Fabrication of Nb-based superconducting single electron transistor

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Abstract

We have fabricated Nb/(Al-)AlO$_x$/Nb junctions with a single electron transistor (SET) geometry using conventional e-beam lithographic technique. It was possible to reach a clearly defined superconducting gap of 0.75 meV as measured in the current vs voltage ($I - V$) characteristic curve, which corresponds to T_c of 4.6 K. The Josephson coupling energy was comparable to the charging energy, $E_J \approx E_c = 30 - 40$ μeV.

Key words: Single electron transistor; Josephson effect; Superconductivity

Nb-based single Cooper pair transistor (SCT) has attracted interest [1–3] because of its large superconducting gap. The fact that Nb has a much larger superconducting gap energy than Al [Δ_{Nb}(bulk) $\approx$ 1.5 meV and $\Delta_{Al} \approx$ 0.2 meV] [4] suggests that the quasiparticle tunneling will be strongly suppressed for Nb-based structures compared with Al-based structures [5]. This is particularly important in the application of these devices as squbits [6] for which quasiparticle contamination is harmful. Thus a demonstration that it is possible to fabricate Nb-based SCT by conventional e-beam lithography is highly significant.

So far two different methods have been adopted to realize Nb-based sub-micron junctions. One is the conventional two angle evaporation technique with a stencil mask consisting of polymethylmethacrylate (PMMA) and co-polymer [P(MMA-MAA)] resist [1]. The Nb film made this way is not of good quality and it was believed this was because it degraded due to contamination from outgassing from the resists during the Nb evaporation. The second method is the multilayer technique by which Nb/(Al-)AlO$_x$/Nb tri-layers are formed *in situ*, followed by the fabrication process *ex situ* [2]. In spite of the reliability of the insulating layer and the high-quality superconducting Nb electrodes, the complicated multi-layer process makes it more difficult to reduce the size of junctions and to align the electrodes on the sub-micron scale than with the self-alignment techniques.

Contrary to the common belief, however, it is possible to manufacture high quality Nb/(Al-)AlO$_x$/Nb tunnel junctions by the conventional two angle evaporation technique with PMMA and coopolymer resist as a mask. Our results were obtained with a standard e-beam lithography process that followed common procedures and conventional recipes [7]. We fabricated Nb/(Al-)AlO$_x$/Nb junctions with a single electron transistor geometry (see the lower right inset of Fig. 1). The 20 nm thick Al layer was evaporated on the 53 nm thick Nb layer. The Al layer was subsequently oxidized in a static oxygen pressure of 100 mbar for 5 minutes. Then the third layer of Nb was deposited at a different angle.

The $I - V$ curve shown in Fig.1, recorded at a temperature around 100 mK, clearly shows a superconducting gap, $\Delta_{Nb} \approx$ 0.75 meV. This is about 66% of the expected value, assuming T_c of both electrodes and island is 7 K [7]. The suppression of the superconducting gap could be due to the existence of an incompletely oxidized Al layer. For this sample the total film thickness of Nb and a not-fully oxidized Al layer is estimated as 106 nm and at most 20 nm, respectively.

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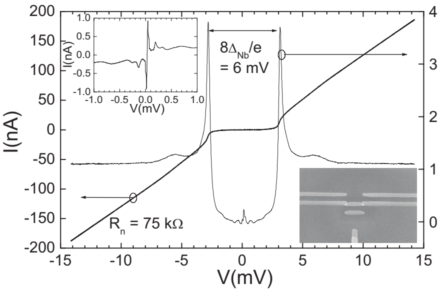

Fig. 1. $I-V$ and $dI/dV-V$ characteristic of Nb/(Al-)AlO$_x$/Nb junctions at a temperature around 100 mK. $\Delta_{Nb} = 0.75$ meV. Inset (upper left): zoom of the $I-V$ curve around zero bias voltage. Inset (lower right): scanning electron micrograph of the Nb/(Al-)AlO$_x$/Nb junctions. The width of Nb electrode is about 0.24 μm.

Figure 2 shows examples of the gate modulated current at a bias voltage $V_b = 0.17$ mV as well as the gate modulated switching current I_{sw} which is measured with the Josephson critical current (see the upper left inset of Fig.1). A comparison of the modulation period with that of a Al/AlO$_x$/Al SET with the same geometry indicates that the period we observed in Fig. 2 corresponds to e/C_g, where C_g is the gate capacitance. If we use the simple estimate that the crossover temperature T^* below which only $2e$ period appears is $T^* \approx T_c/5$ [5] we have $T^* \approx 900$ mK. The factor 1/5 pertains to Al but is not expected to be dramatically different for Nb since it is the logarithm of an effective number of electrons. Even though the sample temperature is far below T^* we have not observed the $2e$ periodicity so far. One reason could be the existence of nonequilibrium quasiparticles which have survived in spite of the introduction of quasiparticle traps close to the junctions. Further study on this problem is needed.

For the sample in Fig.1 and 2(a) the Josephson coupling energy $E_J = (h/4e^2)\cdot(\Delta_{Nb}/2R_n) \approx 32$ μeV was comparable to the charging energy $E_c \approx 35$ μeV. The latter was determined from the $I-V$ curves as function of gate voltages.

The upper left inset of Fig. 1 shows the $I-V$ curve around zero bias voltage. The magnitude of the critical current is about 1 nA which gives $E_J = \hbar I_c/2e \approx 2$ μeV which is one order of magnitude smaller than the value from the formula $E_J = (h/4e^2)\cdot(\Delta_{Nb}/2R_n)$. In addition to the critical current peak, a clearly visible second current peak is also observed. It is believed to arise from the resonant tunneling process of Cooper pairs [8]. The Fraunhofer diffraction pattern of the first and the second current peaks, shown in Fig. 2(c), supports this suggestion. The value of λ_L obtained from the scan, 60 nm, is not far from that of λ_L for bulk Nb which is 85 nm [9].

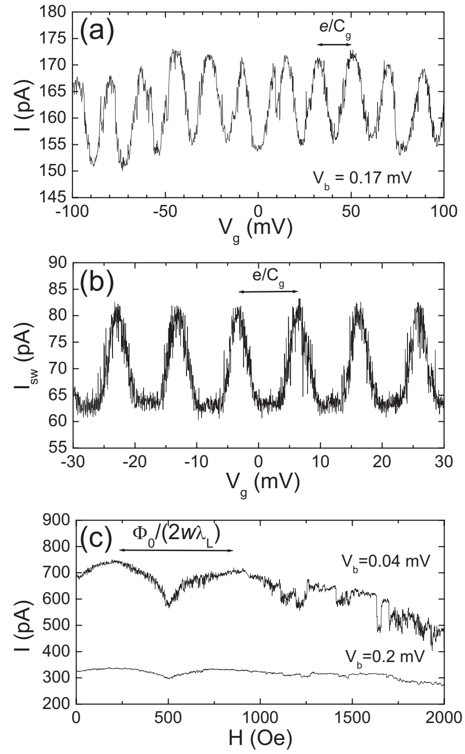

Fig. 2. (a) Gate modulated current with a bias voltage $V_b = 0.17$ mV. (b) Modulation of switching current I_{sw} measured on a sample with different distance between island and gate than sample for (a). (c) Fraunhofer diffraction pattern of the first and the second current peak at $V_b = 0.04$ mV and $V_b = 0.2$ mV, respectively. $\Phi_0 = h/2e$. $w = 0.24$ μm. λ_L is the London penetration depth.

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