CHARACTERIZATION OF DIFFERENT TYPES OF Nb-AIO, BASED JOSEPHSON TUNNEL JUNCTIONS

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Abstract

Three types of Josephson tunnel junctions, standard Nb/AIO, onNb, symmetric Nb/AIO/Nb/AIO/AlO, onAl, and Nb/AIO/AlO, onAl, containing a double oxide layer have been investigated by means of temperature dependent I-V measurements, conductance-voltage measurements, noise analysis, and Auger Electron Spectroscopy scanning across the edge of a sputtered crater profile. In standard junctions frequently small leakage currents have been observed as well as resistance fluctuations, leading to telegraph noise. Both effects can be related to the direct contact between the AlO, and the Nb counter electrode. In none of the symmetric junctions leakage currents larger than 0.01 % of the theoretical maximum critical current have been observed.

The sub-gap current of these junctions is dominated by single- and two-particle tunneling. The SNAP process, that was used to define the junction areas, affects the tunneling mechanisms below the sum-gap voltage, probably by the introduction of barrier inhomogeneities at the edges of the junctions.

The AlO, barrier in symmetric and asymmetric junctions cannot be completely represented by a trapezoidal barrier shape. The metal-insulator interface between Al and AlO, in both junction types is probably not very sharp, which might be due to oxygen diffusion. The metal-insulator interface between AlO, and Nb in standard junctions can be represented by a step-wise increase of the potential barrier, indicating that this interface is very distinct. The AlO, barrier in double oxide layer junctions is not homogeneous and probably contains low barrier channels.

Introduction

On basis of Nb and A1 high quality Josephson tunnel junctions can be made [1]. The junctions are usually made of a Nb base electrode, covered by a thin Al overlayer, that is oxidized and subsequently covered by a Nb counter electrode. This type of junction is normally referred to as SNIS (S = Superconductor, N = Normal metal, I = Insulator). The SNIS configuration, however, has one major drawback. During oxidation of the Al overlayer, water molecules are easily adsorbed at the surface of the AlO, Deposition of Nb directly on top of the AlO, leads to reactions between Nb and surface O-H groups, which may probably cause microcracks between the electrodes [2].

We have studied the effects of the AlO, Nb interface on the junction characteristics. Junctions of type SNIS have been compared with SNINS junctions in which an extra Al layer of various thicknesses is deposited on top of the AlO, prior to the Nb counter electrode deposition. Besides standard I-V measurements, conductance-voltage measurements, noise analyses, and Auger microscopy have been performed. Special attention has been paid to the occurrence of leaks, the shape of the potential barrier, and the presence of leaks, the shape of the potential barrier, and the occurrence of telegraph noise, which is also related to the junction configuration [5].

Finally, Josephson tunnel junctions containing a double oxide layer have been investigated. In this SNIS type of junction the AlO, layer is formed in a two-step process [4]. This probably affects the barrier properties of the dielectric layer.

Junction Fabrication

The Nb/AIO, (Al)Nb trilayer is deposited in a turbo pumped vacuum system. Nb and A1 films were deposited by two DC magnetron sputter guns at a rate of 200 nm/min and 22 nm/min, respectively. During sputtering the oxygen pressure was in the range of 10^-5 mbar. The water pressure was 10^-7-10^-8 mbar. The T, of the Nb films is 9.2 K.

The trilayer configuration of the junctions is listed in Table 1.

The thickness of the Nb base electrodes is 300 nm. The Al overlayer were thermally oxidized in pure O, at 1070°C, during 1 hour. The double oxide layer of the SNINS type junction has been formed in two steps. The Al layer was oxidized in 0.04 mbar O, for 15 minutes. Then a second Al layer of 10 A was deposited and completely oxidized in 27 mbar O2.

The junction areas (20x20, 10x10, and 5x5 pm²) in one thermally oxidized Si wafer were defined by SNAP (Selective Niobium Anodization Process) [5]. To complete the junctions 300 nm Nb was deposited and structured by lift-off, to form contacts with the counter electrodes.

Results on SNIS and SNINS junctions

I-V measurements

The I-V characteristics of the junctions have been obtained with help of a low noise, battery powered current source. A battery powered amplifier with an input noise of 5 nV/Hz and a bandwidth of 80 kHz was used to amplify the voltage across the junction.

The characteristic gap and sub-gap parameters of the Josephson tunnel junctions are listed in Table 2. The sum-gap voltage Vg (= 2A/Δ, where Δ is the superconducting gap of the electrodes at 4.2 K) is an average value of 10 junctions with a standard deviation of 0.01 mV. The theoretical maximum critical current density Jc is obtained from Jc = 1/(2A/Δ), where A is the area of the junction, Rg = 4 mV/Δ, and Io is the critical current.

The sub-gap parameters are obtained by suppressing the zero voltage current by a magnetic field. This enabled an accurate measurement of the sub-gap current in ±5 pm² junctions. In larger junctions the magnetic field induced resonant modes caused extra currents at finite voltages below Vg. This made it very difficult to measure the sub-gap current accurately.

With our sample holder we could measure four ±5 pm² junctions.
Jig. 2) Conductance vs voltage for three different SNINS junctions. The upper curve is from a 3d12 junction and has been dashed. The middle curve is from a 3d15 junction and has no offset. The lower curve is from a 3d4 junction and has no offset.

The area of the junctions is 25 μm². The anodized Nb that surrounds the Nb/Al trilayer apparently affects the sub-gap current. Possibly, the anodized Nb behaves as a low barrier contact between the electrodes. It's also thinkable, that stress is built up at the edges of the AlOx, during anodization, possibly causing barrier inhomogeneities. In none of the SNINS junctions we could observe leakage currents larger than 10⁻¹¹A at 1 mV. Leakage currents show up as temperature independent sub-gap currents, increasing linearly with voltage. Single- and two-particle tunneling dominate the sub-gap currents of the SNINS junctions. In some of the junctions three-particle tunneling also contributes to the current below Vg.

The 5x5 μm² SNINS junctions listed in table 2 contained shorts in three out of four junctions. The 3d17 junctions with larger areas (not shown in table 2) made on the same wafer, all of two-particle tunneling is small, which explains the constant difference between I1 and I1 at cooling down. Two-particle tunneling was not observed in the measurements in ref. 1, which probably explains the higher value of Vm as compared to the values, that we have obtained.

The I-V characteristics of some junctions also showed an onset of extra tunneling at V/3, which indicates the occurrence of three-particle tunneling. The spread in values of the sub-gap currents at 1.6 K between junctions on the same wafer is mainly due to this effect. It is not yet clear, why this extra tunneling at V/3 is not the same in junctions, that were made simultaneously on one wafer, and thus are expected to behave identical.

Another interesting effect is, that in junctions with larger areas I/lco is always smaller than in 5x5 μm² junctions. In junctions of 20x20 μm² values of I/lco = 0.2 % at 1.6 K have been obtained. The anodized Nb that surrounds the Nb/Al trilayer apparently affects the sub-gap current. Possibly, the anodized Nb behaves as a low barrier contact between the electrodes. It's also thinkable, that stress is built up at the edges of the AlOx, during anodization, possibly causing barrier inhomogeneities. In none of the SNINS junctions we could observe leakage currents larger than 10⁻¹¹A at 1 mV. Leakage currents show up as temperature independent sub-gap currents, increasing linearly with voltage. Single- and two-particle tunneling dominate the sub-gap currents of the SNINS junctions. In some of the junctions three-particle tunneling also contributes to the current below Vg.

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had leakage currents. More generally, it's our experience, that SNIS junctions frequently contain microshorts. These results support the hypothesis in ref. 2, that due to reactions between Nb and H_2O, microshorts between the electrodes can occur. The one junction without observable leakage currents had similar sub-gap I-V characteristics as the SNINS junctions, resulting in I_c = 4.6 \times 10^{-1} \, \text{A} at 1.6 \, \text{K}.

The effects of an extra Al layer on V_c can be seen by comparing junctions 3d4, 3d15, and 3d12. The superconducting gap increases slightly if the thickness of the normal conducting Al layers is reduced. The influence of the Al on the sum-gap voltage is, however, very small.

**Conductance-voltage measurements**

With help of a standard lock-in technique dV/dI was measured as function of the voltage across the junction. The induced voltage modulation was typically about 0.5 mV (peak-peak). The output signal of the lock-in amplifier was recorded by computer with help of a 16 bits IOtech ADC488/8S A/D converter, in which the converter is optically isolated from the digital circuitry and the IEEE bus.

The experimental \( \sigma \)-V curves have been fitted by a theoretical conductance-voltage dependence based on a trapezoidal barrier shape [7]. In this model the Metal-Insulator-Metal (MIM) junction is represented by a potential barrier with average barrier height \( \bar{\phi} = 0.5(\phi_{\text{base}} + \phi_{\text{source}} + \phi_{\text{drain}}) \) and thickness \( d \), that impedes the electron flow between the two metallic electrodes. The \( \sigma \)-V characteristics were usually measured at 4.2 K. In order to check whether tunneling is the dominant electron flow mechanism, the \( \sigma \)-V characteristics of a few junctions have also been determined at 77 K. Apart from the superconducting tunneling effects, the characteristics did not change, as expected in case of electron tunneling.

The barrier parameters obtained from fitting the measured characteristics with theory are listed in table 2. In fig. 2 and 3 experimental conductance-voltage curves of 3 different SNINS junctions (3d4, 3d15, and 3d12) and 1 SNIS junction (3d17) are shown. It can be seen, that the \( \sigma \)-V curves of the symmetrical SNINS junctions can be fitted by the (dashed) theoretical curves at voltages above 200 mV. Below 200 mV, the experimental curve deviates from the theoretical curve. Apparently, the AIO_x barrier in SNINS junctions cannot completely be represented by a trapezoidal barrier shape. This probably also explains the differences between the barrier parameters of junctions 3d4, 3d15, and 3d12. One should expect that the barrier shapes of the AIO_x are the same, since the thermal oxidation conditions of these junctions are identical.

The \( \sigma \)-V characteristic of the SNINS junction in fig. 3 can also not be fitted completely with a theoretical curve. The experimental curve has been fitted in two ways. In one case, the barrier parameters are adjusted to obtain the best fit for \( V \leq 0 \), which corresponds to a positively biased base electrode. Below \( V = -200 \, \text{mV} \) the theoretical curve coincides with the experimental curve. At voltages between 0 and -200 mV, however, the two curves deviate in a way very similar to the deviation observed in SNINS junctions. This was to be expected, since the Nb/Al base electrode configuration in both junctions is identical. The other

**Noise measurements**

The noise properties of SNINS 3d4, 3d15, 3d12, and SNIS 3d17 junctions at 4.2 K have been investigated at voltages up to 300 mV. The voltage-time traces were recorded by computer. The use of the computer did not affect the observed noise properties. The occurrence of telegraph noise in small junctions is usually explained by the presence of localized states in the barrier, where electrons can be trapped or released, thereby introducing a
With help of Auger line profiles information about the AlO₃-Nb interface has been obtained. For this purpose, a special sample was prepared. On top of a Si wafer 20 nm Al was deposited. The Al surface was thermally oxidized in 267 mbar pure oxygen for 1 hour, and subsequently covered by 300 nm of Nb.

In a UHV system (background pressure: 3×10⁻¹⁰ mbar) a crater profile was etched in this sample, with help of an ion beam. Directly after this etching Auger line scans were made across the edge of the crater profile. These scans had to be made within 1 minute, to avoid that the Al and Nb were covered with residual gasses present in the chamber. Nb preferentially adsorbed CO and CO₂. Al mainly adsorbed H₂O. The angle between the sample surface and the surface of the crater edge equals 0.06 degrees. The information depth is about 60 Å, which is three times the inelastic mean free path of the Auger electrons.

In fig. 5 an Auger line scan across the AlO₃-Nb interface is shown. It can be seen, that oxygen is always detected together with Al. There is no position where Nb and O are detected in absence of Al, which indicates that diffusion of oxygen into the Nb layer occurs. The decay of Nb, which is relatively long as compared to the Al decay, may suggest that Nb has diffused into the AlO₃ layer. It is, however, very likely, that this long decay is caused by sputter artifacts.

**Results on double oxide SNINS junctions**

The conductance-voltage characteristics of double oxide SNINS junctions can not be fitted by the theoretical curves, as can be seen in fig. 6. At low voltages the conductance is almost the same as in junctions of type 3d4, but above ± 10 mV dI/dV strongly increases. The experimental curve in this figure is typical for all junctions of this type. In SNINS junctions the barrier shape is apparently not trapezoidal. The $\sigma$-V curves can be explained by the presence of low barrier channels in the AlO₃, that become highly conductive at voltages above 10 mV. This indicates, that the second Al layer does not cover the AlO₃ completely. The noise measurements on SNINS junctions with variable thicknesses of the second Al layer did already suggest that.

The gap and sub-gap parameters of SNINS junctions are comparable to standard SNIS junctions.

**Conclusions**

High quality SNINS Nb/Al Josephson tunnel junctions with leakage currents below 0.01 % of the zero voltage current have been made. The reproducibility of the fabrication process is very good. The sub-gap tunneling current in these junctions is dominated by single- and two-particle tunneling. In some junctions also three-particle tunneling was observed. The occurrence of two- and three-electron tunneling indicates, that the barrier in the SNINS is inhomogeneous. The measurements suggest, that the anodized Nb, that surrounds the junctions, affects the sub-gap current. It is very likely, that the SNAP process, that was used to define the area of the junctions, causes barrier inhomogeneities at the edges of the junction. It may be expected, that SNEP (Selective Niobium Etching Process) affects the sub-gap current to a lesser extent, which would explain the high value of $V_c$ in ref. 1.

The AlO₃ barrier in SNINS junctions cannot completely be represented by a trapezoidal barrier shape. It is possible, that due to oxygen diffusion, the potential barrier at the Al-AlO₃ interface increases rather smoothly, instead of step-wise. It is not yet clear, whether barrier inhomogeneities at the edges of the junctions affect the $\sigma$-V characteristics.

In standard SNIS junctions frequently microshorts are present and resistance fluctuations occur, which both can be related to the direct contact between the AlO₃ and the Nb counter electrode. M. Ronay and E.-E. Latta have proposed a mechanism, that can very well account for both effects [2]. They suggested, that during oxidation of Al the pores of the AlO₃ become sealed by surface O-H groups. When Nb is deposited on top of the AlO₃, the O-H groups react with Nb to form NbO₂, thereby opening up the pores and causing microshorts. We think, that due to this process also localized states are formed at the AlO₃-Nb interface. These localized states may give rise to resistance fluctuations.

The metal-insulator transition between the AlO₃ and the Nb is sharp, as was concluded from $\sigma$-$V$ measurements and supported by Auger Electron Microscopy. The AlO₃ barrier in double oxide layer SNIS Nb/Al junctions is not homogeneous and probably contains low barrier channels. However, good superconducting tunneling properties can be obtained. This offers the possibility to make good quality junctions with high normal resistance. The quality might even be improved by using an SNINS configuration.

**References**