Investigations on $Nb/Al - AlO_x - Al/Nb$ tunneling junctions: the influence of the Al-thickness.

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Abstract

A $Nb/Al - AlO_x - Al/Nb$ five-layer process using a movable mechanical slit and a single lithographical and etching step for junction-detector applications is briefly described. In order to build devices using the quasiparticle-trapping concept, we varied the thickness of the Al films from 1 nm to 120 nm and measured the superconducting gap parameter as a function of temperature and magnetic field. The temperature dependence of the sub-gap current in the range of 0.45 to 4.2 K was measured. Deviations from thermally activated behavior due to imperfections in the tunneling barrier are often observed.

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1 Introduction

Tunneling junctions with superconducting electrodes are promising candidates for the fabrication of X-ray detectors with a high energy resolution [1]. If the device is biased at a voltage below the superconducting gap voltage at low temperature, the tunnel current reflects the thermal equilibrium distribution of quasiparticles (qp). **Excess** qp created by the absorption of an X-ray photon in one superconducting electrode may tunnel accross the oxyde barrier and can be sensed as a charge pulse. In the ideal case, the amount of collected charges is proportional to the amount of qp charge carriers (broken Cooper pairs) produced by the initial X-ray event. Different energy-loss mechanisms are present, however, and thus degrade the energy resolution of the device [2]. One important loss channel is due to qp recombinations. Booth [3] proposed the use of two superconducting layers with different energy gap parameters connected to a tunnel barrier. In such a system, the excess qp created in the absorber layer diffuse into the trap layer and encounter a potential well (smaller gap). Trapping has been demonstrated to be effective for X-ray detection devices [4, 5] using two superconductors with different gap parameters as well as with devices made out of one superconductor in contact with a normal metal [6]. In principle, trapping can take place in any region where superconductivity is weakened,

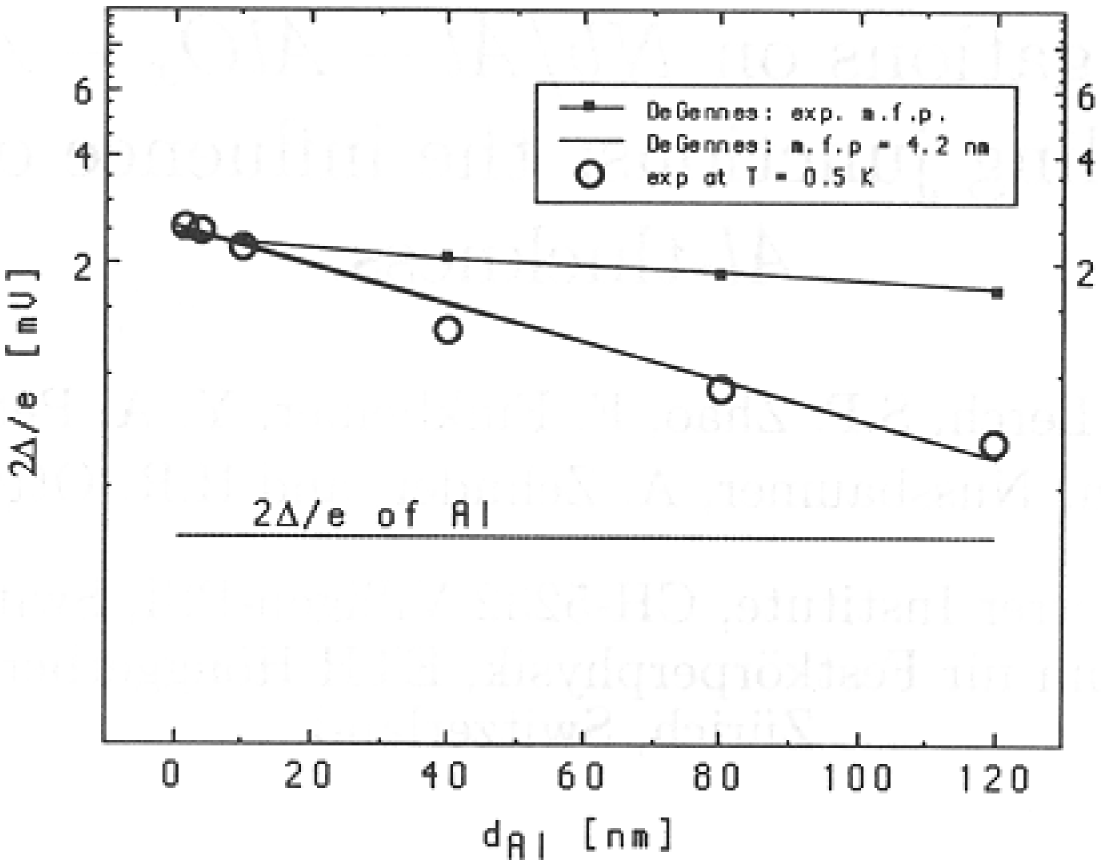

Figure 1: Semi-log plot of the effective superconducting gap as a function of *Al* film thickness.

for example at the substrate-film interface or within the core of an Abrikosov vortex. Quasiparticles trapped in such regions cannot tunnel anymore and are lost.

In a sandwich consisting of two different superconductors the proximity effect [7] is known to modify the superconducting properties of both layers in contact. Thus, when studying devices involving as much as five layers, one of which being the tunnel barrier, the knowledge of the influence of parameters like thickness of the layers, temperature, or applied magnetic field on the junction characteristics is of importance. The problem of the quasiparticle relaxation rates in proximity effect systems has been modelled by Golubov et al. [8], and experimentally studied by Houwman et al [9] for devices with thin *Al* trapping layers. In the following we present preliminary experimental results taken on a set of symetrical $Nb/Al/Al_2O_3/Al/Nb$ junctions with *Al* film thicknesses ranging from 10 to 120 nm. An quantitative analysis of this data using different proximity-effect models will be presented elsewhere.

2 Sample preparation

The fabrication procedure has previously been described in detail [10]. Briefly, we use sputtering techniques in UHV environment and deposit first a *Nb*− followed by an *Al* film through a mechanical mask onto r-plane oriented Al_2O_3 or random oriented SiO_2 substrates. Then, the oxidation step is accomplished in a partial pressure of oxygen, and we finally adjust the slit mask without breaking the vaccum in the chamber before the deposition of the second *Al* and *Nb* films. The position of the mask is chosen in order to produce a 100 μm by 5 mm overlap across the substrate. The junction area, ranging from 20 x 20 μm^2 to 100 x 100 μm^2, is defined in a single photolithographical step followed by reactive ion etching in an SF_6/Ar mixture.

3 Results

Current-voltage (IV) curves (not shown) were measured in a classical 4-point configuration. We determined $2\Delta_{eff}(T, d_{Al})/e$ from the steep current rise due to qp tunneling, the Josephson current of the device being suppressed by a magnetic field of a few Gauss applied parallel to the plane of the junction. The current increase at the gap feature sharpens with decreasing temperature. Above the energy-gap feature, there is a clear "constant-current" feature characteristic for SIS devices including an electrode with 2 materials having different energy gaps. This second feature rounds smoothly off if T and/or d_{Al} increase. We observed no indications for assymetrical junctions in the IV curves, and the critical temperatures of the top and bottom electrodes were the same within 4 to 10 % irrespective of the *Al* film thickness.

The dependence of $2\Delta_{eff}(T, d_{Al})/e$ upon d_{Al} measured at 0.5 K is first shown (open circles) in Fig. 1. A clear decrease of the gap with increasing *Al* thickness is observed. The effective gap follows approximately the form $\Delta(T, d_Al) \propto \Delta(T)exp(-d_{Al}/\xi)$ [7] where $\Delta(T)$ is the temperature dependent function describing the gap parameter of the (weakly) perturbed superconductor (here *Nb*), $\xi_{dirty} = (\hbar v_F l_{Al}/6\pi k_B T)^{1/2}$ is the length over which the superconducting properties of the *Nb* layer diffuse into the *Al* layer. In this relation v_F and l_{Al} are the Fermi velocity of electrons and the electronic mean free path (m.f.p) in the *Al* film respectively, T is temperature. The solid line in Fig. 1 is obtained with $\Delta(T) = 2.51mV$, a value in good agreement with the one measured on devices with thin *Al* films, with an electronic mean free path (m.f.p) l_{Al} of 4.2 nm and a temperature of 0.5 K. The electronic m.f.p can be affected by surface scattering as well as by the volume impurity content. We observed a clear dependence of the m.f.p. with film thickness in separate experiments on *Al* films and *Nb/Al* bilayers deposited under the same conditions as the junctions. In single *Al* films, the m.f.p. changes linearily from 5 to 30 nm if the film thicknesses varies from 10 to 120 nm. For *Nb/Al* bilayers, the m.f.p varies (not linear) from 5 to 62 nm over the same thickness range of *Al* with a constant *Nb* thickness of 200 nm. The m.f.p. value we introduced into DeGennes' relation correponds to the limit of thin films. In order to take into account the thickness dependence of $l_{Al}(d_{Al})$ we inserted the measured m.f.p. values of bilayers in DeGennes' relation using a temperature of 0.5 K and a prefactor of $\Delta(0.5\ K) = 2.51mV$. The result is presented with a solid line together with squares in Fig. 1. The agreement is less satisfactory. The dashed line shows the gap value of *Al*.

The temperature dependence of the effective gap is presented in Fig. 2. For the device with the thinnest *Al* film, the gap parameter is temperature independent below 4 K already and is reminiscent of a BCS-like behavior. On the other hand devices with thicker *Al* electrodes show a much stronger temperature dependence of the gap which is due to the temperature dependence of the proximity effect between *Nb* and *Al* itself.

The temperature dependence of the measured critical current is shown in Fig. 3. The deviation from BCS-like behavior can be visualized by using the relation [11] between the energy gap $\Delta(T)$ and the tunneling current density $j_c(T) = (\pi\Delta(T)/2eAR_n)\ tanh(\Delta(T)/2k_BT)$ where R_n is the junction's tunneling resistance, and A the tunneling barrier area. We computed j_c using this relation with the data shown in Fig. 2. The result is shown in Fig. 4. As expected, the temperature dependence of the critical current data is stronger than the one obtained with the BCS-prediction. This again reflects the temperature dependence of the exponent in the proximity effect expression. The data shown are similar

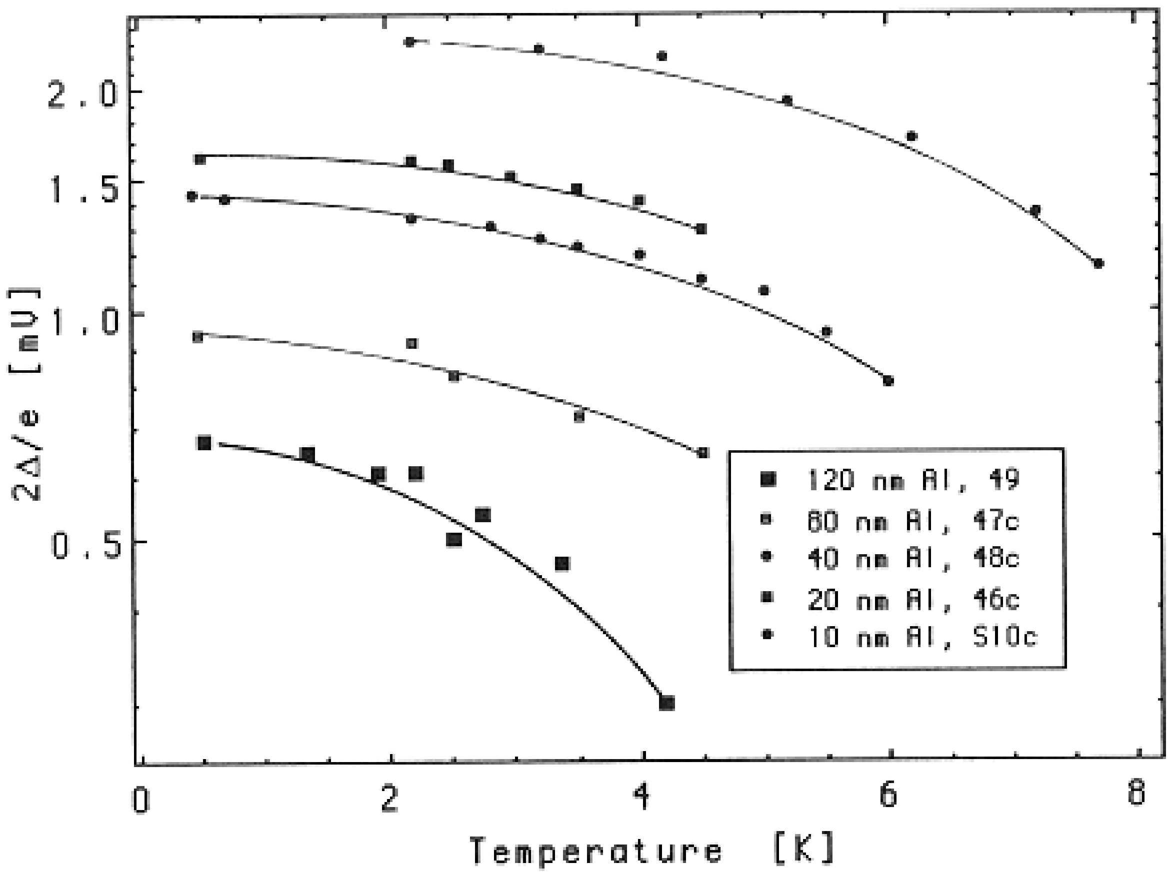

Figure 2: Effective superconducting gap measured as a function of temperature for devices with different *Al* film thicknesses.

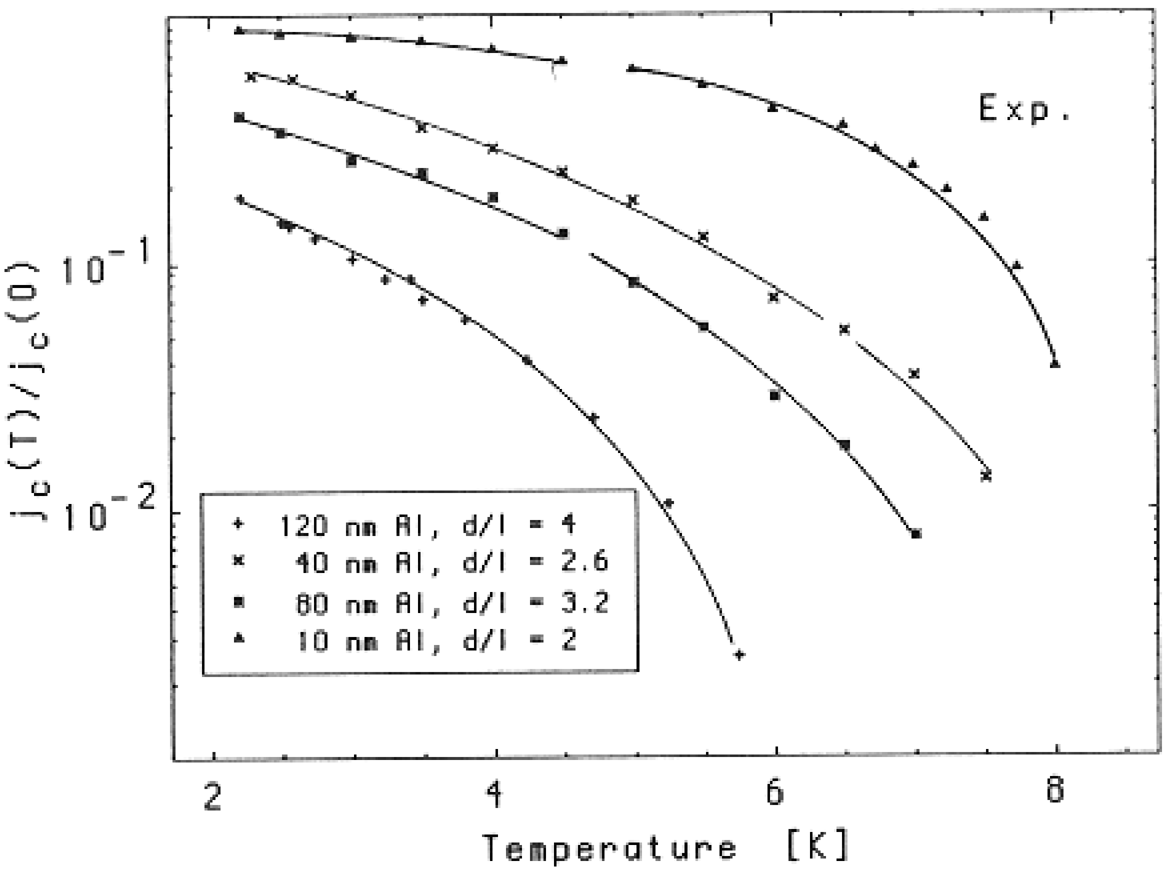

Figure 3: Experimental critical current densities as a function of temperature.

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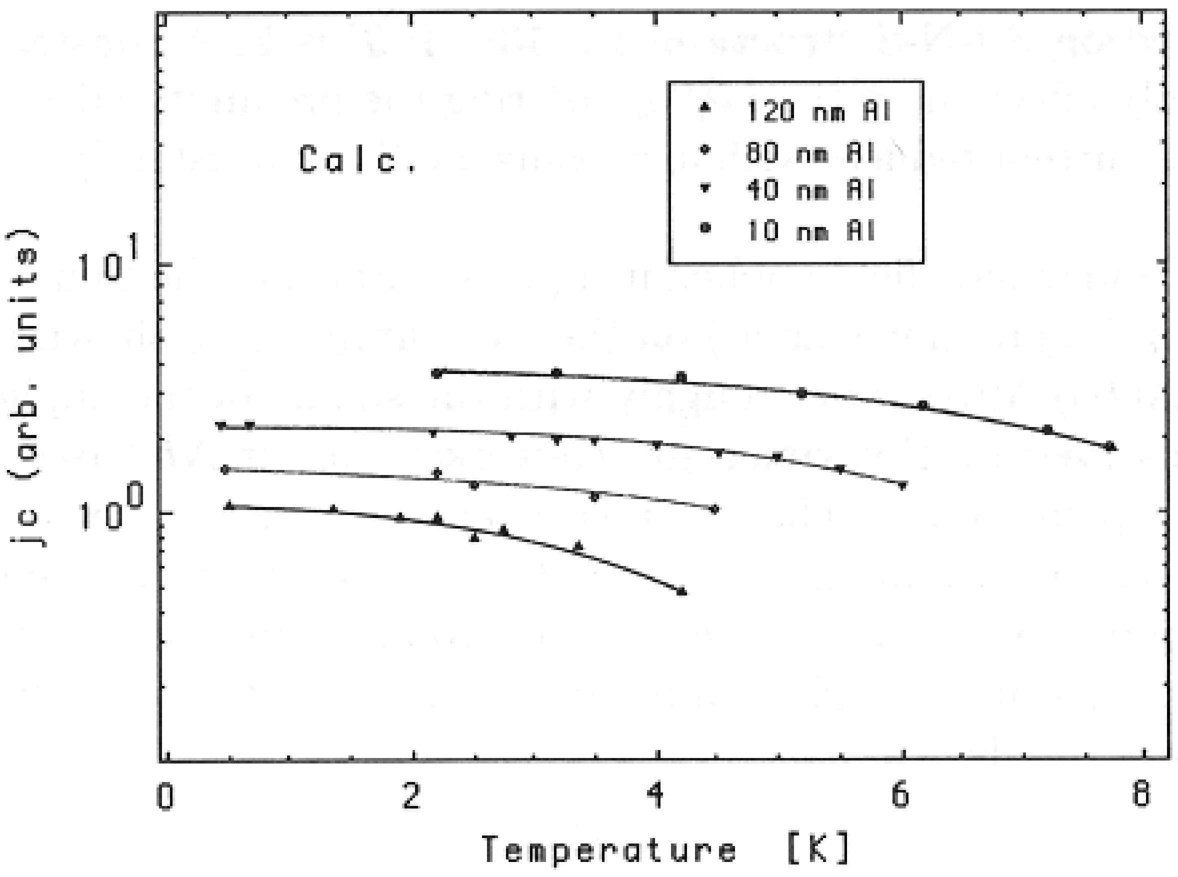

Figure 4: Critical current densities as a function of temperature computed with the data shown in Fig. 2 and the BCS relation.

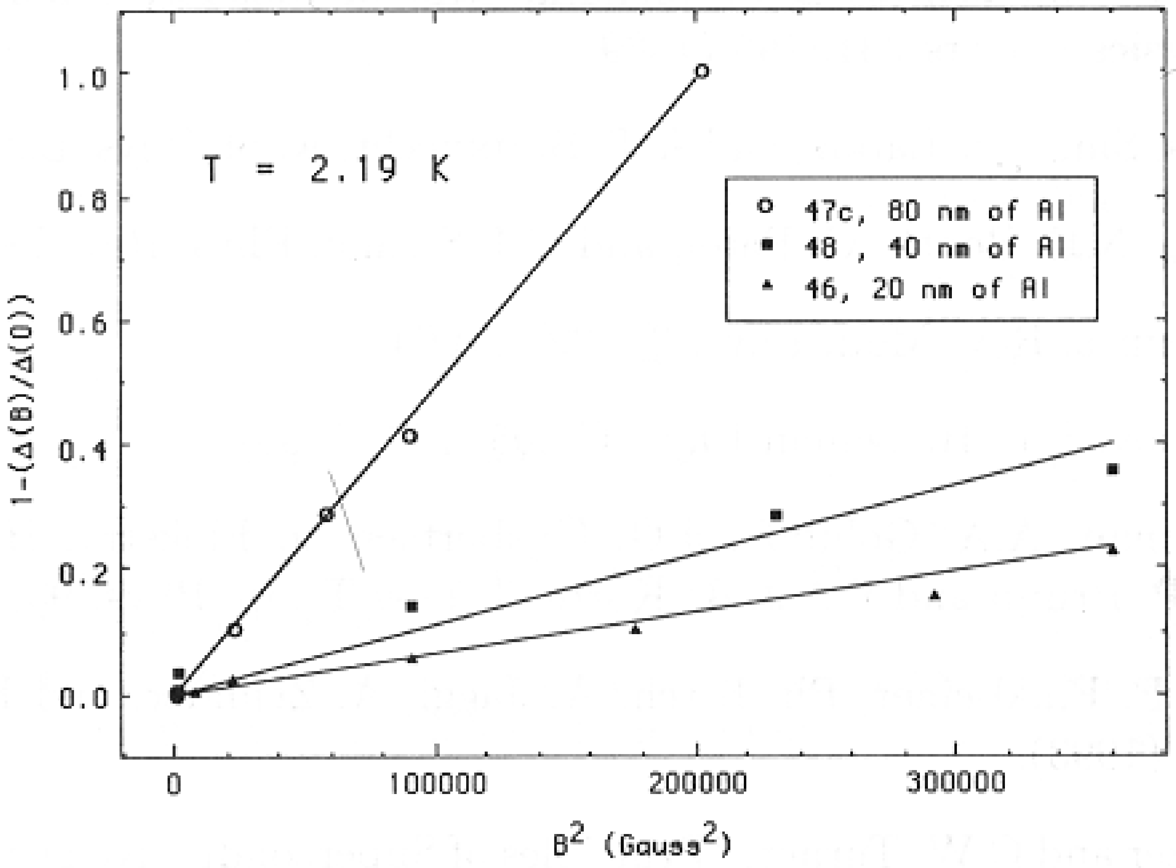

Figure 5: Energy-gap change $1 - (\Delta(B)/\Delta(0))$ as a function of B^2.

to those obtained on S-I-N-S structure [12, 13]. If T is kept constant, a change in Al thickness will only affect the ratio d_{Al}/l_{Al} entering the proximity effect expression for the gap. The critical current reduces with increasing d_{Al}/l_{Al}, consistently with the observation made earlier.

The effect of a magnetic field applied in a plane parallel of the tunnel barrier and larger than ϕ_o/A (A is the junction's area) on the gap parameter is shown in Fig. 5. The gap reduction $1-(\Delta(B)/\Delta(0))$ varies roughly with the square of the applied field. A similar behavior was observed by Houwman and co-workers [9] for Nb-based junctions with Al film thicknesses up to 25 nm. The observed change is consistent with the pair-breaking effect due to screening currents flowing near the surface layer of a type II superconductor.

With our simple fabrication technique we produce junctions that enable the study of the influence of parameters like temperature, magnetic field, Al-film thickness on the basic properties of the device.

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