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FABRICATION AND MEASUREMENT OF SUPERCONDUCTING Nb-BASED JUNCTIONS

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Abstract. The fabrication of Niobium-based junctions is a well-known difficult problem in nanotechnology. Here we report on the fabrication of single Nb/(Al-)AlO_x/Al junctions using two-angle beam lithography and on their subsequent *I-V* measurement. The structures that we succeeded to fabricate display pronounced Josephson-effect features and a fairly steep quasiparticle current at the gap energy.

1. INTRODUCTION

The use of Niobium as a material for nanoscale superconducting devices such as small Josephson junctions, single-electron transistors, Cooper pair transistors, pumps, and other arrays could lead to a significant improvement in their functioning.

Indeed, the superconducting gap of bulk Nb is almost one order of magnitude larger than that of Al (Δ_{Nb}=1.4 meV while Δ_{Al}=0.18 meV) which is the material used for the fabrication of most of these devices. This not only leads to larger currents and voltages, thus improving the signal-to-noise ratio, but is also expected to alleviate problems such as the quasiparticle poisoning of the small islands.

Due to this quasiparticle effect, it is difficult to obtain a 2e-periodic gate modulation in many of the multi-junction devices [1]. A larger superconducting gap would reduce at least the number of quasiparticles created by thermal excitation and by non-equilibrium transport mechanisms. An even more exciting idea is to create heterostructures with say Nb islands connected through Al leads. In this case, 1e poisoning effect will be considerably reduced, since it costs energy for an excitation to be localized on the island (in other words, the gap of Nb acts as an energy barrier, making the island inaccessible to unwanted quasiparticles). The larger the gap difference between the island and the leads, the smaller the lifetime of a quasiparticle on the island. This idea has been very recently tested in Al-only structures, by enhancing the gap of the Al island in a single-electron transistor [2].

However, although fabricating superconducting devices from Nb presents clear advantages in theory, in practice this is a difficult material to use; unlike for example Al, Cu, and Pb, which are soft metals; the standard shadow evaporation technique cannot be applied in a straightforward manner for refractory metals (Nb, W, or Ta). The reason is the outgassing from the PMMA polymer and co-polymer resists used as a mask during the high-temperature evaporation of Nb. Several techniques have been invented to circumvent this problem, such as multilayer techniques that typically protect the mask with a layer of a semiconductor [3], *in-situ/ex-situ* techniques [4-6], or the use of a polymer (PES, Phenylen-ether-sulfone) with larger glass and decomposition temperatures [7].

2. FABRICATION METHOD

We have fabricated single Nb-Al junctions using e-beam lithography on a double layer of PMMA and P(MMA-MAA) resist, followed by two-angle evaporation of Al and Nb in an UHV chamber with a large

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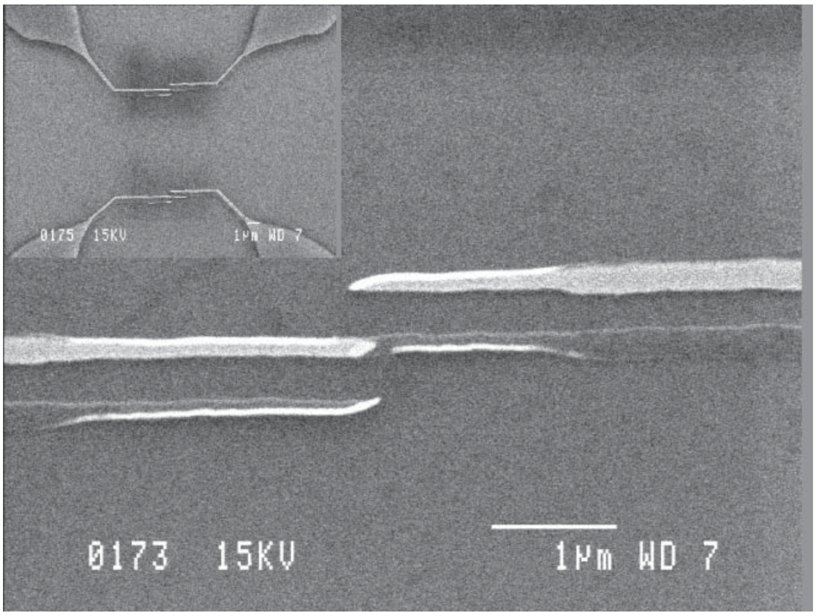

Fig. 1. A typical sample of an Al-Nb junction. The bright line (middle-left) is Nb, the more darker one (middle-right) is Al. The junction is formed at the white spot in the center of the figure. The extra lines are an artefact due to the shadow evaporation of the material through the two cuts in the mask. The brighter edges that appear at the margin of both the Al and Nb electrodes are due to the evaporation material accidentally piling up inside the mask. The upper-left inset is a lower-magnification picture of the same sample.

separation between the crucible and the sample holder. This helps in lowering the effective temperature of the Nb atoms near the sample, thus reducing the outgassing of the resist. The method can be also used to produced Nb-only structures such as wires and superconducting single-electron transistors [8,9]. In addition, we have pre-evaporated Cu at a high angle (70 degrees) to cover the edges of the mask. This strengthens the resist and further prevents melting and outgassing. Moreover, to avoid the effects of the mask being too much exposed to extra heat, we start by evaporating 30 nm Aluminum, then oxidize in static oxygen pressure of 30 mbar for 4 minutes, then evaporate 40 nm Niobium on the top of the oxide layer, at a different angle. A typical sample looks like that shown in Fig. 1. The structure is grown on a 250 nm thick SiO_2 layer obtained by the oxidation of a Silicon wafer in a small furnace.

This method has the advantage of high simplicity and allows the fabrication of small junctions, with sizes of about 100 nm x 100nm. Also the samples fabricated are chemically stable, and they can be kept typically for 2-3 weeks in a low humidity environment without a significant alteration of their properties.

3. MEASUREMENTS

Several samples with Al/Nb junctions have been fabricated and measured at temperatures ranging from about 200 mK to 4.2K. The samples displayed almost identical features. An example is shown in Fig. 2, which presents the current and the conductivity as function of bias voltage. At $\Delta_{Al}+\Delta_{Nb}$=1.55 meV, the conductance has a peak, corresponding to a steep raise in the current. For the gap of Al at 200 mK we can assume a value of 0.2 meV (measured in other previous experiments), slightly higher than the bulk value due to thin-film effects. This results in 1.35 meV for the gap of Niobium, fairly close to the bulk value (1.40 meV). We have then a significant improvement in the quality of our samples, compared for example with [8,9], where the gap of Nb was measured to be only 66% of the bulk value. This result can be confirmed experimentally in the following way: at higher temperatures but below the critical temperature of thin-film Al (see Fig. 3) a new feature develops in the conductance: the so-called singularity-matching peak, a result of the structure of the density of states in the two superconductors. This feature appears at $\Delta_{Al}+\Delta_{Nb}\big|_{T=1.17K}$= 1.11 meV, where the gaps correspond to the higher temperature. The sum of the gaps can be also determined

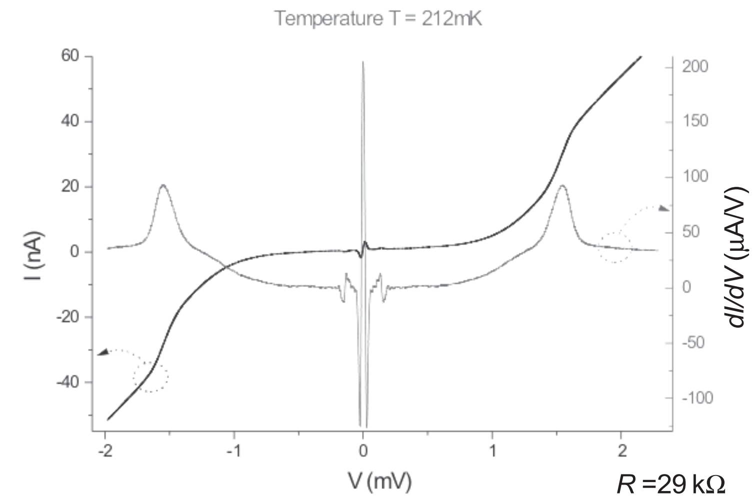

Fig. 2. Results of the measurement of the *I-V* and *dI/dV* characteristics at a relatively low temperature. The measurements of the conductance are done using a lock-in amplifier technique. The sample displays a clearly defined quasiparticle current above the excitation threshold given by the sum of the gaps. The Josephson current at zero bias is visible, resulting in a high peak in the conductance. Other features at low bias, more visible in the conductance, are due to Cooper pair resonances with the electromagnetic environment.

from the bias voltage where the quasiparticle transport starts, and it is 1.48 meV at this temperature. Therefore, the gap of Al is 0.18 meV and that of Nb is 1.30 meV. The effect of temperature is most pronounced in the case of Al (10% decrease), while the Nb gap is diminished only by 3.7%. In Fig. 2 the Josephson effect is clearly visible at zero bias voltage. The critical current is I_c= 3 nA, corresponding to a Josephson energy $EJ=hIc/2e$= 6 μeV. At low bias voltages, a series of peaks in the conductance develops. These are due to resonances between the Josephson oscillations and the modes of the electromagnetic environment. A similar phenomena is observed in various other structures, most notably in superconducting SET's [10]. These features are remarkably resilient with the temperature, as

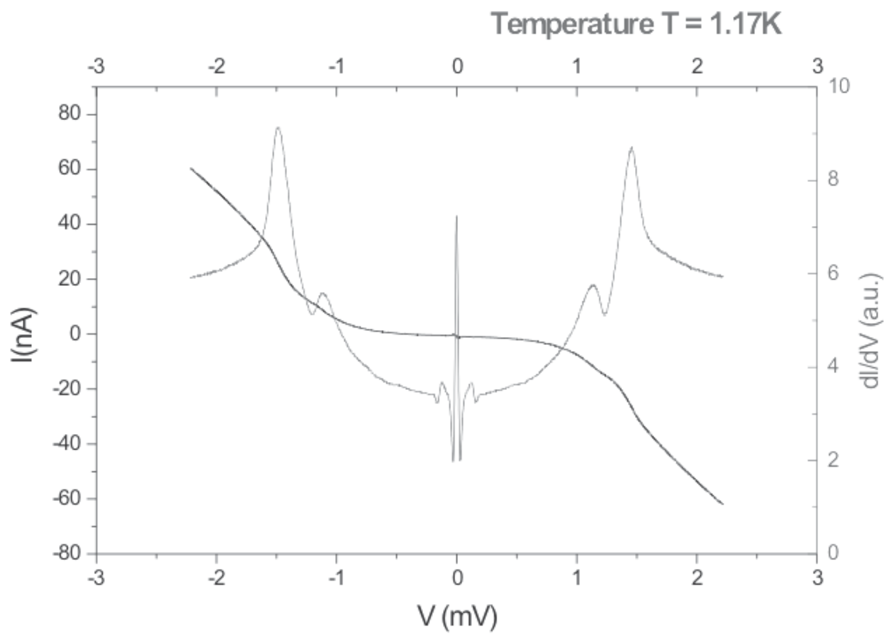

Fig. 3. Current and conductance versus bias voltage at a temperature slightly below the critical temperature of Al. The quasiparticle states are populated by thermal excitations, therefore features such as singularity-matching peaks become visible. The resonances are remarkably resilient even at these temperatures.

can be seen from Fig. 3, and they disappear exactly at the phase transition of Al, thus proving that they are related to the existence of Cooper pairs and Josephson tunnelling.

4. CONCLUSIONS

As the interest in the applied science community in the physics and functioning of nanoscale superconducting devices is increasing, due to their potential relevance for metrology and quantum computing, new methods to fabricate in a reliable way high-quality junctions made of various materials are becoming topical. This paper describes a technology for fabricating Nb-based junctions and the subsequent measurements demonstrating that the method is reliable and produces high-quality junctions. The data show well-defined Josephson and quasiparticle characteristics. Further experiments are needed to test this method in the case of multi-junction structures.

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