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PROXIMITY EFFECT IN Nb/Al,AlOxide,Al/Nb JOSEPHSON TUNNEL JUNCTIONS

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Abstract--Regions with reduced energy gap induced by the proximity effect give rise to quasi-particle loss in Josephson junction X-ray detectors, but may also be used advantageously for quasi-particle collection.

The influence of the thickness of the Al proximity layers in $Nb/Al_1,Alox,Al_2/Nb$ Josephson tunnel junctions on the electrical characteristics has been investigated theoretically and experimentally. Theoretically it is found that the strength of the proximity effect is mainly determined by the proximity parameters γ_{M1} (γ_{M2}) of the electrodes. Good fits of the measured IV-curves with theory were obtained for junctions with thicknesses d_{Al1} ranging from 4 to 25 nm and d_{Al2}=3nm, with $\gamma_{M2}\approx 0.12$ and $\gamma_{M1}/\gamma_{M2}=d_{Al1}/d_{Al2}$. For all junctions the proximity knee remains more pronounced than predicted. The measured $I_c(T)$ and $V_g(T)$ curves could be fitted, taking $\Delta_{0S}/k_BT_{cS}\approx 1.92$ for Nb.

I. INTRODUCTION

X-ray detectors for astronomy applications are developed on the basis of Nb/Al,Alox,Al/Nb tunnel junctions [1]. In such devices the tunnel junction is biased in the quasi-particle (q.p.) tunneling regime, mostly below half the sumgap voltage. An impacting X-ray photon (with energy E_X) creates a cascade of hot phonons and q.p.'s that relax to the bandgap. The excess q.p. density gives rise to an excess tunneling current, which is measured.

The energy resolution $\Delta E/E_X$ of a junction detector is proportional to $N^{-1/2}$, with N the number of tunneling q.p.'s. This number is mostly reduced compared to the total number of created excess q.p.'s by various loss mechanisms.

In practical devices often regions with reduced energy gaps are present. A fraction of the excess q.p.'s is trapped in these regions by energy relaxation and is in most cases lost for tunneling.

A proximity layer adjacent to the barrier with lower energy gap and smaller volume than the layer, in which the X-ray photon is absorbed, works as a trap for the q.p.'s. Such a layer can be used advantageously to collect the excess q.p.'s from the large volume of the absorber layer. It was shown that a large signal gain can be obtained if a trapping layer is used compared to the case without such a layer [2].

In general a very high dynamical resistance R_D at the bias point increases the signal and facilitates the demands on the read-out electronics. In SIS junctions with electrodes with the same properties in theory very high and even negative R_D can be obtained. However, at the low operating temperature T_{op} of X-ray detectors $T_{op}/T_{cS} \leq 0.15$, often leakage currents show up, that dominate the dynamic resistance. In junctions with dissimilar electrodes a peak shows up in the subgap at the gap difference voltage. The associated negative resistance may compensate the leakage resistance and very high dynamic resistances might be obtained. Such asymmetric junctions can be obtained in the Nb/Al system by employing different Al layer thicknesses at the base and the counter electrode.

The effects of proximity layers on the superconducting properties have often been described by the McMillan proximity effect tunneling model [3]. This model assumes a potential barrier with low transparency at the interface of the layers and layer thicknesses less than the coherence lenghts of the metals. However, in real structures the metals are mostly in close electrical contact and the layer thicknesses generally exceed the coherence lengths. More recently a microscopic model of the proximity effect in SN-bilayers was developed, which is based on the calculation of the coordinate dependence of the Green's functions [4]. This model was extended to SS'-bilayers and to the calculation of the characteristics of SS'IS"S junctions [5]. It was found that the proximity effect in such devices is dominantly characterized by a single parameter γ_M, describing the strength of the proximity effect, for each electrode.

Further the trapping rate of (superconducting)

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proximity layers on a bulk superconducting layer has been determined theoretically as function of γ_M [6]. With the results of these calculations the q.p. collection process can be treated much more accurately.

In this paper we present the first results of a systematic study on the proximity effect in Nb/Al-junctions. A series of Nb/Al$_1$,Alox,Al$_2$/Nb junctions with different d_{Al1}/d_{Al2} ratios of Al layer thicknesses, but constant d_{Al2} has been fabricated. We measured current-voltage characteristics, as well as the temperature dependence of the critical current and the gap voltage. The measurements were described with the results of the microscopic model of SS'IS"S junctions. Fairly accurate values for the γ_M-parameter could be determined, that are used for the calculation of q.p. trapping rates [1].

II. THEORY

In the microscopic model for SS'IS"S junctions the Green's functions $G(\omega,\vec{x})$ and $F(\omega,\vec{x})$, and the order parameter $\Delta(\omega,\vec{x})$ are calculated as function of the distance from the surface of the S' layer into the SS'-bilayer.

It is assumed that the critical temperature of the bulk superconductor (S) is larger than that of the proximity layer (S') $T_{cS}>T_{cS'}$; $d_S \gg \xi_S \gg l_S$; $l_{S'}<d_{S'} \ll \xi_{S'}$ ($d_{S,S'}$, $\xi_{S,S'}$, $l_{S,S'}$ are the thickness, coherence length and electron mean free path in the S resp. S' layer). The latter conditions imply that 1) both layers are in the dirty limit; 2) the order parameter $\Delta(x)$ and the Green's functions relax to their bulk values deep in the S-layer; 3) the functions G, F, and Δ are assumed to be constant over the S' layer; 4) the T_c of the bilayer is not reduced compared to the T_{cS} of the bulk S-metal. Details on this model of the proximity effect are given elsewhere [4,5].

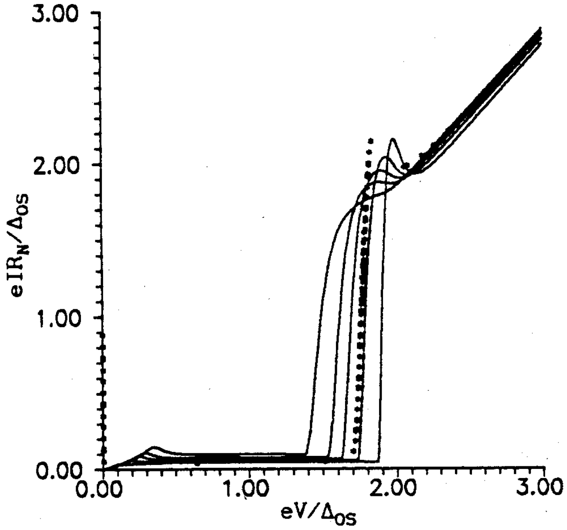

Fig.1: Current-voltage characteristics of SS'IS"S junction with $\gamma_{M1}/\gamma_{M2}=5$ and $\gamma_{M2}=0.05$; 0.1; 0.15; 0.2; 0.3 for the curves with decreasing gapvoltages respectively, at $T/T_{cS}=0.46$ (solid curves). Exp. data of Nb/Al junction with γ_M-ratio=5 (*).

In the calculations presented here it is assumed that there is no potential barrier at the interface between the S and S' layer. This means that the boundary parameter $\gamma_B=(2l_{S'}/3\xi_{S'})(R/(1-R)) \ll 1$, where the boundary reflection coefficient R is equal to $R=(v_{FS}-v_{FS'})^2/(v_{FS}+v_{FS'})^2$, with v_{FS} ($v_{FS'}$) the Fermi-velocities in S (S').

The proximity parameter $\gamma_M=(\sigma_{S'}\xi_S/\sigma_S\xi_{S'}) \times (d_{S'}/\xi_{S'})$ with $\sigma_{S,S'}$ the normal state conductivities of the S and S' metals, determines predominantly the extend of the influence of the proximity layer. The critical temperature ratio $T_{cS}/T_{cS'}$ influences the calculations only little, and the results presented here apply also to cases with somewhat different T_c-ratios. The relevant parameter is $\log(T_{cS}/T_{cS'})$ and its variation can be taken into account by means of a renormalization procedure [7].

With the assumptions $l_S \ll \xi_S$ and $l_{S'} \ll \xi_{S'}$ tunneling out of the bulk can be neglected and the tunneling currents can be expressed in terms of the Green's functions at the S'I, respectively IS" interfaces.

In the present calculations we consider the case of a Nb/Al sandwich taking $T_{cS}=9.2K$ and $T_{cS'}=1.3K$. In first instance we are interested in junctions with a thin Al layer, thickness $d_{S''}$, at the counter electrode and an Al layer with variable thickness, $d_{S'}$, at the bottom electrode.

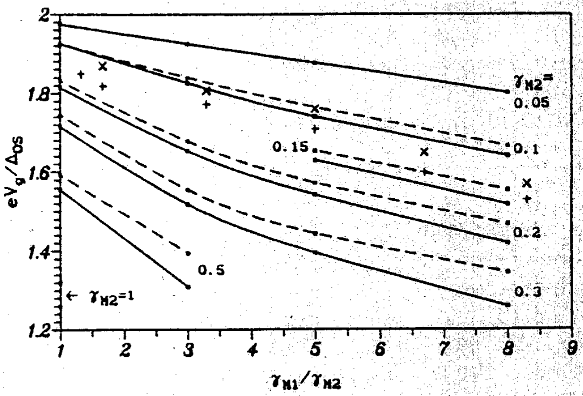

Fig.2 Reduced gapvoltage as function of γ_M-ratio in SS'IS"S-junctions with γ_{M2} as parameter, Theory: —— ($T/T_{cS}=0.46$), - - - ($T/T_{cS} \ll 1$); experimental data: + (4.2K), x (1.6K).

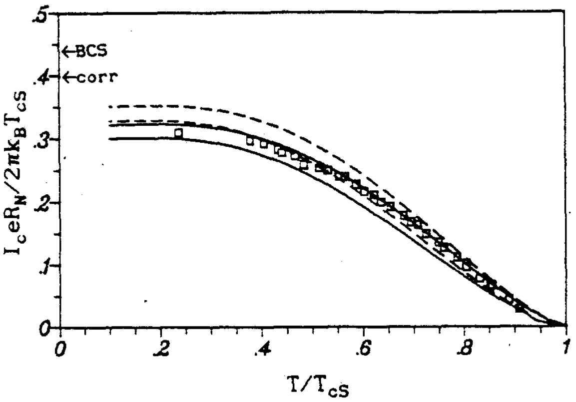

Fig.3 Reduced critical current versus reduced temperature for SS'IS"S junction with $\gamma_{M1}/\gamma_{M2}=5$, $\gamma_{M2}=0.1$ (upper) and 0.15 (lower curves): theory: - - -; corrected for $\Delta_{0S}/k_BT_{cS}=1.92$: ——. Experimental data of junction with $d_{S'}/d_{S''}=5$: □. $I_c(T=0)$ in the case of no proximity: ←BCS (Δ_{0S}/k_BT_{cS} $=1.76$); ←corr. ($\Delta_{0S}/k_BT_{cS}=1.92$).

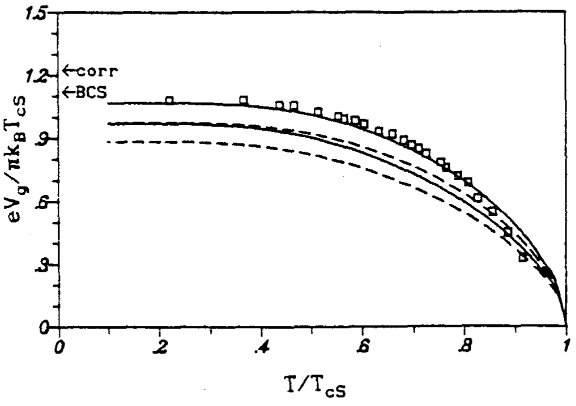

Fig.4 Reduced gapvoltage versus reduced temperature for SS'IS"S junction with $\gamma_{M1}/\gamma_{M2}=5$, $\gamma_{M2}=0.1$ (upper) and 0.15 (lower curves): theory: - -; corrected for $\Delta_{0S}/k_BT_{cS}=1.92$: ——. Experimental data of junction with $d_{S'}/d_{S''}=5$: □. $V_g(T=0)$ in the case of no proximity: ←BCS ($\Delta_{0S}/k_BT_{cS}=$ $=1.76$); ←corr. ($\Delta_{0S}/k_BT_{cS}=1.92$).

The junctions can thus be characterized by γ_{M2} and the ratio $\gamma_{M1}/\gamma_{M2}=d_{S'}/d_{S''}$.

In fig.1 the calculated IV-curves (solid lines) at a relative temperature of $T/T_{cS}=0.46$ (corresponding to T=4.2K for Nb) for different γ_{M2}-values and $d_{S'}/d_{S''}=5$ are plotted. Some features, which are typical for all junctions can be seen clearly. With increasing γ_{M2}: a) the sumgap voltage V_g decreases, b) the current rise at the gap voltage becomes less steep, c) the bump in the subgap current grows, and d) the proximity knee at the top of the current rise becomes less pronounced.

In fig.2 the theoretical V_g (obtained as the extrapolation of the current rise to zero current) is plotted as function of the γ_M-ratio for different values of γ_{M2} at $T/T_{cS}=0.46$ (solid lines), respectively $T/T_{cS}\ll 1$ (dashed lines). With increasing γ_M-ratio and/or γ_{M2} V_g decreases, as may be expected because of the increasing strenght of the proximity effect.

III. MEASUREMENTS

Nb/Al,Al-oxide,Al/Nb Josephson tunnel junctions were fabricated [8] with different thicknesses $d_{S'}$ of the base electrode Al-layer (4,5,10,15,20, and 25nm) and the same thickness $d_{S''}$ of the counter electrode Al-layer (nominally 3nm). The Nb electrode thicknesses d_S are 300nm.

For a comparison with SS'IS"S theory we estimated the proximity parameter γ_M and the boundary parameter γ_B. From measured resistance ratios of thick Nb and Al films and literature values for the room temperature resistivities we obtained $\sigma_{S'}/\sigma_S=4.2$. The electron mean free paths (mfp) in Nb and Al were calculated to be 27nm resp. 424nm at LHe temperatures. Literature values for the coherence lenghts are about $\xi_{Nb}(0)\approx 40$nm and $\xi_{Al}(0)\approx 1.1\mu$m. Thus the S-layer obeys the condition $l_S<\xi_S\ll d_S$. In our junctions the thickness $d_{S'}$ ($d_{S''}$) of the S' (S") layer is (much) less than the bulk mfp. This means that the mfp is limited by the thickness of the Al layer. The coherence length $\xi_{S'}$ is then of order $(\xi_{Al}(0)\cdot l_{S'})^{1/2}\approx(\xi_{Al}(0)\cdot d_{S'})^{1/2}\gg d_{S'}$. It follows that the conditions $d_{S'}\ll\xi_{S'}$; $d_{S''}\ll\xi_{S''}$ are fulfilled, but most likely not $l_{S'}<d_{S'}$; $l_{S''}<d_{S''}$. Substitution shows that γ_M is of order 0.15.

The ratio $l_{S'}/\xi_{S'}\approx(d_{S'}/\xi_{Al}(0))^{1/2}$ is maximally about 0.15. The reflection coefficient is calculated to be about 0.33. This results in $\gamma_B<0.05\ll 1$, which means that no effect of the interface between the Nb and Al layers on the characteristics of the junctions is to be expected.

The IV-characteristics of the junctions were measured at 4.2K and 1.6K. Further the supercurrent $I_c(T)$ and the sumgap voltage $V_g(T)$ were measured as function of temperature. For comparison of the experimental results with theory we took as scaling parameters $\Delta_{0S}/e=1.5$mV and R_N as dV/dI at 4.5mV. (For $V>1.25V_g$ the theoretical IV-vurves are nearly parallel to $I=V/R_N$.)

In fig.1 the normalized measured IV-characteristic of a typical junction with $d_{Al1}/d_{Al2}=15\text{nm}/3\text{nm}=5$ is plotted (stars). It is seen that the slope and the place of the current rise can be described very well for $\gamma_{M2}\approx 0.12$. Good fits with theory are obtained for all junctions using about the same γ_{M2}-value. However, the proximity knee that is measured is more pronounced than predicted, even for the junctions with the largest $d_{S'}$. This discrepancy might be explained as follows. The model assumes weak-coupling superconductivity in all layers. However, if this condition is not fulfilled this will show up most strongly at the bandgap and thus in the shape of the proximity knee. Secondly, the proximity model assumes that the dominant tunneling process takes place from the S'I resp. IS" interface, due to the assumption of short mfp's. In our junctions this condition is not fulfilled rigidly because of the long mfp in the S' and S" layers. Also the S layers l_S is relatively long. Thus the tunneling q.p.'s probe the DOS in the electrodes over much larger distances than the model assumes. The ratio Δ_{0S}/k_BT_{cS} was reported to be about 1.92 and up to 2.1 for Nb and Al resp. [9], instead of the BCS-value 1.76, indicating deviations from weak-coupling superconductivity in both metals. Thus deviations from the model calculations may be expected.

In fig.2 the reduced sumgap voltages eV_g/Δ_{0S}, measured at 4.2K (+ signs) and 1.6K (x signs), are plotted as function of the ratio γ_{M1}/γ_{M2}. With increasing γ_M-ratio the eV_g/Δ_{0S} values decrease, as may be expected. The measurements are consistent with a γ_{M2} value of about 0.12. Thus the γ_{M1} and γ_{M2} values are in the range 0.1...1, which is of the same order of magnitude as the estimated value for γ_M.

In fig.3 the critical current $I_c(T)$ of the same device as shown in fig.1 is given as function of the reduced temperature T/T_{cS}, with T_{cS}=9K. In this figure I_c is normalized with $eR_N/2\pi k_BT_{cS}$. The theoretical curves for γ_{M2}=0.1 and 0.15 and γ_{M1}/γ_{M2}=5, shown as dashed curves, are larger than the measured values. In the model the current normalization factor assumes the BCS-ratio Δ_{0S}/k_BT_{cS}=1.76. Taking into account the value 1.92 of Nb, which is consistent with the values of our scaling parameters Δ_{0S} and T_{cS}, the solid curves are obtained. These show a much better fit with the experimental data at all temperatures.

The same rescaling procedure was applied in fig.4 showing the normalized bandgap energy $eV_g/\pi k_BT_{cS}$ of the same device versus reduced temperature. Also here a much better fit is obtained if the correction is applied. The deviations of the experimental data at the higher temperatures are probably due to a systematic error in the determination of the sumgap voltage from the measured IV-curves. The determination of V_g is more difficult at higher temperatures.

IV CONCLUSIONS

The measured IV-characteristics of Nb/Al_1,AlOx,Al_2/Nb junctions with Al thickness d_{Al1} varying from 4 to 25nm (d_{Al2}=3nm), can be fitted very well with a microscopic model of the proximity effect in SS'IS"S junctions. For all junctions the same value for the proximity parameter $\gamma_{M2}\approx0.12$ is found, taking $\gamma_{M1}/\gamma_{M2}=d_{Al1}/d_{Al2}$. The proximity knee is larger than predicted for all junctions. This is ascribed to a probing depth of tunneling q.p.'s that is larger than is assumed in the model, due to the large electron mfp's in the Al layers. $I_c(T)$ and $V_g(T)$ measurements can be fitted fairly accurately with theory, if the value Δ_{0S}/k_BT_{cS}=1.92 of Nb is used for the normalization.

The value of γ_M, determined from a V_g-measurement can be used directly to calculate an effective trapping rate.

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