Niobium Tunnel Junctions with Multi-Layered Electrodes

Pavel N. Dmitriev, Andrey B. Ermakov, Alla G. Kovalenko, Valery P. Koshelets
Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Mokhovaya 11, 103907 Moscow, Russia

Nickolay N. Iosad,
Department of Applied Physics and Materials Science Centre, University of Groningen, Nijenborgh 4, 9747 AG Groningen, the Netherlands

Alexander A. Golubov
Low Temperature Division, Department of Applied Physics, University of Twente, P.O. box 217, 7500 AE Enschede, The Netherlands

Michael Yu. Kupriyanov
Institute of Nuclear Physics, Moscow State University, Vorobyovy Ghory, 119899, Moscow, Russia

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 ofthe 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_x-Nb tunnel junctions are basic elements of most low-T_c superconducting electronic devices and circuits. In particular the SIS-mixers based on the high quality Nb-AlOx-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 δV_g are required. It is especially important for relatively low frequency devices (f ~ 100 – 300 GHz) since δV_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-AlOx-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_x/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.

Manuscript received September 14, 1998
The work was supported in parts by the Russian Program for Basic Research and the Russian SSP "Superconductivity".

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_2O_3 (d = 80 nm). A trilayer structure Nb-Al/Al_2O_3-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).

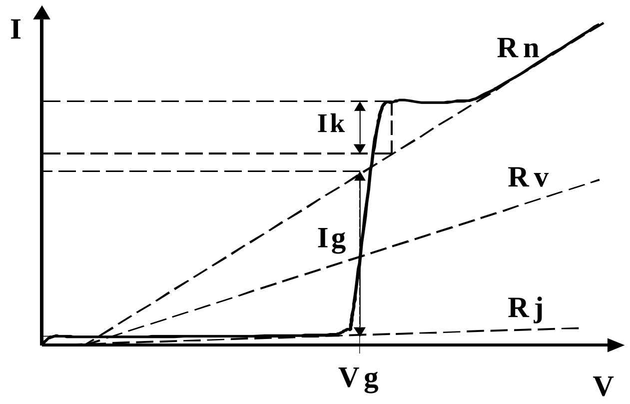

Fig. 1 Definition of the main parameters for the model SIS IVC.

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 μm^2 for our technology. The knee does not changed 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 μm^2 were used for this study; to minimize the influence of edge effect the data for A > 1500 μm^2 are presented below.

III. THEORY

According to the Werthamer tunnel theory the IVC of the Nb-Al/Al2O3-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:

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

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: γ is a measure of the strength of the proximity effect between S and S' metals, whereas γ_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 γ can be estimated from RRR measurements of thin S/S' films, while the γ_B is an adjustable parameter. In practice both γ and γ_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: ξ_{Nb} = 15 nm, ξ_{Al} = 40 nm, γ = 0.3, γ_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 $\Delta_g < \Delta^{bulk}_{Nb}$ with large weight of filled subgap states in the energy range $\Delta_g < E < \Delta^{bulk}_{Nb}$. 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.

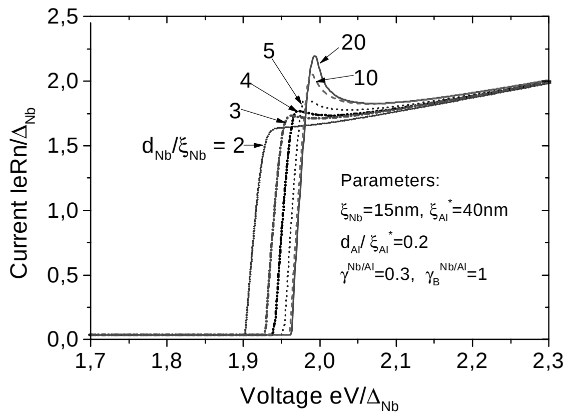

Fig. 2 Calculated IVCs for the S-S'/I/S structure at parameters corresponding to d_{Al} = 8 nm. The thickness of the base electrode varies from 30 to 300 nm.

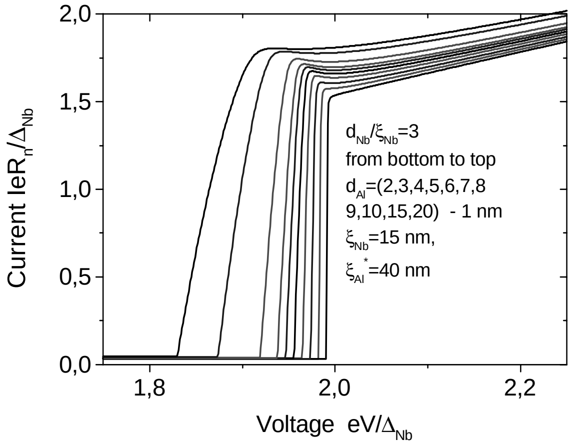

Fig. 3 Calculated IVCs for the S-S'/I/S structure at parameters, corresponding to d_{Nb} = 45 nm. The thickness of the Al layer varies from 2 to 20 nm.

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-AlO$_x$-Nb JUNCTIONS (A=7200 μ^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

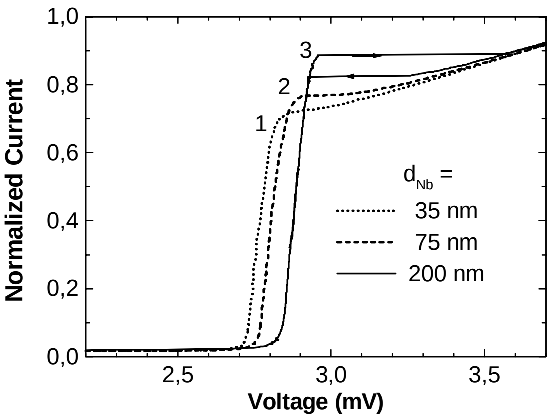

Fig. 4 Experimentally measured IVCs at d_{Al} = 9 nm for 3 different thickness of the base electrode.

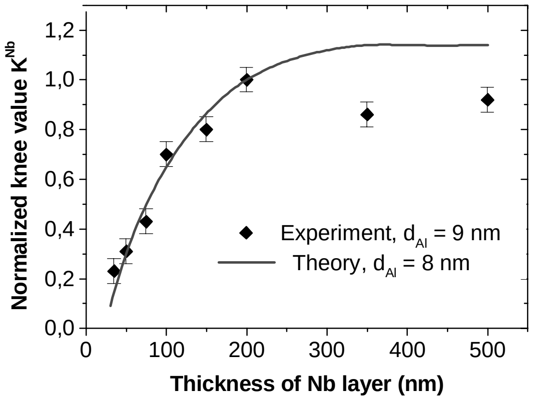

Fig. 5 Calculated and measured values of the knee (normalized to the value at d_{Nb} = 200 nm) versus thickness of the Nb base electrode.

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-AlO$_x$-Nb JUNCTIONS (A=1700 μ^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.

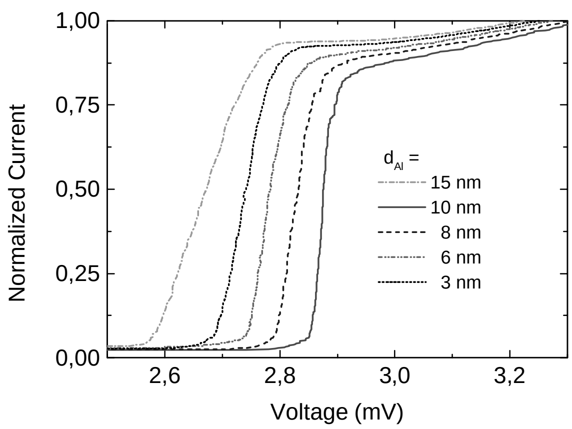

Fig. 6 Experimentally measured IVCs at d_{Nb} = 50 nm for 5 different thickness of the Al layer.

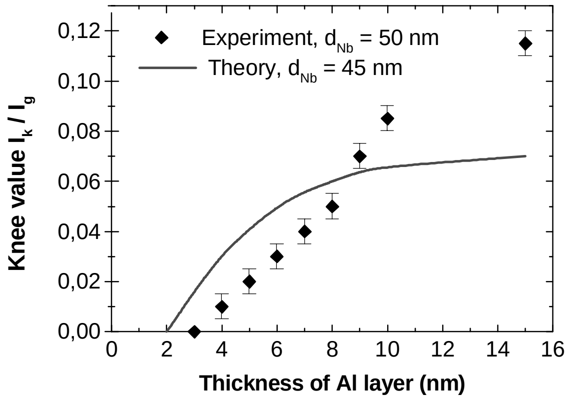

Fig. 7 Dependence of the knee value on the Al thickness (calculations and experiment).

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} ¤ 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).

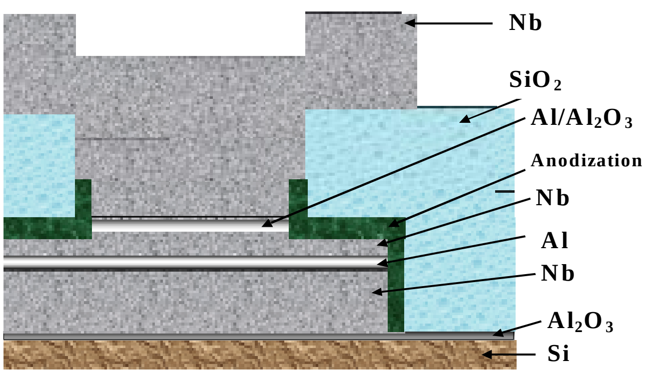

Fig. 8 Schematic cross-section of the $Nb/Al^a/Nb^a$-Al/AlO_x-Nb structure with an additional Al interlayer.

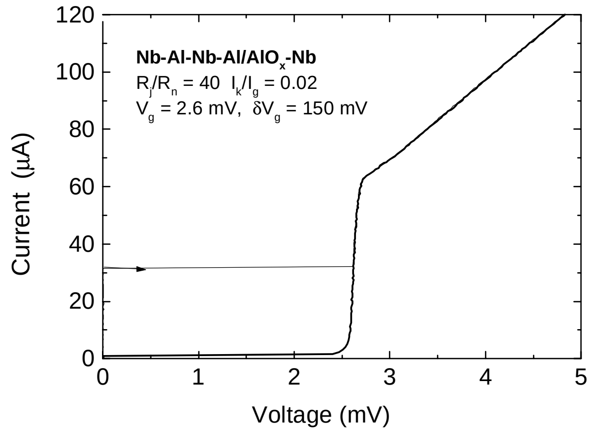

Fig. 9 IVC of the $Nb/Al^a/Nb^a$-Al/AlO_x-Nb junction at thickness of the additional Al layer d_{Ala} = 5 nm and d_{Nba} = 50 nm.

The introduction of an additional Al interlayer into $Nb/Al/AlO_x/Nb$ 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 $Nb/Al^a/Nb^a$-Al2/AlOx-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.

Authors would like to thank Willem Luinge for useful comments

References

[1] J. M. Rowell, M. Gurwitch, and J. Geerk, “Modification of tunneling barriers on Nb by a few monolayers of Al”, Phys. Rev. B., vol. 24, pp. 2278-2281, 1981.

[2] M. Gurwitch, W. A. Washington, and H. A. Huggins, “High quality refractory Josephson tunnel junctions utilizing thin aluminum layers”, *Appl. Phys. Lett.*, vol. 42, pp. 472-474, 1983.

[3] S. Morohashi, and S. Hasuo, “Experimental investigations and analysis for high-quality Nb/Al-AlO_x/Nb Josephson junctions”, *J. Appl. Phys.*, vol. 61, pp. 4835-4849, 1987.

[4] T. Imamura, T. Shiota, and S. Hasuo, “Fabrication of High Quality Nb/AlO_x-Al/Nb Josephson Junctions: I – Sputtered Nb Films for Junction Electrodes”, *IEEE Trans. on Appl. Supercond.*, vol. 2, pp. 1-14, March 1992.

[5] V.P. Koshelets, S.A. Kovtonyuk, I.L. Serpuchenko, L.V. Filippenko, and A.V. Shchukin, “High Quality Nb-AlOx-Nb Tunnel Junctions for Microwave and SFQ Logic Devices”, *IEEE Transactions on Magnetics*, vol. 27, pp. 3141-3144, 1991.

[6] A.A.Golubov, E.P.Houwman, J.G.Gijsbertsen, V.M.Krasnov, J. FLokstra, H.Rogalla “Proximity effect in superconductor-insulator-superconductor Josephson tunnel junctions: theory and experiment”, *Physical Review B*, vol. 51, 2 pp. 1073-1089, 1995 .

[7] A.A.Golubov, A.W.Hamster, M.Yu.Kupriyanov, J.Flokstra, H.Rogalla, “Characterization of junctions based on multilayer electrodes for application as X-ray detectors”, *Proceedings of the LTD-7 conference*, Munchen, pp. 16-17, 1997.

[8] T. Imamura, T. Shiota, and S. Hasuo, “Fabrication of High Quality Nb/AlO_x-Al/Nb Josephson Junctions: II – Deposition of Thin Al Layers on Nb Films”, *IEEE Trans. on Appl. Supercond.*, vol. 2, pp. 84-94, June 1992.