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VOLTAGE INDUCED VARIATIONS OF THE TUNNEL BARRIER IN Nb/Pb JUNCTIONS

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ABSTRACT

It has been recentely shown that in Nb/Pb junctions having the tunnel barriers grown by r.f. plasma oxidation, large bias voltages induce at room temperature permanent but reversible changes of the I-V characteristics and in particular changes of the Rnn values. In this paper similar variations of thermally oxidated junctions are reported, and a more simple behaviour has been found.. Different I-V characteristics, corresponding to different values of Rnn, have been drown at 77 K on both r.f. and thermal junctions. The voltage dependences of both the conductance and its logarithmic derivative has been studied. A preliminary evaluation of the induced variations of the tunnel barrier parameters is also performed.

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1. - INTRODUCTION

For the purpose of using superconducting tunnel junctions as proportional detectors for low energy ionizing particles (SLEND experiment at L.N.F.-I.N.F.N., Italy), the absence of spurious leakage currents may be a decisive point. In spite of the short quasiparticle recombination time in Nb and Pb, we are studying Nb/Pb tunnel junctions because of their very good mechanical properties and good thermal cycling stability. Unfortunately, the structure of the tunnel barrier made-up by Nb oxides, is quite complicated and dependent on the particular fabrication process(1,2). It leads to a not simple analysis of the I-V characteristic of these junctions, in which different current contributions have been distinguished: tunnel through the trapezoidal tunnel barrier, tunnel in channels connecting both electrodes, resonant tunnel generated by the localized states, etc...(3).

In the past we analyzed the I-V characteristic of junctions having a tunnel barrier fabricated by r.f. plasma oxidation and with resistances high enough to be biased at voltages higher than the barrier height. In these junctions, at room temperature, instabilities of the tunnel barrier induced by the applied voltages have been found(4). These instabilities generate permanent but reversible changes of the I-V characteristics and in particular of the value of the resistance measured at few millivolts in the normal state (Rnn)(5). Niobium diodes showed this kind of instabilities since 1970(6). In such diodes the oxide thickness was thick enough to suggest the exclusion on a conduction based on the tunnel effect. Otherwise in our junctions, for values of Rnn in a liquid helium bath greather than 20 Kohm, the typical tunnel structure, generated by the superconducting density of states, appear.

In this paper both junctions with r.f. and thermal oxidation have been analyzed. In sect. 2 the previously reported instabilities on r.f. junctions are summarized and instabilities observed in thermal junctions are reported. In sect. 3 we show the different I-V characteristics of the junctions at 77 K corresponding to different values of Rnn generated at room temperature. Moreover a preliminary analysis of the corresponding tunnel barrier is performed.

2. - VOLTAGE INDUCED INSTABILITIES

Nb/Pb junctions have been analyzed between room and liquid nitrogen temperatures. The I-V characteristics have been carried out in the usual four contacts configuration by using a very high impedance low-noise True Instrumentation Amplifier(7) and an HP 7090A measurement plotter system linked to a personal computer. The experimental set-up is shown in the inset of Fig. 1 where the Nb voltage electrode is connected to the positive

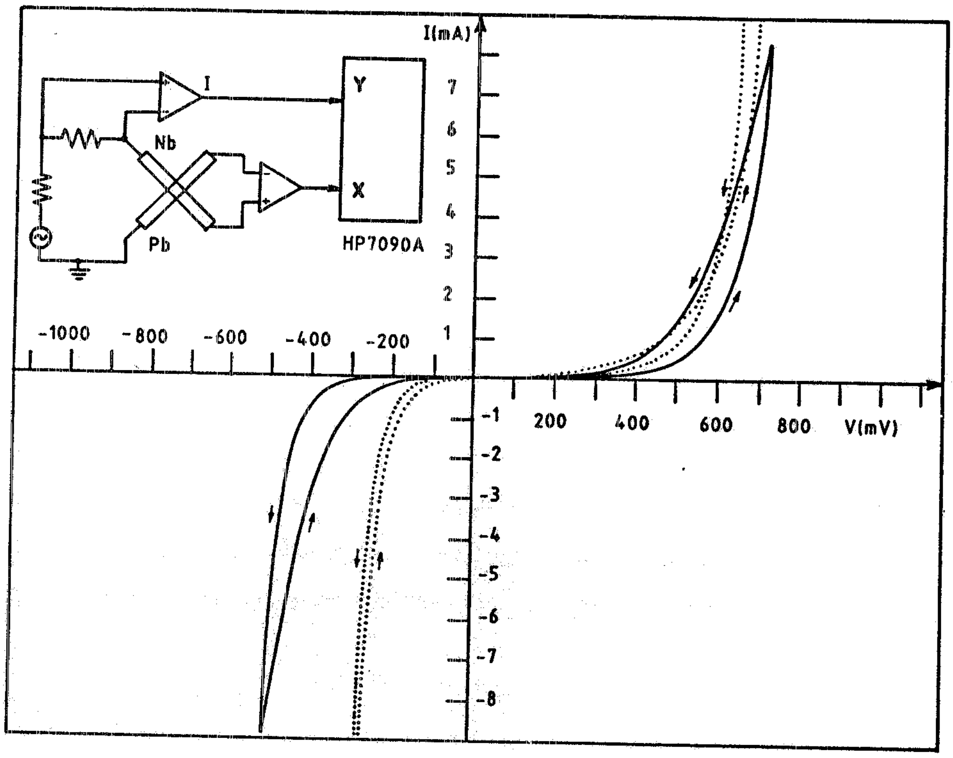

FIG. 1 - I-V characteristics at room temperature for: 1) a thermal junction (solid line); 2) a r.f. junction (dotted line).

input of the amplifier. By biasing the junction with a current generator voltage drifts appear; the drift speed is an increasing function of both the temperature and the bias voltage value. The drifts cannot be ascribed to self-heating effects but are related to permanent changes of the barrier structure. The time necessary for these barrier variations is comparable with the measurement scanning time so that the apparent I-V characteristics are function of the scanning time. Drifts to higher absolute voltages correspond to increase of the tunnel probability. In order ot understand the effects of high polarization voltages on the junctions only the positive or the negative part of the I-V characteristics have been analyzed with increasing values of the maximum current. The scanning time was of the order of 10 msec and the values of Rnn were measured just before and after the I-V recording.

a) r.f. Plasma Oxidized Junctions

Tunnel junctions with the tunnel barrier obtained by plasma oxidation show at room temperature a rather complex behaviour: both for positive and negative voltages two opposite effects exist, which respectively lead to an increasing and a decreasing of the tunnel probability. For positive voltages lower or larger than a threshold (typically equal to 450 mV), drifts toward respectively larger or lower values of voltages are dominant. In this way, scanning the I-V characteristic, hysteresis appear which are respectively clockwise and counterclockwise covered. The threshold value is not constant but it appears to depend on Rnn, so it decreases if Rnn decreases. For low applied voltages the Rnn increases are gradual and controllable, while for large voltages the Rnn decreasing are quite sharp. For negative voltages, scanning the I-V characteristic with a maximum applied voltage lower than 350 mV, a counterclockwise hysteresis appears, and a smooth Rnn decreasing takes place. If the 350 mV threshold is exceeded, a clockwise hysteresis can be observed, and rough variations of Rnn are measured. Following the described procedures the Rnn values can be indefinitely increased or decreased, so that variations up to a factor 250 have been obtained in some samples. At the liquid nitrogen temperature the drift speed is much slower; in any case the presence of two opposite effects leads to voltage oscillations, which are present for rather large voltages ($V > 650$ mV, $V < -850$ mV).

b) Thermal Oxidation

Thermally oxidated junctions appear more stable than the r.f. ones, and a simpler behaviour can be observed. In this paper we describe junctions oxidated at about 200 C for some hours, which have at 300 K values of specific Rnn of about 5 ohm·cm^2. At room temperature the asymmetry of the I-V characteristics between positive and negative voltages is weaker than the corresponding asymmetry present in r.f. junctions as shown in Fig. 1.

As shown in Figs. 2a, 2b, independently of the voltage values, for positive and negative voltages, respectively clockwise and counterclockwise hysteresis are observed. If a constant sweeping time is used, the increasing of the drift speed with the absolute voltage value leads to an increasing of the width of the hysteresis cycle and to apparent negative dynamical resistances. In an analogous way of r.f. junctions, a clockwise and a counterclockwise hysteresis correspond to respectively permanent increasing and decreasing values of Rnn; but for these junctions with positive voltages up to 1.3V, the maximum increasing of Rnn has been of a factor of about 1.5, and the subsequent maximum decreasing has been lower than 2. All the measured variations appear smooth and a saturation effect exists: if a maximum voltage is applied to the junctions, the values of Rnn have a maximum variation, and only the application of larger voltages can change Rnn further on.

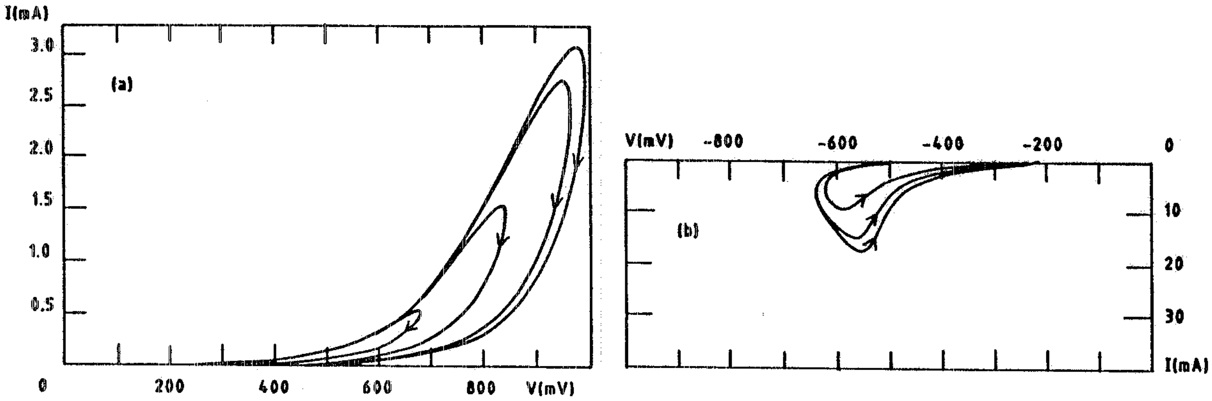

FIG. 2 - Hysteretic effects at room temperature in a thermal junction for: a) positive voltages; b) negative voltages.

3. - ANALYSIS OF THE I-V CHARACTERISTICS AT 77 K

As well known, informations about the heights of the tunnel barriers can be directly obtained by the values of voltages at which maxima of the logarithmic derivative $D = d \ln (I/V) / dV$ of the conductance appear. In our junctions this analysis can be performed at room temperature only for voltages low enough to avoid hysteresis: for higher voltages the drifts give rise to apparent spurious maxima. For this reason the following iterative procedure has been used:

1) measurement of Rnn at 300 K;
2) cooldown at 77 K and recording of both Rnn (77K) and the full I-V characteristic;
3) heating of the junction at room temperature and check of Rnn;
4) variation of the tunnel barrier by the application of large voltages.

Unfortunately, restrictions given both by the measurement apparatus and by noise made the experimental data incomplete for a full understanding of the variations of the tunnel barrier.

a) r.f. Junctions

In the Fig. 3 the log I versus V plot of the same junction both at room and 77 K temperature are reported. In a qualitative agreement with previously reported data, for our high resistance junctions the ratio between the high and low temperature resistance is very large.

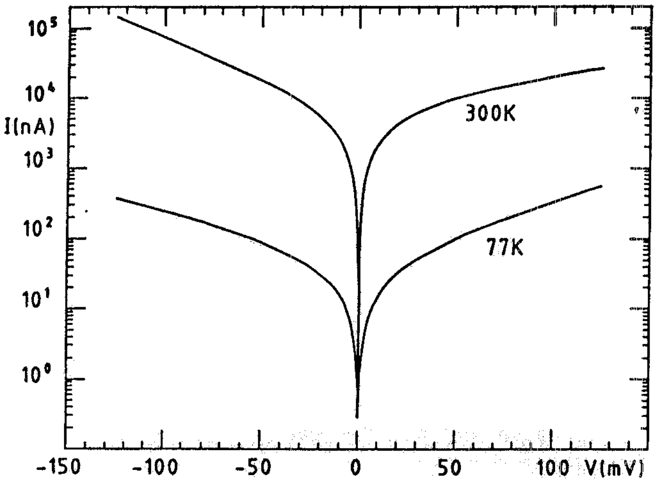

FIG. 3 - Log I versus V characteristics at 300 K and 77 K of a r.f. junction (sample 138H4M); Rnn(300)= 4.2 Kohm, Rnn(77)=625 Kohm.

As shown in Fig. 3, we remark that, for the same absolute voltage value, at room temperature the current in the positive portion of the characteristic is lower than the corresponding value in the negative portion; on the contrary, the asymmetric behaviour is inverted at 77 K. In Fig. 4 the log I versus V characteristics of the same junction, corresponding to two different values of Rnn, are reported.

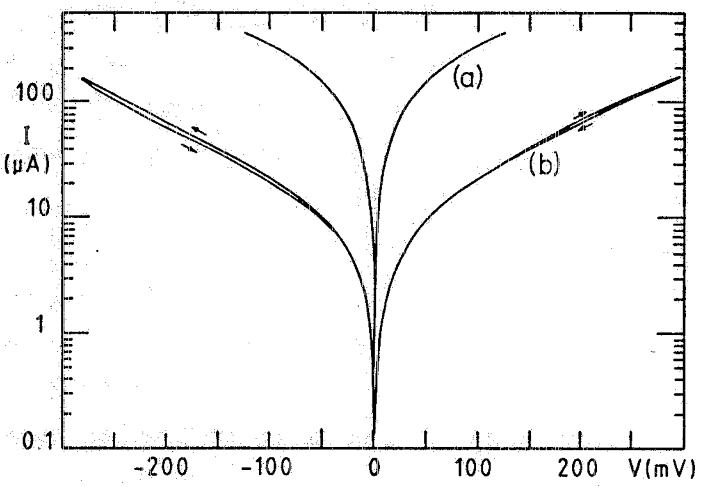

FIG. 4 - I-V characteristics of the same r.f. junction (138H4S) corresponding to two different values of Rnn, respectively equal to (a) 350 ohm and (b) 4 Kohm.

The analysis of the derivative D for both data of Figs. 3 and 4 does not show clear maxima in the analysed voltage range. In Fig. 5 for the same junctions but corresponding to a different value of Rnn, the plot of Log I/V versus voltage is reported, where clear maxima of D appear for V = 75 mV and V = -125 mV.

By changing the I-V characteristic with the described procedure, variations of the maxima have been measured. In Tab. I the voltage values of the maxima and the corresponding values of Rnn are summarised.

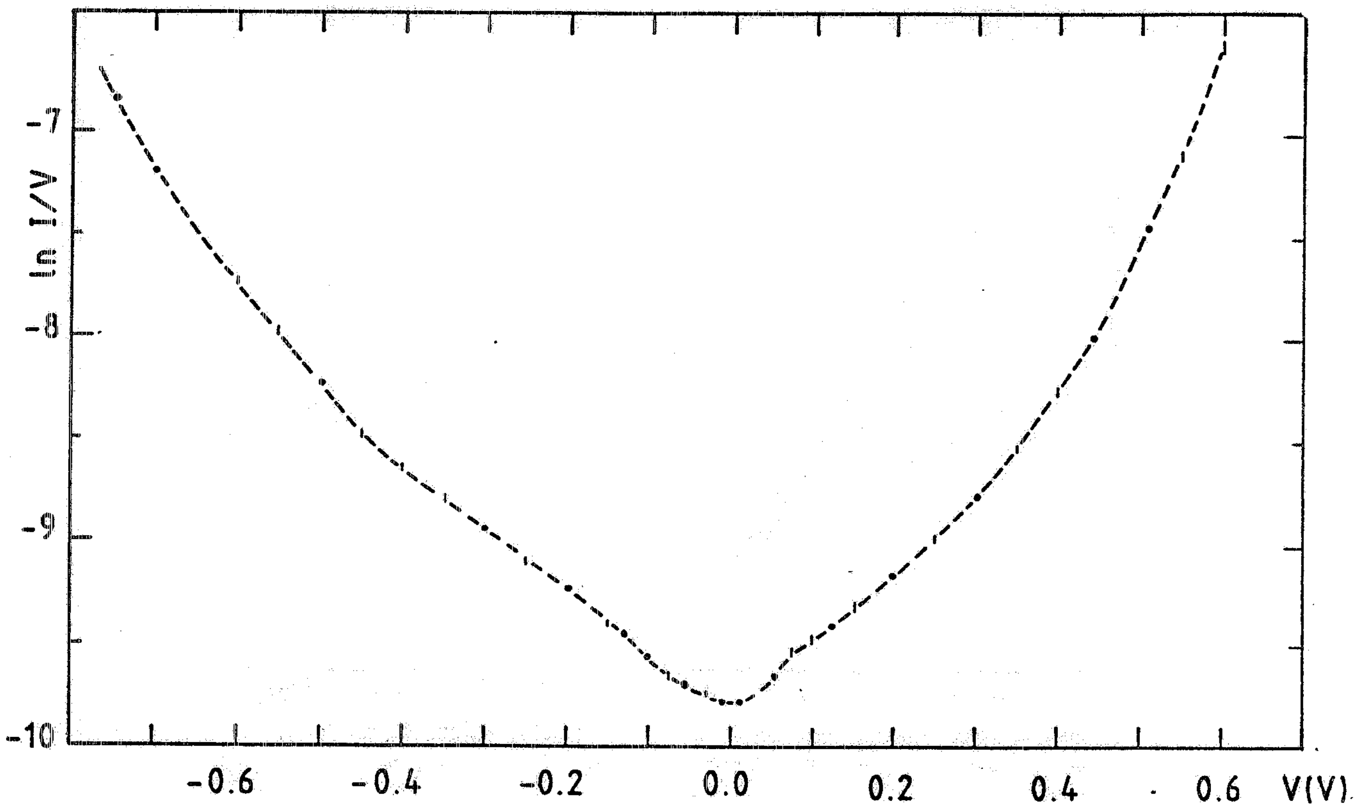

FIG. 5 - Log I/V versus V of a r.f. junction (sample 138H4S) with Rnn(300K) = 3200 ohm.

TABLE I - Main features of the analysis r.f. junctions

sample	dimensions (μm)	Rnn(77K) (ohm)	Rnn(300K) (ohm)	+V(max) (mV)	-V(max) (mV)
138H4M	150 x 150	625.0 K	4.2 K	350	400
138H4M	150 x 150	322.0 k		700	900
138H4S	40 x 40	17.7 K	3.2 K	75	125
138H4L	750 x 750	28.1 K	97.0	250	<100

b) Thermal Oxidation

In Fig. 6 in the semilogarithmic scale the I-V characteristics of the same junction for both room and 77 K temperature corresponding to different values of Rnn are reported. In these measurements the Nb voltage electrode has been connected to the negative input of the amplifier.

The accuracy of our measurements apparatus does not allow of accurate current measurements on the same full scale set-up for more than 2 - 3 decades, so that, in order to

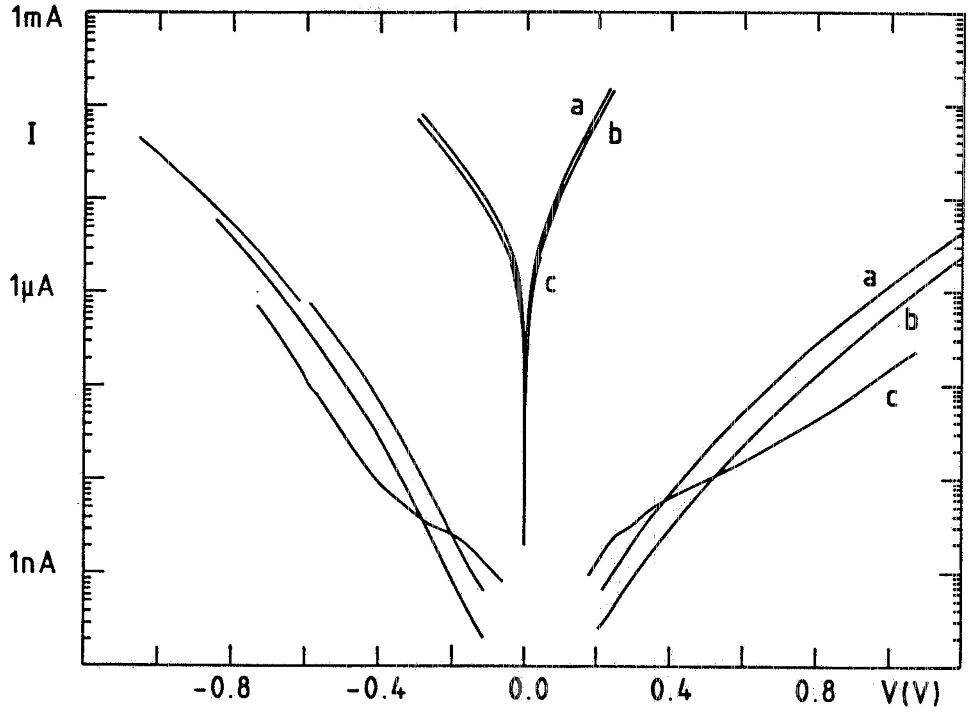

FIG. 6 - Room temperature and 77 K characteristics of the same thermal junction (sample 196E4M) corresponding to different values of Rnn: a) Rnn(300K)=17.9 Kohm; b) Rnn(300K)=23.0 Kohm; c) Rnn(300K)=38.5 Kohm.

record a complete I-V characteristic, the set-up must be changed two or three times, giving rise to measurement errors which are evident in the connection points between the covered ranges. Moreover, for the lower portion of the I-V characteristics of our very high resistance junctions, the presence of both noise and digital errors does not allow of the analysis of D for voltages lower than about 100-200 mV. Out of this range, D appears positive and a decreasing function of the voltage, so that, if D is equal to zero for V = 0, a maximum must exist in the non analysed voltage range. In Tab. II the values of Rnn and the actual information of the maxima are summarised.

TABLE II - Main features of the thermal junction 196E4M

sample	dimensions (μm)	Rnn(77K) (ohm)	Rnn(300K) (ohm)	+V(max) (mV)	-V(max) (mV)
196E4M	150 x 150	215 M	38.5 K	220	150
		600 M	17.9 K	<220	<150
		> 600 M	23.0 K	<200	<200

In conclusion, the experimental data clearly show that permanent variations of the tunnel barrier exist in connection with both the hysteresis of the I-V characteristics and the Rnn variations. These barrier variations have been measured in Nb/Pb junctions with tunnel barriers grown both with thermal oxidation and with r.f. plasma oxidation of the Nb base layer. In general thermal junctions show a simpler behaviour and appear more stable, so that in this case not very large variations of Rnn can be induced. The incompleteness of the performed measurements does not allow up to now a good understanding of which tunnel mechanism is changed by the applied voltages.

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