To be submitted to
Physics Letters A

ISTITUTO NAZIONALE DI FISICA NUCLEARE
Laboratori Nazionali di Frascati

LNF-85/16(P)
20 Maggio 1985

F. Celani, S. Catà, S. Pace and A. Ferrigno:

VOLTAGE INDUCED INSTABILITIES OF THE TUNNEL BARRIER IN Nb/Pb JUNCTION

Servizio Documentazione
dei Laboratori Nazionali di Frascati
Cas. Postale 13 - Frascati (Roma)

INFN - Laboratori Nazionali di Frascati
Servizio Documentazione

LNF-85/16(P)
20 Maggio 1985

VOLTAGE INDUCED INSTABILITIES OF THE TUNNEL BARRIER IN Nb/Pb JUNCTION

F. Celani, S. Catà
INFN - Laboratori Nazionali di Frascati - 00044 Frascati (Italy)

S. Pace, A. Ferrigno
Dipartimento di Fisica dell'Università di Salerno - 84100 Salerno (Italy)

ABSTRACT

The I-V characteristic of rather high resistance Nb/Pb tunnel junctions has been analyzed. At rather high voltage (V>100 mV) evident instabilities of the tunnel barrier have been observed both at room and liquid nitrogen temperatures.

These effects lead to unusual I-V characteristics which depend on the measuring time. We observed negative values of the dynamic resistance and variations of the normal tunneling resistance by a factor larger than 250.

1. - INTRODUCTION

In the framework of possible applications of superconducting tunnel junctions as ionizing particles detectors (SCODET experiment at INFN, Italy) we studied the stability and the structure of the tunnel barrier of Nb/Pb junctions.

In the last few years the normal tunneling behaviour(1,2) of tunnel barriers grown by oxidation of the Nb electrode has been analyzed: it has been shown the existence of different contributions to the tunnel current(3). The rather complex tunnel behaviour of Nb based junctions appears to be related to the large number of Nb oxides, which give rise to a complex barrier structure dependent on both the oxide thickness and the particular oxidation process.

In high resistance junctions it is possible to measure the I-V characteristic at rather high voltage values without destroying the junctions by self heating effects. In addition, it is possible to observe the instability effects of the barrier generated by such high electric fields.

These effects have been recently observed in Nb/Pb junctions with tunnel barries grown by plasma oxidation of the Nb-electrode(4). In particular at 300 K, for constant values of the bias current, we observed voltage drifts as a function of the time. The voltage drifts cause some hysterisis in the I-V characteristic, which depends on the time necessary for the drawing of this characteristic.

If the measured voltage is the difference between the Nb film and the Pb film voltages, a positive drift (a voltage increase) is observed for a voltage of a few hundred positive millivolts. For higher positive voltages or for negative voltages, a negative drift can be measured. Moreover the drift voltage velocity is an increasing function of the temperature and at room temperature it increases with $|V|$.

In the past, similar effect have been measured in:

a) Al-Al oxide - Al junctions[5]

b) Al-Al oxide - Pb junctions[6]

c) Pb/Bi/I_n - oxide - Pb/Bi junctions[7].

For Al-Al oxide - Al junctions the resistance increases by applying a voltage to the junction at low temperature or by exposure to light.

For Al-Al oxide - Pb junctions if the Pb electrode is positive the resistance decreases, while, if the Pb is negative, the resistance increases.

For Pb-Bi junctions R_{NN} decreases when the base electrode is negative and increases if it is positive.

To explain such effects, models involving both electron trapping in the barrier and ionic motion have been used.

In spite of the very large interest devoted to the study of Nb based junctions both for digital and analogical applications[8], the voltage induced instability effects of these junctions have not been reported in the literature.

2. - EXPERIMENTAL RESULTS

In this paper we report the results of an analysis of the voltage induced variations of the I-V characteristic at room temperature, where many different behaviours have been observed. We show that the variations of the tunnel barrier are permanent but can be changed by proper current/voltage pulses. In particular, we analyze the variations of the normal tunneling resistance $R_{NN}= dV/dI_{V\rightarrow 0}$).

We analyzed Nb/Pb junctions with a tunnel barrier grown by plasma oxidation of the base Nb electrode. Further information of the fabrication process are given elsewhere[4,9].

The typical I-V characteristic at liquid nitrogen temperature is shown in Fig. 1. In the insets both the experimental set up and the equivalent circuit of the junction are shown.

At room temperature the presence of a rather high voltage drift velocity makes very difficult the measure of the I-V characteristic in a time short enough to avoid tunnel barrier variations. Indeed, the presence of a rather high junction capacitance limits the possibility of an indefinite increasing of the measurements speed. The order of magnitude of the unity-area capacitance is indirectly known by measurements on "Fiske steps" appearing in Josephson junctions, which have values of R_{NN} much lower than the junctions analyzed in this paper. The linear and exponential

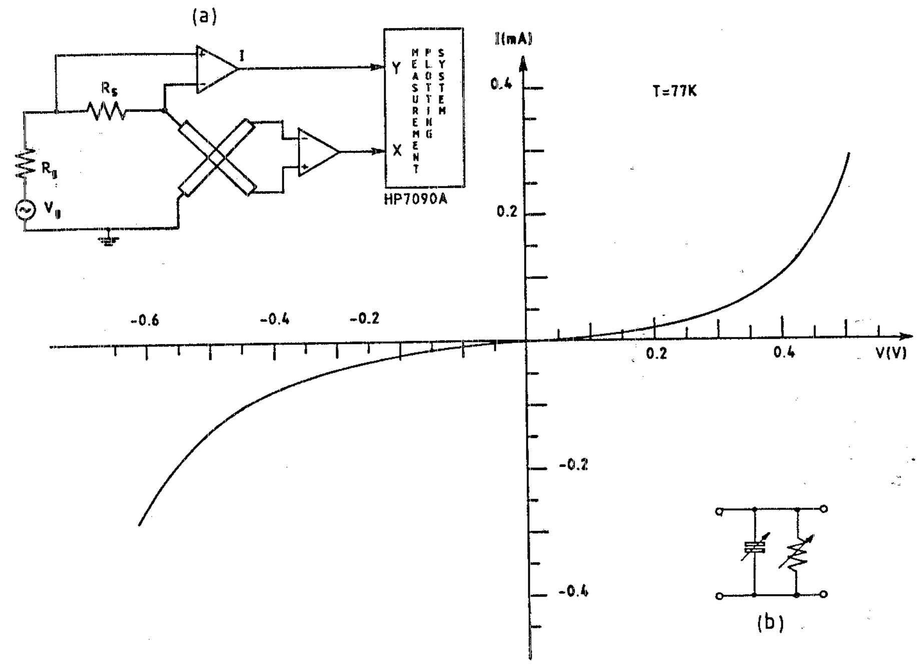

FIG. 1 - Typical I-V characteristic of a high resistance Nb/Pb tunnel junction at 77 °K: a) Experimental set up; b) Equivalent circuit.

dependence of respectively the capacitance and the R_{NN} on the oxide thickness makes this rough evaluation good enough for our purpose. We assume for the specific capacitance the value of ~ 30 $\mu F/cm^2$. On the same substrate (corning glass 7059) three cross geometry junctions have been fabricated with a capacitance respectively of 750 pF, 7 nF, 170 nF.

Some care has been taken in the experimental set-up to avoid phase shift effects generated by the junction capacitance and the external circuitry. For the measurements, single triangular, trapezoidal and sinusoidal voltage (V_g) pulses have been used. In Fig. 2a-f, the positive part of the I-V characteristics is shown for different values of the maximum applied voltage.

In Fig. 2a, due to the presence of a positive voltage drift, a clockwise hysteresis appears, which increases with the applied bias current. Moreover, the analysis of other similar I-V characteristics performed with larger value of T_W shows an increase of the hysteresis loop with the increase of T_W.

In Fig. 2b, a rarely observable characteristic is shown: in this case, before the maximum current is reached, a high speed positive drift of the voltage appears, but at the maximum of the current a new dominant negative drift appears. However, typically, as the applied voltage increases, the I-V characteristic shown in Fig. 2c appears: both the drifts appear, the positive dominant for low voltage as well as the negative for higher voltages.

A further increase of the applied signal give rise to I-V characteristic shown in Fig. 2d or 2f: above a threshold voltage, a very large negative drift appears, so that a negative resistance behaviour

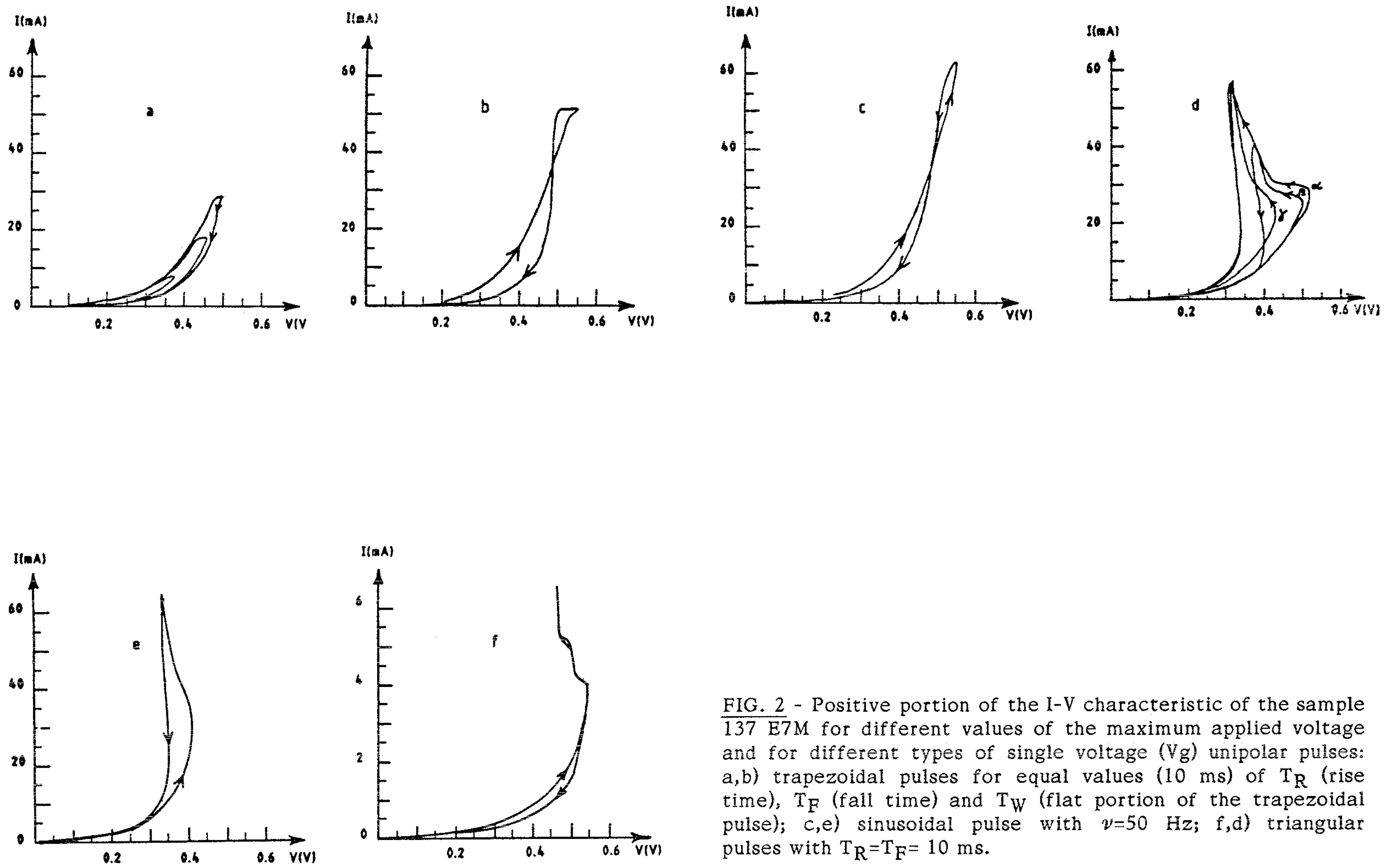

FIG. 2 - Positive portion of the I-V characteristic of the sample 137 E7M for different values of the maximum applied voltage and for different types of single voltage (Vg) unipolar pulses: a,b) trapezoidal pulses for equal values (10 ms) of T_R (rise time), T_F (fall time) and T_W (flat portion of the trapezoidal pulse); c,e) sinusoidal pulse with ν=50 Hz; f,d) triangular pulses with $T_R=T_F$= 10 ms.

is observed. The drift velocity is very high, so that the negative resistance is in somecase determined by the load line. This rapid voltage fall is sometime irreversible (Fig. 2d), sometime reversible (Fig. 2f). In the first case, subsequent voltage generator pulses give I-V characteristics like that of Fig. 2d α, β, γ where the voltage threshold decreases.

In Fig. 2e it is shown the I-V characteristic after a large (>20) number of identical pulses. It indicates very clearly some large decreasing of the tunnel barrier. In any case, both in Fig. 2d, 2e, 2f large portions of the I-V characteristic show negative dynamic resistance both for increasing and for decreasing values of the bias current.

A rather different and a more regular behaviour can be observed in the negative portion of the I-V characteristic.

In Fig. 3a,b the negative portion of the I-V characteristic is shown for different values of the maximum voltage.

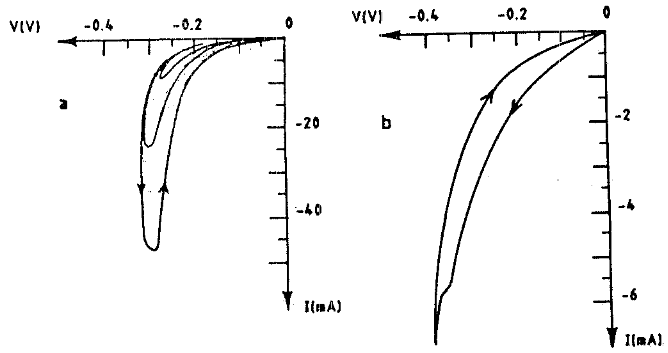

FIG. 3 - Negative portion of the I-V characteristic: a) Low voltage, anticlokwise behaviour; trapezoidal pulses with $T_R=T_F=T_W=$ 10 ms; b) High voltage, clokwise behaviour; triangular pulses with $T_R=T_F=$ 5 ms.

For voltages lower than $\simeq$ 350 mV an anti-clockwise hysteresis appears (Fig. 3a). The drift velocities increase as |V| increases, so that, since for increasing |I| the drift tends to decrease |V|, for a sufficiently high drift velocity, negative dynamic resistances appear. Also in the negative portion of the I-V characteristic appears some threshold voltage, which determines some sudden variation of the tunnel barrier. The corresponding I-V characteristic is shown in Fig. 3b.

In order to obtain numerical evaluation of the permanent variations of the tunnel barrier, the normal tunnel resistance $R_{NN}= dV/dI_{V\to 0}$ has been measured both before and after the I-V characteristic drawing. Small voltage pulses generate small decrease of R_{NN}, for example a pulse <100 mV decreases R_{NN} from 500Ω to 450Ω; pulses as in Fig. 2a-c cause a R_{NN} increase, for example such pulses vary R_{NN} from ~ 500Ω to ~800Ω; pulses as in Fig. 2d-f generate large decrease of the resistance, for example from ~ 500Ω to ~100÷200Ω.

For negative voltages, the pulses of Fig. 3a and Fig. 3b generate respectively an increase and a decrease of R_{NN}.

Large resistance increases can be obtained with longer rectangular pulses with an amplitude as in Fig. 2a.

Up to now we do not get the complete control of the process, since the effect of a pulse is a function of the junction conditions before the pulse. However, during a three month measurement period, we have changed the R_{NN} at least 20 times by a factor >2, and, among these, at least 10 times by a factor >5. In three cases the resistance is changed by a factor >15 and the maximum variation has been from 24Ω to 6500Ω corresponding to a factor >250.

However, the tunnel barrier variations appear to be permanent but they are reversible, so that the R_{NN} can be increased or decreased an idefinite number of times.

Methodical measurements of the stability of the tunnel barrier up to now have not been performed: small R_{NN} drifts have been observed in some cases. The stability has been checked for few R_{NN} values: the values 284Ω, 2800Ω are stable for some days within few percent.

At the liquid nitrogen temperature the processes appear not easily controllable: usually very slow voltage drifts can be observed at low voltages but if a threshold voltage is exceeded, voltage oscillations are generated(4) and up to now the R_{NN} variations are not predictable.

3. - DISCUSSION AND CONCLUSIONS

The observed behaviour appears more complicated than analogous R_{NN} variations measured by other authours(5,6,7) on Al-Al oxide-Al, Al-Al oxidePb, Pb/Bi/In -oxide-Pb/Bi junctions.

The complexity may be related to the rather complex structure of the oxide of Nb based junctions.

Different ions can have different mobilities and activation energies, so that a large number of processes can be involved and it is not easy to understand the effect on the different tunnel current contributions(1).

Low voltage effects seem to be strongly temperature dependent, so that it is presumable that they are related to ion mobility.

High voltage effects are sharp and can be related to some threshold effects.

The rather long time stability of the R_{NN} indicates that phenomena involving electron trapping in the barrier cannot play a significant role.

In conclusion, large R_{NN} variations induced by voltages have been observed in Nb/Pb junctions. The related tunnel barrier variations give rise to "anomalous" I-V characteristic, whose shape is a function of the measurement time and of the voltage drift velocity of the junction.

In particular, in some cases negative dynamic resistances appear.

Some care is needed because of the effects of the time constant (RC) of the junction itself and of the external circuitry.

Permanent but reversible variations of R_{NN} by factor >200 have been observed.

The adjustability of the tunnel barrier can be very useful for optimizing the coupling of the junctions with the external word in a large number of applications. In fact, the wanted reproducibility and large area uniformity of a tunnel barrier cannot be easily reached through the usual fabrication process.

A better understanding of the induced variation of the tunnel barrier requires a more accurate analysis of the I-V characteristic both at room and at low temperature.

Moreover, a systematic study of the drift voltage velocity could be useful for a better understanding of the involved processes.

ACKNOWLEDGEMENTS

We would like to thank Prof. J. Halbritter at KfK (RFG) for discussions on the resonant tunneling, Prof. C. Natoli and A. Savoia of LNF (Italy) for stimulating discussions about ion mobility. Moreover, we thank Dr M. Baffa, of LNF for his valuable support in data acquisiton and experimental set-up.

REFERENCES

(1) J. Halbritter, KfK-Report-3728 (Kernforschungszentrum, Karlsruhe, 1984).
(2) J.H. Magerlein, J. Appl. Phys. 55, 4027 (1984).
(3) J. Halbritter, Surf. Sci. 122, 80 (1982).
(4) F. Celani, S. Pace and M. Baffa, Phys. Lett. A111, 141 (1985).
(5) J. Kadlec and K.H. Gundlack, Thin Solid Films 20, 287 (1974).
(6) G. Hernàndez, D. Montalvo and T.A. Will, J. Appl. Phys. 53, 1065 (1982).
(7) K.H. Gundlack and H. Konishi, App. Phys. Lett. 46, 441 (1985).
(8) A. Barone and G. Paternò, Physics and Application of the Josephson Effect (Wiley, 1982).
(9) V. Lacquenti, G. Marullo and R. Vaglio, IEEE Trans. Magn. Mag. 15, 593 (1979).