

## Niobium Tunnel Junctions with Multi-Layered Electrodes

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**Abstract - The current-voltage characteristics of the niobium - aluminum oxide - niobium tunnel junctions have been studied systematically and compared with numerical simulations based on the microscopic theory of the proximity effect. The thickness of the base niobium layer is varied from 35 to 500 nm while the thickness of the aluminum layer is kept constant (about 9 nm). In a separate series of experiments the aluminum thickness is varied from 2 to 30 nm for two fixed thickness of the base electrode: 50 and 200 nm. The appropriate conditions for a full suppression of the so called "knee" structure at the gap voltage in the current-voltage characteristic are experimentally determined and theoretically interpreted in the framework of the microscopic theory. The influence of the additional layer of aluminum in a composite base electrode on the properties of the tunnel junction have been studied in dependence on the aluminum thickness and distance of this layer from the barrier. The obtained results demonstrate that the current-voltage characteristics of tunnel junction can be engineering by an appropriate layer thickness of compound base electrode.**

### I. INTRODUCTION

Nowadays the Nb-AlO<sub>x</sub>-Nb tunnel junctions are basic elements of most low-T<sub>c</sub> superconducting electronic devices and circuits. In particular the SIS-mixers based on the high quality Nb-AlO<sub>x</sub>-Nb tunnel junctions have the noise temperature limited only by the fundamental quantum value  $hf/2k$ ; these devices are currently used in the most mm and submm radio-telescopes. To realize quantum limited performance the SIS tunnel junctions with small leakage current  $I_l(V)$  under the gap voltage and minor energy gap spreading  $\delta V_g$  are required. It is especially important for relatively low frequency devices ( $f \sim 100 - 300$  GHz) since  $\delta V_g$  has to be much smaller than the frequency quantum  $hf/e$  and the leakage current at a bias voltage of about  $V_g - hf/2e$  determines the noise of the mixer. Any additional structure on the IVC of the junction considerably decreases the operation range of the mixer. The fabrication technology of Nb-AlO<sub>x</sub>-Nb tunnel junctions is based on the fact that a thin Al layer

appears between Nb and isolator barrier and the tunnel structure is Nb/Al/AlO<sub>x</sub>/Nb. It results in suppression of the Nb gap and appearance of the so-called knee structure due to proximity effect. In this report we present the study of the knee dependence on the thickness of the base Nb electrode and additional Al layer. The experimental results are compared with numerical calculations based on microscopic theory of the proximity effect.

### II. JUNCTION FABRICATION AND MEASUREMENTS

The SIS tunnel junctions were fabricated by using Selective Niobium Etching and Anodization Process (SNEAP) [3], [4] on the crystalline Si substrates covered by a buffer layer of Al<sub>2</sub>O<sub>3</sub> ( $d = 80$  nm). A trilayer structure Nb-Al/Al<sub>2</sub>O<sub>3</sub>-Nb was deposited in single vacuum run by using dc-magnetron sputtering for both Nb and Al films ( $P_{Ar} = 1 \cdot 10^{-2}$  and  $5 \cdot 10^{-3}$  mbar, deposition rate was of about 2 and 0.2 nm/s for Nb and Al correspondingly) [5]. The substrates were thermally attached to the holder under temperature control. Pure oxygen at appropriate pressure was used for the formation of the tunnel barrier (oxidation temperature 21 C, time = 20 min). The SIS junction area was defined by RIE followed by anodization, the thermally deposited SiO layer of about 270 nm is used as insulator.

A computer based data acquisition system is employed to measure the SIS tunnel junction IVCs. All measurements were done at  $T = 4.2$  K. The system operates in the constant current mode. This system collects the measured data, and computed junction parameters (up to 17 for a single sample). All data will be stored in a data base for further use (optimization of technological procedure, using real IVCs for computation and so on). The definition of the knee value is illustrated in Fig. 1. The knee current  $I_k$  is defined as the point of maximum deflection of the IVC from the  $R_n$  line.  $I_k$  is normalized to the quasiparticle current jump  $I_g$  at the gap voltage  $V_g$ . The value of  $I_g$  is evaluated as a current at  $V_g$  between lines of  $R_n$  and leakage resistance  $R_j$ . The value of  $V_g$  is determined at crossing of the bisector between  $R_n$  and  $R_j$  with measured IVC (see Fig. 1).

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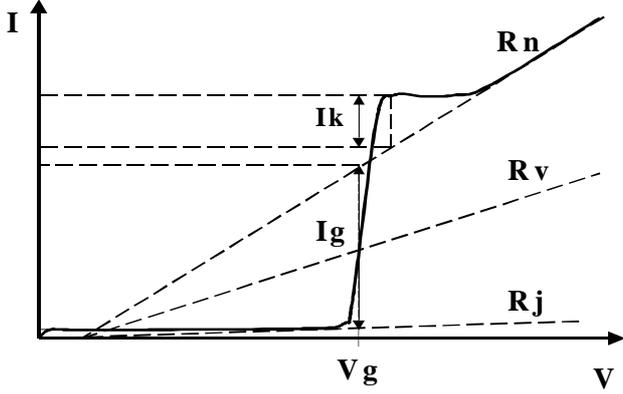


Fig. 1 Definition of the main parameters for the model SIS IVC.

The knee value strongly depends on many technological parameters and can be suppressed considerably by edge effects. The properties of the tunnel barrier on the perimeter of junction are different from the central part. It is caused by suppression of the gap due to plasma etching and especially anodization. As a result of averaging of the currents in the different parts of the junction the gap voltages is smeared and the knee is suppressed, especially for micron size junctions. The contribution of the outer part is decreased with increasing junction area  $A$  up to an  $A$  of about  $1500 \mu\text{m}^2$  for our technology. The knee does not change at further increase of the junction size since the contribution of perimeter becomes negligible. The external interference can also considerably suppress the knee for small junctions. Junction areas from  $120$  to  $7200 \mu\text{m}^2$  were used for this study; to minimize the influence of edge effect the data for  $A > 1500 \mu\text{m}^2$  are presented below.

### III. THEORY

According to the Werthamer tunnel theory the IVC of the Nb-Al/Al<sub>2</sub>O<sub>3</sub>-Nb (S-S'-I-S) tunnel junction depend on the quasiparticle density of states (DOS) in the S' layer (Al). We have calculated the DOS on the basis of the microscopic proximity effect model for S-S' bilayers described in [6]. The model assumes short electron mean free path (dirty limit conditions) both in S (Nb) and S' (Al) materials. The parameters of the problem are:

$$\gamma = \frac{\rho_s \xi_s}{\rho_s \xi_s^*} = \sqrt{\frac{D_{s'}}{D_s} \frac{N_{s'}(0)}{N_s(0)}}, \quad \gamma_B = \frac{R_B}{\rho_s \xi_s^*}.$$

Here  $\xi_s = \sqrt{D_s / 2\pi T_{cs}}$ ,  $\xi_s^* = \sqrt{D_{s'} / 2\pi T_{cs}}$ ,  $D_{s,s'}$ ,  $\rho_{s,s'}$  and  $N_{s,s'}(0)$  are the coherence lengths, the diffusion coefficients, the normal state resistivities and the electronic densities of states in the normal state of S and S' metals,  $T_{cs}$  is the critical temperature of S metal, and  $R_B$  is the product of the resistance of the S-S' boundary and its area.

These parameters can be understood as follows:  $\gamma$  is a measure of the strength of the proximity effect between S and

S' metals, whereas  $\gamma_B$  describes the effect of the potential barrier and/or Fermi velocities mismatch between these layers. Given the values of  $N_{s,s'}(0)$ , the value of  $\gamma$  can be estimated from RRR measurements of thin S/S' films, while the  $\gamma_B$  is an adjustable parameter. In practice both  $\gamma$  and  $\gamma_B$  may be determined from the fit to the data for IVC and for  $T_c$  of S/S' bilayer as a function of layer thickness'  $d_s, d_{s'}$ . The best fit with the experiment gives us the following set of the parameters:  $\xi_{Nb} = 15 \text{ nm}$ ,  $\xi_{Al} = 40 \text{ nm}$ ,  $\gamma = 0.3$ ,  $\gamma_B = 1$ . These parameters were used for IVC calculations, see Fig. 2, 3.

Calculations in the above model show that DOS in the S' layer has an energy gap  $\Delta_g < \Delta_{Nb}^{bulk}$  with large weight of filled subgap states in the energy range  $\Delta_g < E < \Delta_{Nb}^{bulk}$ . That leads to the appearance of the knee structure on the IVC. As is shown below, the knee disappears in the regime of thin S, S' layers. While some theoretical predictions have been made before [7], no systematic experimental study and comparison with the data was performed to date.

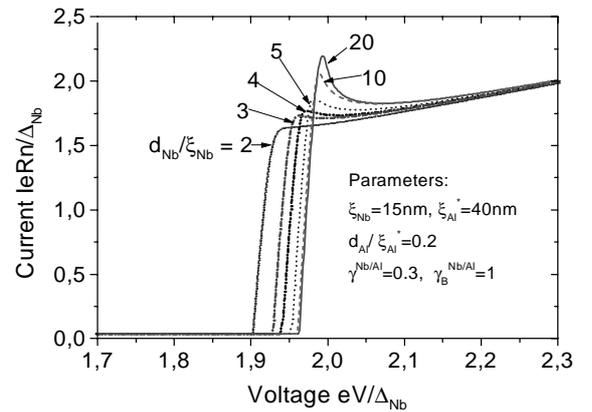


Fig. 2 Calculated IVCs for the S-S'/I-S structure at parameters corresponding to  $d_{Al} = 8 \text{ nm}$ . The thickness of the base electrode varies from 30 to 300 nm.

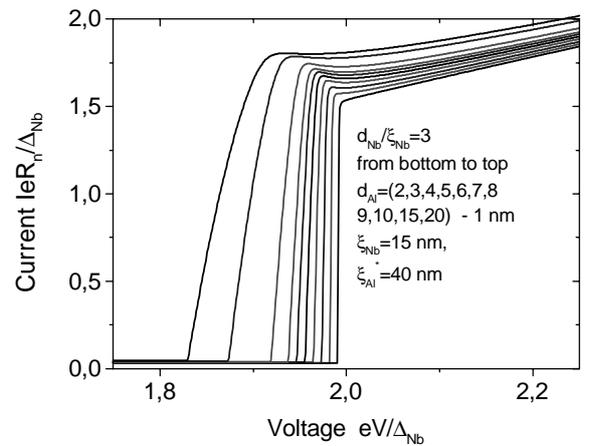


Fig. 3 Calculated IVCs for the S-S'/I-S structure at parameters, corresponding to  $d_{Nb} = 45 \text{ nm}$ . The thickness of the Al layer varies from 2 to 20 nm.

#### IV. RESULTS AND DISCUSSION.

The experimentally measured IVCs at different thicknesses of the base Nb electrode for  $d_{Al} = 9$  nm are presented in Fig. 4, the currents are normalized to  $I(4$  mV). The values of the knee determined from both theoretical and experimental curves, as well as the measured values of  $V_g$  are listed in the Table 1.

TABLE I  
PARAMETERS OF Nb-AIO<sub>x</sub>-Nb JUNCTIONS ( $A=7200 \mu^2$ ) for  $d_{Al} = 9$  nm

$d_{Nb}$ , nm	$I_k^*/I_g^*$ (theory for $d_{Al}=8$ nm)	$I_k/I_g$	$V_g$ , mV
35	0.04	0.055	2.75
50	0.85	0.075	2.77
75	0.145	0.105	2.79
100	0.185	0.17	2.82
150	0.245	0.195	2.84
200	0.285	0.245	2.86
350	0.325	0.21	2.86
500	0.325	0.225	2.86

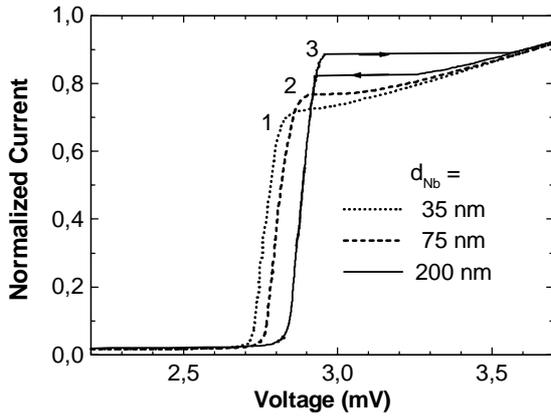


Fig. 4 Experimentally measured IVCs at  $d_{Al} = 9$  nm for 3 different thickness of the base electrode.

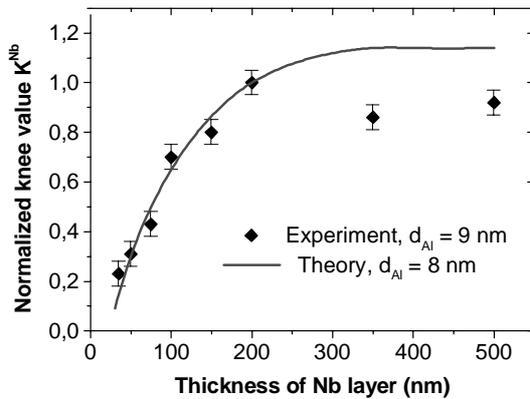


Fig. 5 Calculated and measured values of the knee (normalized to the value at  $d_{Nb} = 200$  nm) versus thickness of the Nb base electrode.

The normalized knee value  $K^{Nb} = I_k(d_{Nb})/I_k(200 \text{ nm})$  is shown in Fig. 5. One can see that the experimental dependence coincides well with the theory up to  $d_{Nb} = 200$  nm. At further increase of the Nb thickness the surface morphology of the sputtered Nb films changes considerably [8]. As a result the Al layer is not uniform and the measured knee (averaged over the junction area) is lower than the calculated one.

To avoid the morphology effect a thin Nb base electrode ( $d_{Nb} = 50$  nm) was used to study the knee dependencies on the Al thickness. The experimental IVC's for different Al thickness are shown in Fig. 6. It should be noted that the Al thickness is decreased at the oxidation, so 1 nm was subtracted from the initial value in the calculations (see Fig. 3). The obtained data are summarized in Table 2, the knee value as a function of Al thickness is shown in Fig. 7.

TABLE I  
PARAMETERS OF Nb-AIO<sub>x</sub>-Nb JUNCTIONS ( $A=1700 \mu^2$ ) for  $d_{Nb} = 50$  nm

$d_{Al}$ , nm	$I_k^*/I_g^*$ (theory)	$I_k/I_g$	$V_g$ , mV
2	0	-	-
3	0.016	0	2.86
4	0.031	0.01	2.85
5	0.041	0.02	2.84
6	0.05	0.03	2.83
7	0.056	0.04	2.81
8	0.060	0.05	2.78
9	0.062	0.07	2.77
10	0.065	0.085	2.73
15	0.07	0.115	2.66

The experimental dependency has a different slope as compared with the calculated curve. Furthermore at  $d_{Al}$  of about 8 nm the measured knee value abruptly increases and exceeds the theoretical one. An identical dependence is experimentally obtained for the thicker  $d_{Nb} = 200$  nm. This discrepancy can not be explained by uncertainty in the Al thickness.

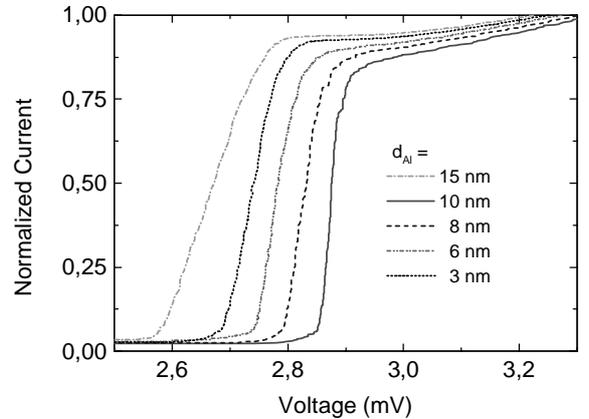


Fig. 6 Experimentally measured IVCs at  $d_{Nb} = 50$  nm for 5 different thickness of the Al layer.

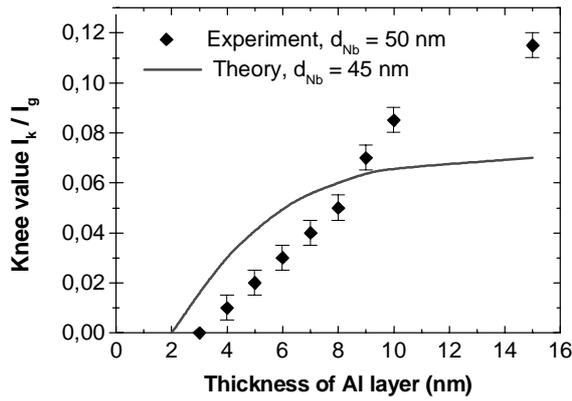


Fig. 7 Dependence of the knee value on the Al thickness (calculations and experiment).

This disagreement could be caused by a number of reasons: i) the transition from the surface electron scattering in the Al film to the bulk one; ii) additional DOS broadening due to inelastic scattering and/or Nb gap inhomogeneity along the junction. The theory is not strictly applicable to ultrathin Al films with surface scattering. The crossover from surface to bulk scattering takes place at a certain  $d_{Al}$ , the theory becomes valid and describes the increase of the knee value.

According to the obtained results thin Al layers ( $d_{Al} < 5$  nm) should be used to realize a "knee-free" IVC. This thin layer does not cover completely the Nb surface for thick Nb films ( $d_{Nb} \approx 200$  nm) because of its morphology. As a result the  $R_j/R_n$  ratio is considerably decreased with a reduction of the Al thickness ( $R_j/R_n$  is 40, 25, 12, 3 for  $d_{Al} = 7, 5, 4, 3$  correspondingly). Thin base Nb ( $d = 50$  nm) is completely covered by Al down to  $d_{Al} = 3$  nm (see Fig. 6);  $R_j/R_n$  is of about 40 for all used Al thickness.

The SIS junctions with thin Nb base electrode have almost ideal IVC but are not suitable for high frequency application since  $d_{Nb} < \lambda_L^{Nb} = 90$  nm, that considerably increases the inductance of the microwave elements. To overcome this problem an additional Al layer is introduced in the Nb base electrode to realize a "knee-free" IVC for reasonably thick base Nb (see Fig. 8).

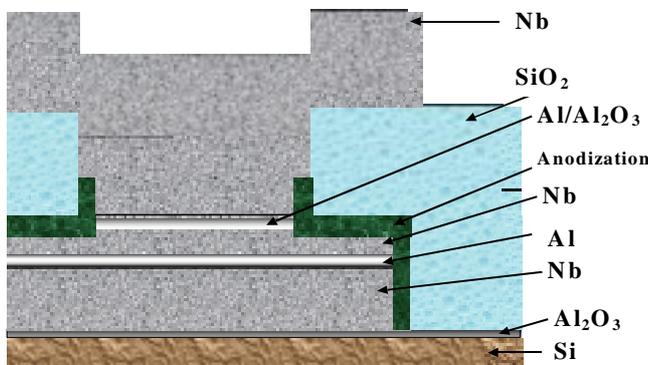


Fig. 8 Schematic cross-section of the Nb/Al<sup>0</sup>/Nb<sup>1</sup>-Al/AIO<sub>x</sub>-Nb structure with an additional Al interlayer.

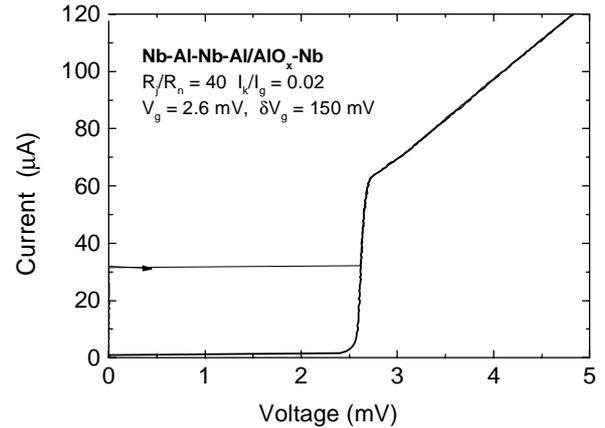


Fig. 9 IVC of the Nb/Al<sup>0</sup>/Nb<sup>1</sup>-Al/AIO<sub>x</sub>-Nb junction at thickness of the additional Al layer  $d_{Al} = 5$  nm and  $d_{Nb} = 50$  nm.

The introduction of an additional Al interlayer into Nb/Al/AIO<sub>x</sub>/Nb structures leads [8] to steeper IVC and disappearance of the knee structure. The reason is that with introduction of such a layer the order parameter in thin Nb-Al bilayer near the barrier becomes spatially homogeneous and thus the density of states in this bilayer becomes BCS-like with smaller energy gap. The experimental IVC for Nb/Al<sup>0</sup>/Nb<sup>1</sup>-Al/AIO<sub>x</sub>-Nb structure is shown in Fig. 9. One can see that this IVC is very close to the "ideal" one with slightly reduced gap voltage.

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