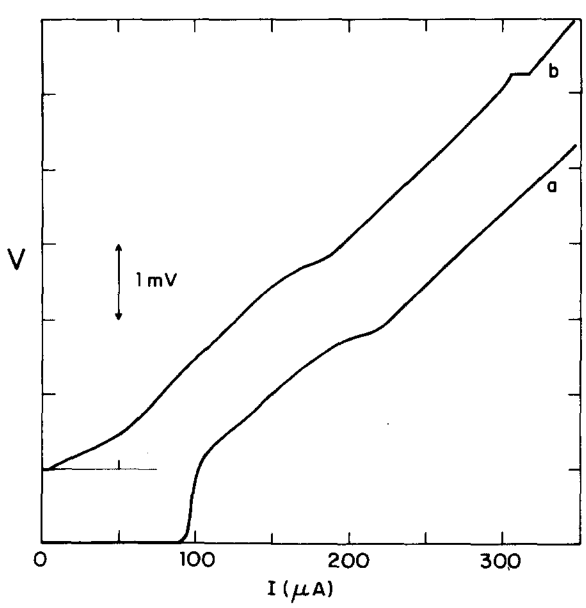

FIG. 3. Typical high-quality (class I) nonhysteretic dc I-V curves (a) without incident radiation and (b) with 119-μm radiation which induces a step at 5.22 mV. This junction has $R=23\ \Omega$ and $I_cR=2.2$ mV.

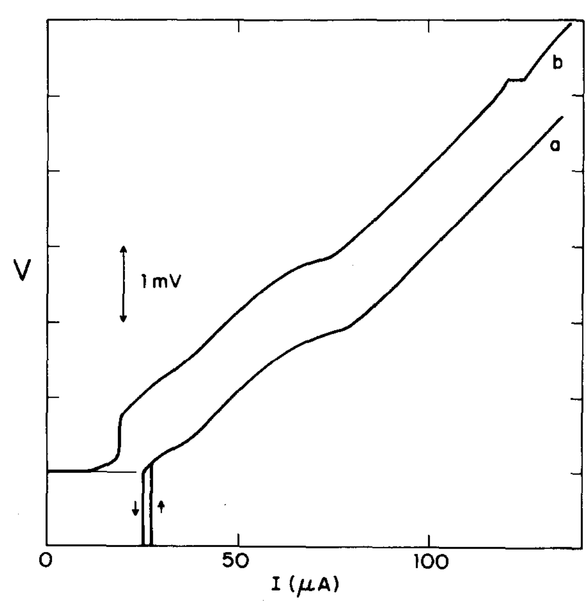

FIG. 4. Typical high-quality (class I) hysteretic dc I-V curves (a) without incident radiation and (b) with 119-μm radiation which induces a step at 5.22 mV. This junction has $R=54\ \Omega$ and $I_cR=1.5$ mV.

TABLE II. Class I hysteretic contacts.

$R(\Omega)$	$I_c(\mu A)$	I_cR(mV)	V_j/I_cR	I_{ex}/I_c	V_{gap}(mV)	S
162	6.8	1.1	0.39	1.17	3.0	2.6
136	9.5	1.3	0.49	1.19	3.0	2.4
125	8.8	1.1	0.50	1.45	2.9	2.0
104	9.6	1.0	0.62	1.23	3.1	2.8
88	21.6	1.9	0.65	0.60	3.0	3.5
86	17.4	1.5	0.59	1.0	2.9	4.2
66	25.8	1.7	0.47	1.18	2.9	2.6
54	27.8	1.5	0.69	0.79	2.9	3.9
50	36.6	1.8	0.61	0.50	3.0	2.6
30	73.9	2.2	0.49	0.71	2.8	4.5
14	157.0	2.2	0.49	0.77	2.7	2.3

ation. The fourth and higher harmonics of 496-μm radiation were also always seen, and when the current widths of these steps were normalized to the zero-power critical current and corrected for noise rounding and heating, their power dependence was consistent from contact to contact.[12] This class of point contacts is the only one that shows this consistent behavior.

The differential resistance of the initial steep voltage rise was very large for high-quality junctions, and, for some junctions, it was impossible to maintain a stable dc bias on the rise with the current bias used. In fact some of our high-quality junctions were clearly hysteretic, as illustrated by the example in Fig. 4(a). Except for the hysteretic voltage onset, this I-V curve is quite similar to that shown in Fig. 3, with the same sort of excess current, similar gap structure, and a high value of S. This similarity is further shown by Table II which lists the same parameters as Table I for a number of high-quality hysteretic junctions. There is not the same consistency in the values of I_cR and I_{ex}/I_c as there is in Table I. However, those junctions that have low-I_cR products tend to

TABLE III. Class II contacts.

$R(\Omega)$	$I_c(\Omega A)$	$I_cR(mV)$	V_j/I_cR	I_{ex}/I_c	V_{gap}(mV)	S
145	10.3	1.5	0.41	1.22	2.8	2.0
132	6.8	0.9	0.52	1.43	2.7	1.7
111	9.0	1.0	0.50	1.33	2.8	1.6
86	15.1	1.3	0.46	1.11	2.7	1.4
41	31	1.2	0.49	0.86	2.7	1.4
37	35.2	1.3	0.54	1.12	2.6	1.6
31	67.7	2.1	0.43	0.78	2.5	1.6
31	75	2.3	0.50	0.63	2.7	1.4
25	60	1.5	0.49	1.02	2.7	1.6
21	76.2	1.6	0.41	0.78	2.5	1.3
19	126	2.4	0.42	0.82	2.5	1.7
18	100	1.8	0.49	0.75	2.5	1.3
17	100	1.7	0.47	0.88	2.7	1.4
17	135	2.3	0.40	0.64	2.5	1.9
13	126	1.6	0.61	0.83	2.5	1.5

have $I_{ex}/I_c > 0.8$, consistent with an erroneously low measurement of I_c due to premature voltage switching induced by extraneous noise. As shown in Fig. 4(b), these curves also exhibit a strong high-frequency ac Josephson current, since the 119-μm-laser-induced step is readily visible.

2. Class II

The I-V curve in Fig. 5(a) is an example of a marginal-quality point contact, and Table III lists the characteristics of a number of these junctions. The I_cR products of these junctions are generally lower than those of the high-quality junctions, typically between 1.0 and 1.8 mV. They have the same sharp voltage onset, which is also occasionally hysteretic, and again have $V_j \sim 0.5 I_cR$. However, the gap-related structure is somewhat less pronounced than that of the high-quality junctions, with $S \lesssim 2.0$ while the energy-gap voltages are somewhat lower than class I junctions, with V_{gap} be-

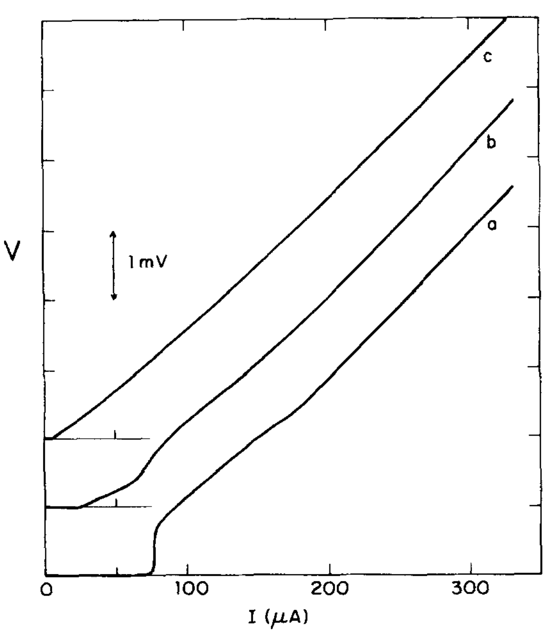

FIG. 5. Typical marginal-quality (class II) dc I-V curves (a) without incident radiation and (b) and (c) with increasing 119-μm radiation showing no step. This junction has $R = 21\ \Omega$ and $I_cR = 1.6$ mV.

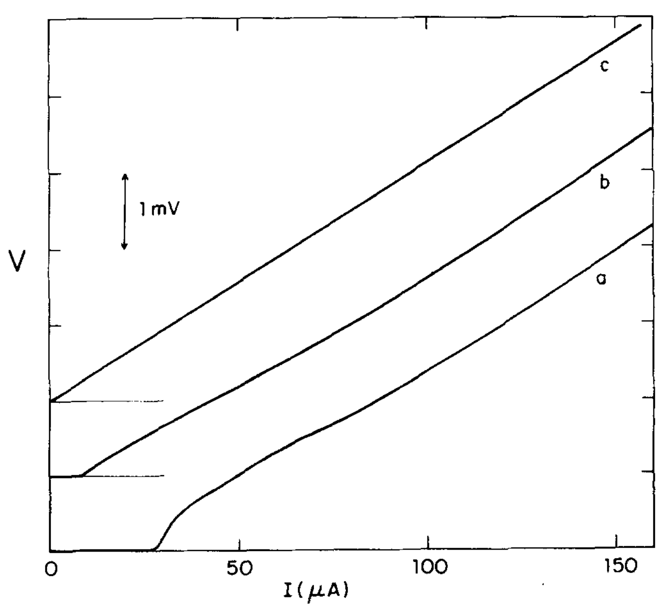

FIG. 6. Typical poor-quality (class III) dc I-V curves (a) without incident radiation and (b) and (c) with increasing 119-μm radiation. There is no step, even though laser power could be coupled into the junction to drive it Ohmic. (c). This junction has $R = 33\ \Omega$ and $I_cR = 0.9$ mV.

TABLE IV. Class III contacts.

$R(\Omega)$	$I_c(\Omega\text{A})$	I_cR	V_j/I_cR	V_{ex}/I_c	V_{gap}(mV)	S
80	5	0.40	0.5	1.1	1.6	1.1
50	10	0.50	0.7	1.0	2.8	1.1
50	3	0.15	0.6	0.43	2.0	1.05
48	11	0.50	0.5	1.6	2.3	1.3
30	10	0.30	0.8	1.4	1.8	1.2
28	21	0.59	0.3	1.2	2.2	1.1
26	10	0.26	0.7	1.1	2.3	1.1
15	30	0.45	0.4	0.8	1.1	1.1
12	80	0.96	0.7	0.72	2.0	1.1
5	140	0.70	0.4	1.3	2.3	1.1

tween ~2.5 and 2.8 mV. Again there is a large excess current above the gap, although the values of I_{ex}/I_c are not as consistent from junction to junction as they are for those in class I. These junctions do not exhibit a step at 5.22 mV when irradiated by *any* amount of power at the 119-μm laser line, as shown, for example, by the *I-V* curves in Figs. 5(b) and 5(c) for increasing laser powers. Here, the reduction in the critical current with increasing laser power serves both as a confirmation that laser power is in fact coupled into the junction, and as a guide to the amount of power coupled in. The 496-μm radiation usually produces two or three steps in these junctions, but the high harmonics seen with class I point contacts are not seen with these.

3. Class III

The type of point contact represented by the *I-V* curve shown in Fig. 6(a) is typical of the poorest class of junctions we see. The I_cR products of these junctions are quite low ($\lesssim 1.0$ mV) and the initial voltage jump is not as sharp as it is on the better-quality junctions, with V_j not as well defined. There is practically no gap structure at all, with S very close to 1.0. V_{gap} is also not as well defined as for the high-quality junctions, but is generally considerably lower than the typical values for class I and II contacts. There is, however, always an excess current above the gap, and the *I-V* curves are frequently hysteretic. Table IV lists the parameters for a number of these junctions, for comparison with the other classes. This class of junctions shows no high-frequency ac Josephson effect at all, as is illustrated by the example in Figs. 6(b) and 6(c), which shows no step at 5.22 mV for increasing power from the 119-μm laser line. These junctions are again clearly coupling to the radiation and for this particular junction there was enough laser power to drive it completely Ohmic. The *I-V* curves of this class sometimes show a step at 1.25 mV when irradiated with 496-μm radiation, but the second harmonic is rarely seen. This sort of junction is never used in any of our laser work, and the contact is always remade when one is obtained.

B. High-voltage behavior

In a previous publication,[13] we have shown that the maximum number of steps induced by 496-μm-laser radiation in various point contacts increases roughly linearly with the value of S for each junction. An alternate way of showing the correlation of the sharpness of the gap structure with the high-frequency ac Josephson effect is to look for the minimum value of S required to see a step at a given voltage. In Fig. 7, we have plotted S versus I_cR, using open points for junctions that showed an ac Josephson effect at voltages higher than 5 mV and solid points for those that did not. The criterion used was the appearance of the first step for 119-μm radiation (circles) and the fourth step for 496-μm radiation (squares). It is clear that there is a minimum value, $S \approx 2.0$, necessary for the existence of the ac Josephson effect above 5 mV. There does not appear to be as strong a correlation between the existence of the high-frequency ac Josephson effect and the I_cR product. In Fig. 7, the points with horizontal arrows are data from hysteretic *I-V* curves, where the full I_c may not be measured. If $1.25I_{ex}$ is used as a measure of I_c (i.e., if one assumes $I_{ex}/I_c = 0.8$), then both the hysteretic and nonhysteretic junctions which show steps above 5 mV all have $I_cR \gtrsim 1.6$ mV. However, many junctions with high-I_cR products have $S \lesssim 2.0$ and these do not show a step at or above 5.0 mV. Thus, while a high-I_cR product is a necessary condition, the best indication of the existence of the strong high-frequency ac Josephson effect is a large value of S. This gives a useful prescription for recognizing point contacts with good high-frequency performance from the shape of their dc *I-V* curves.

All of our point contacts exhibit an excess current, I_{ex}, which falls off slowly with voltage above the gap, but persists to voltage levels of ~35–50 mV. Alimenko *et al.*[14] have measured I_{ex} as a function of voltage in Nb point contacts and make the unsubstantiated claim that the excess current is proportional to the strength of the ac Josephson effect. In our experiments, we have a direct test for the existence of the ac Josephson effect and find an excess current in *all* junctions, whether or not they show a step above the gap. Thus, the ac Josephson effect cannot be the primary cause of the excess current. Instead, the fall off of I_{ex} with voltage is more likely due to simple Joule heating[2,5,15] than to the decrease of the ac Josephson current.

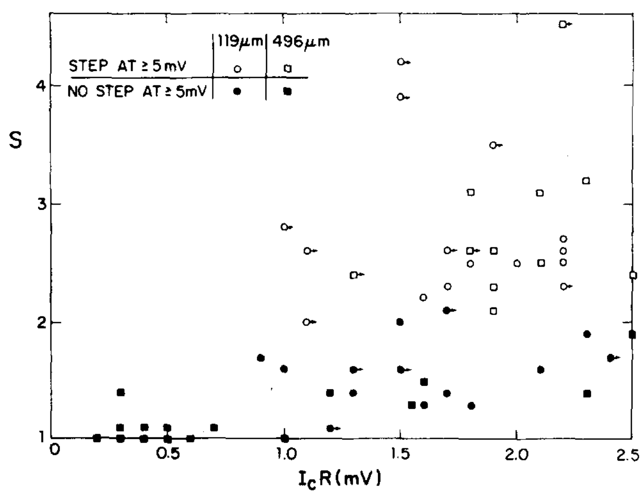

FIG. 7. S versus I_cR. The points with horizontal arrows are data from hysteretic junctions where the full I_c may not be measured, so their I_cR products may be erroneously low. Note that FIR steps are seen (open symbols) only for $S \gtrsim 2$.

IV. DISCUSSION

In additon to their practical import, our measurements can be examined to see what light they shed on the long-standing issue of whether point contacts are best modeled as tunnel junctions or as metallic constrictions. Models have been developed to described Josephson-effect devices with each of these types of weak links. However, as the somewhat ill-defined structure of a point contact is approached, the distinctions between the predictions of the two models become less apparent. For example, if the characteristic size of a constriction, a, is less than the electron mean free path, l, so that an electron can pass through the barrier without scattering, the metallic constriction is expected to become more "tunnelinglike" in its behavior.[16,17] On the other hand, the I-V curves of small-area high-current-density (low RC) tunnel junctions are predicted to become similar in many respects to those of metallic constrictions.[17,18] Thus, the more fundamental conceptual issue is whether there are, indeed, significant differences between the two types of barriers which persist even in the limit of very small cross-sectional areas.

Our high-quality (class I) point contacts show striking reproducibility from junction to junction, both in their dc I-V curves and in their high-frequency performance, suggesting that their behavior is converging on that of the "ideal" clean low-capacitance point contact.[13] We thus have a set of reproducible features on the dc I-V curves which can be compared with theoretical predictions and with experimental results from Josephson-effect devices having more clearly defined geometries, in an attempt to determine the physical structure of the minute contact region.

Of all the features on the dc I-V curves, the energy-gap structure and voltage seem to correlate most strongly with the existence of the ac Josephson effect and the high-frequency performance of the junction. The values of V_{gap} of our high-quality (class I) junctions generally tend to be slightly greater than the 2.8 mV commonly quoted for other Nb point contacts[4,14] and are comparable to the V_{gap} measured for Nb/Nb tunnel junctions.[19] However, they are still slightly lower than the 3.12-mV energy gap of pure bulk Nb.[20] It is possible that the pressures exerted on the extremely small area of the point, while the contact is made, work harden the metal in the vicinity of the contact, causing a reduction in the energy gap. There is also some evidence[21] for the existence of suboxides on the surface of niobium with a lower T_c of ~ 7.2 °K, implying $2\Delta/e \approx 2.5$ mV. It is thus possible to speculate that the cause of the lowered V_{gap} of our class II and III junctions is a remaining layer of niobium suboxide at the contact region. This implies that a clean surface, giving as high a V_{gap} as possible, is necessary to obtain high-quality junctions, and suggests that our class I point contacts may be entirely free of any oxide layer.

The shape of the gap structure that we observe consists of a relative decrease in the current *below* the gap voltage. This is typical of the shape observed in very "clean" Nb point contacts and in the Nb junctions used for high-frequency mixing experiments.[4] However, this shape contrasts with that observed in low-impedance microbridges, for which a relative decrease in the current just *above* the voltage is typical.[22,23] The similarity of the gap-structure shape we observe to that seen in oxide tunnel junctions suggests labeling this shape "tunnelinglike." In fact, however, Yanson has observed both types of shapes in metallic constrictions in his studies of the I-V curves of metallic shorts through dielectric layers.[16] He sees the current decrease change continuously from just above the energy gap to just below as the resistance changes from $R \lesssim 1$ to $R \gtrsim 20\,\Omega$, and as the coherence length, $\xi(T) \gtrsim a$ to $\xi(T) \gg a$. Thus, small high-impedance metallic constrictions can also show "tunnelinglike" behavior, undercutting the meaningfulness of this label.

Explanations of the gap and subharmonic gap structures have drawn a distinction between "multiparticle tunneling" and "Josephson self-coupling" as possible causes.[24,25] This distinction is meaningful only for *subharmonic* gap structure, since multiparticle tunneling reduces to single particle tunneling for the structure at the energy gap, and is included within the self-coupling theory.[26] Because of the very steep voltage rise to $V_j \approx 0.5 I_c R$, the only subharmonic gap structure we are able to see is that at half the energy gap. This structure is similar in shape to the structure at the gap, but is much less pronounced. Thus, although we observe strong correlation between the ac Josephson effect and the structure at the energy gap,[13] we cannot draw firm conclusions about the causes of the subharmonic gap structure.

Werthamer's frequency-dependent self-coupling (FDSC) theory[26] has been used to calculate the I-V curve of a current-biased zero-capacitance (high-current-density) tunnel junction.[17,18] As shown in Fig. 8, the calculated I-V curve has large currents below the gap voltage (unlike the more usual tunnel-junction I-V curves) as well as a decrease in the current just below V_{gap}, in qualitative agreement with the I-V curves of our high-quality point contacts. However, the calculation assumes a singular BCS density of states in the electrodes and does not account for the effects of noise or current-induced disequilibrium, all of which must be includ-

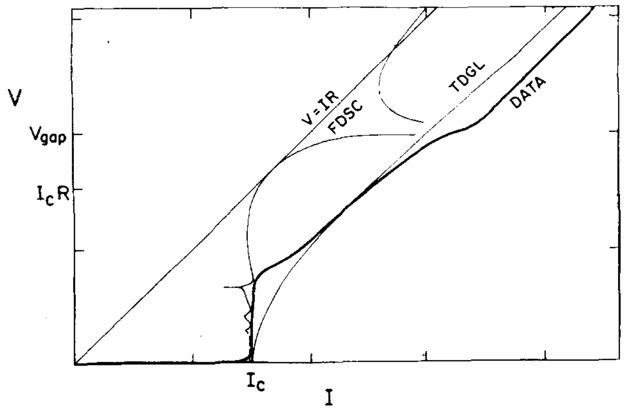

FIG. 8. Comparison of a typical high-quality nonhystretic dc I-V curve with two theoretical calculations. Both calculated I-V curves are scaled to have the same resistance as the data, with the FSDC calculation fitted to have the same energy-gap voltage, and the TDGL calculation fitted to have the same critical current as the data.

ed in a realistic manner if quantitative comparison with our data is to be made.

A feature of the I-V curves which is more likely to provide the basis for a conceptual distinction between tunnel-junction and metallic-constriction behavior of point contacts is the measured excess current at high voltages which is quite consistently about $0.8I_c$ in our junctions, and which we have shown is *not* related to the strength of the Josephson effect at high frequencies. Such an excess current is observed in all the various forms of metallic microbridges, but not thus far in tunnel junctions. The only theories which have provided a possible explanation for this feature consider the dynamics of the superconducting order parameter inside a continuous metallic link. Calculations of I-V curves using time-dependent Ginzburg-Landau (TDGL) theory show that the finite relaxation time of the order parameter inside the metallic constriction of a VTB can cause an apparent excess current.[27,28] In this description,[27] the strongly superconducting banks hold up the magnitude of the order parameter at the ends of the constriction, and effectively decrease the voltage drop across the bridge required to drive a given current. The magnitude of this insufficient voltage is asymptotically voltage independent and is equivalent to an excess current. However, the exact shape of the calculated I-V curve depends both on the length, L, of the constriction and on the value of the order parameter relaxation time, τ. Since this model assumes that the superconducting banks have an undepressed order parameter ("rigid" boundary conditions) the choice of an appropriate L is problematic for the point-contact geometry, where the boundaries are not well defined. The TDGL curve[28] shown in Fig. 8 is for $L=\xi$, and for the value of τ predicted by microscopic theory for a superconductor in the dirty limit, and has an excess current of $\sim 0.70I_c$, in reasonable agreement with our experimental I_{ex}. However, other calculations[29] have indicated that the behavior of the order parameter in the banks near the constriction may also play an important role in determining the properties of the bridge, making the assumption of "rigid" boundary conditions inadequate. Clearly more theoretical work is required before a more quantitative comparison with our data can be attempted.

Other explanations of the excess current seem less likely to apply here. Deaver and Pierce[30] considered a relation oscillation model that is essentially an equivalent circuit model with an additional inductance in series with the Josephson element of the RSJ circuit. This model predicts a smaller excess current of $0.5I_c$ and requires a large series inductance, which seems unlikely in junctions where ac Josephson currents flow well above the gap frequency. The phase slip models of Reiger *et al.*[31] and Skocpol *et al.*[32] estimate an excess current of $0.5I_c$ and $0.67I_c$, respectively, but were created to described slow variations on the scale of the Ginzburg-Landau relaxation time, and therefore are not suitable for point contacts at high voltages.

Finally, the noise temperatures due to heating caused by power dissipation in the junction are in agreement[12] with those predicted by the heating theory of Tinkham *et al.*,[5] which is derived explicitly for a metallic constriction, and seem to be inconsistent[33] with the extra shot noise expected for tunnel junctions. Thus, as a whole, the experimental evidence seems to suggest that our point contacts are best modeled as extremely small metallic constrictions, although the distinction between metallic-constriction and tunnel-junction behavior is perhaps somewhat blurred. It will be interesting to see whether the new generation of very small-area high-current-density tunnel junctions which can now be fabricated show Ohmic or excess-current type behavior above the gap. Ohmic behavior would tend to establish that there are some irreducible differences between metallic constrictions and tunnel junctions, despite the obvious generality of the Josephson phenomena in weak links.

V. SUMMARY

This paper has presented the results of a detailed study of the high-frequency behavior of niobium cat-whisker point contacts, using radiation from an optically pumped FIR laser at 119 and 496 μm. The contacts were made with a combination of mechanical adjustment and high-current-density burn-in, a technique we have found to be quite successful for producing high-quality junctions. Based on the number of steps shown with the FIR radiation, the different types of junctions commonly obtained were classified, and their high-frequency behavior was correlated with the shape of the dc I-V curve. The high-quality junctions were found to have quite reproducible characteristic features on their dc I-V curves, including an I_cR product near the theoretical maximum (~ 2.2 mV), a very sharp voltage rise of $V_j \sim 0.5I_cR$, energy gap voltages between ~ 2.8 and 3.1 mV, a very pronounced gap structure, and an excess current of $I_{ex} \sim 0.8I_c$ above the gap. This now gives a useful prescription for recognizing high-quality junctions based on their dc I-V curves, without the need for a high-frequency test.

To describe the sharpness of the structure at the energy gap we have used the parameter S, defined as the ratio of the differential resistance just above the gap to the differential resistance just below the gap. We find that S is a more sensitive parameter than I_cR in determining the high-frequency behavior and has a strong correlation with the highest voltage at which the ac Josephson effect still exists. High-quality junctions with $S \gtrsim 2.0$ always showed a step at 5.22 mV with 119-μm radiation. In contrast, we found no evidence to link the excess current to the ac Josephson effect as has been suggested.[14]

Finally, we have compared the features of the dc I-V curves of our high-quality junctions with various theoretical predictions. We find that the experimental evidence seems to support modeling our point contacts as very small metallic constrictions, rather than tunnel junctions. However, the distinction between the two models becomes somewhat blurred for the point-contact geometry, and a more realistic theoretical treatment seems necessary for a complete description of the data.

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