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Subgap conductivity in SIN-junctions of high barrier transparency

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Abstract

We investigate the current–voltage characteristics of high-transparency superconductor–insulator–normal metal (SIN) junctions with the specific tunnel resistance $\rho \lesssim 30\ \Omega\ \mu m^2$. The junctions were fabricated from different superconducting and normal conducting materials, including Nb, Al, AuPd and Cu. The subgap leakage currents were found to be appreciably larger than those given by the standard tunnelling model. We explain our results using the model of two-electron tunnelling in the coherent diffusive transport regime. We demonstrate that even in the high-transparency SIN-junctions, a noticeable reduction of the subgap current can be achieved by splitting a junction into several submicron sub-junctions. These structures can be used as nonlinear low-noise shunts in rapid-single-flux-quantum (RSFQ) circuitry for controlling Josephson qubits.

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1. Introduction

In the past decades, the mechanisms of the conductivity through the superconductor–insulator–normal metal (SIN) tunnel interface have been extensively studied. Due to the superconducting energy gap Δ in the quasiparticle density of states, the current through such an interface is generally suppressed at low temperatures, $k_BT \ll \Delta$, and subgap bias voltages, $V \lesssim V_g \equiv \Delta/e$, giving rise to a low-voltage nonlinearity in the IV-curve [1]. Recently this, the most common property of SIN-contacts has been found to be rather useful, e.g., for reducing generation of quasiparticles by building the current shunts into the Josephson-junction qubits [2] or for avoiding an extra decoherence [3] in all-Josephson RSFQ-qubit integrated systems [4].

In particular, the thermal noise produced by the resistively shunted Josephson junctions in a standard RSFQ-circuitry, brings into being an additional source of qubit decoherence [3]. It was shown however that this effect can be minimized, by using the nonlinear damping that is provided by an SIN-junction of low asymptotic resistance, R_N, and a high value of the nonlinearity parameter $\eta \equiv [G(0)R_N]^{-1}$, where $G(0)$ is the zero-bias conductivity of the shunt. The dynamics of SIN-shunted Josephson junctions has recently been analyzed in detail on the basis of a standard tunnelling model of the SIN-junction (see Ref. [5]). The feasibility was demonstrated to ensure both a high damping at the characteristic Josephson frequency $\omega_C \equiv 2eV_C/\hbar$, where $V_C = I_CR_N$ is the characteristic voltage and I_C the critical current, and, due to the high impedance of the SIN-junction at subgap voltages, a sufficiently low noise at qubit frequencies of typically up to ~10–30 GHz $\ll \Delta/h$.

The first experiments on SIN-shunted Nb SIS Josephson junctions [3] have proven the feasibility of the overdamped regime at $T = 4.2$ K. At the same time, however, an unexpectedly weak subgap nonlinearity of the SIN-junctions was observed. In particular, the value of $\eta \approx 6.2$, measured at $T = 1.4$ K in an SIN-junction with a specific tunnel

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resistance of $\rho \approx 135\ \Omega\ \mu m^2$, was much smaller than the values $\eta \gtrsim 100$ which are typical of opaque barriers (see, e.g., Refs. [6,12]), and also far below the simple estimates made for the tunnelling model, yielding a large subgap suppression factor $\propto \exp(-\Delta/k_B T)$ [1]. In view of the previous data, it would be an even more challenging task to achieve a high nonlinearity in SIN-junctions of very low specific resistance, e.g., $\rho \lesssim 30\ \Omega\ \mu m^2$ for the SIN-junctions based on superconducting Al [3], as required for RSFQ operation at qubit temperatures $T \lesssim 50$ mK.

In this paper, we address subgap conductance phenomena in SIN-junctions of very high transparency. During the last decade, the conductance of SIN-structures has been studied both theoretically (see, e.g., Refs. [7–11]) and experimentally (see, e.g., Refs. [6,12,13]). In particular we found that the degree of nonlinearity of our measured *IV*-curves is consistent with predictions of the two-electron tunnelling model which has been developed in a ballistic regime by Blonder, Tinkham and Klapwijk (BTK) [7] and modified by Hekking and Nazarov [10,11] to account also for interference contributions due to coherent electron diffusion. In earlier experiments, the spatial coherence was clearly demonstrated by Pothier et al. [12] in the form of a periodical dependence of the low-bias conductance of the so-called NS-QUID interferometer on the magnetic flux. A spatially coherent enhancement of the two-electron tunnelling amplitude makes the junction conductance topology-dependent. This effect was observed as *zero-bias conductance anomaly* in a thin-film planar NS-interface, which was compared in Ref. [13] with the BTK ballistic transport through an edge-type NS-contact. In our experiment, we compare the values of the nonlinearity parameter η for different junction topologies, varying the junction sizes and/or the width of the adjacent diffusive electrode. We show that a sufficiently strong nonlinearity can be obtained in submicron SIN-contacts with even high-transparency barriers, i.e. in the case of interest for RSFQ-qubit applications.

2. Design of the samples

Two techniques were applied for fabricating the samples. The large reference junctions "NbAuPd" and "NbAl" (see Table 1) were made in a standard sandwich technique which is usually applied for RSFQ-devices (see, e.g., Refs. [14,15]), on the basis of a Nb trilayer, patterned with the help of optical lithography. Both samples had a sophisticated multilayered structure which made a particular analysis of the SIN-junction component difficult. For example, the junction "NbAl" consisted of the metal stack with a pronounced proximity effect between the AuPd and the top Nb layers, and, possibly, between the bottom Nb and the covering Al, separated by a thin oxide barrier only. These Nb-based samples were characterized in a He^4-cryostat at temperatures down to 1.4 K. The data for these two samples, shown in Table 1, represent our rough estimations.

For the sake of simplicity and flexibility of the design, all other junctions were fabricated by means of the Dolan's shadow evaporation process [16]. The full structures were deposited in situ from the e-gun through the single e-beam-patterned PMMA/Ge/copolymer mask with free-hanging bridges. The junctions were formed on the overlapping areas of the first and the subsequent shifted layers, deposited through the same openings in the mask but at different tilting angles of the wafer in respect to the incident material flow. The *IV*-curves were measured at $T \lesssim 0.05$ K in a dilution refrigerator.

The bottom layer of all shadow-evaporated junctions was made of aluminum, with a thickness of $d_B = 30$ nm, and oxidized in a very mild regime (see below) to form a thin tunnel barrier. To be able to put several different structures on the same chip, we used besides a two-layer also a three-layer design, with Cu-, Cu/Cu- or Al/Cu-layers building the top electrodes of the junctions. The junctions "SINTOP" and "SINBOT" were simple two-layer structures with the tunnel areas differing by the factor of two, both

Table 1
Parameters of the samples

Sample code	Materials	Tunnel junction area, $N \times (L \times W)$ (μm^2)	Thicknesses, $d_B, d_T, \ldots$ (nm)	T (K)	R_N (Ω)	ρ ($\Omega\ \mu m^2$)	$[G(0)]^{-1}$ (Ω)	η
NbAuPd	Nb/AlO_x/AuPd	24	180, 100	1.4	16	380	95	6
SINTOP	Al/AlO_x/Cu	0.5×2	30, 50	0.03	27	27	140	5.1
SINBOT	Al/AlO_x/Cu	0.5×1	30, 50	0.03	54	27	360	6.6
1L1F	Al/AlO_x/Cu	0.24×2	30, 30	0.05	29	15	90	3.1
1L1Fmin[a]	Al/AlO_x/Cu	0.24×2	30, 30	0.05	32	15	64	2
1L2F	Al/AlO_x/Cu	$2 \times (0.24 \times 1)$	30, 30	0.05	28	15	88	3.1
1L2Fmin[a]	Al/AlO_x/Cu	$2 \times (0.24 \times 1)$	30, 30	0.05	42	15	113	2.6
1L4F	Al/AlO_x/Cu	$4 \times (0.24 \times 0.5)$	30, 30	0.05	31	15	177	5.7
2L2F	Al/AlO_x/Cu	$2 \times (0.24 \times 1)$	30, 60	0.05	11	5	22	2
2L4F	Al/AlO_x/Cu	$4 \times (0.24 \times 0.5)$	30, 60	0.05	11	5	37	3.4
SISN	Al/AlO_x/Al/Cu	$2 \times (0.25 \times 0.5)$	30, 30, 60	0.026	44	11	1.9 k	43
SISNSIN	Al/AlO_x/Al/Cu + Al/AlO_x/Cu	$2 \times (0.12/0.12^{b} \times 0.5)$	30, 30, 60	0.026	63	11/22[b]	3.3 k	52
NbAl	Nb/AlO_x/Al/AlO_x/AuPd/Nb	100	90, 100, 100, 500	1.45	1.4	150	1.4 k	10^3

[a] In these samples, the normal electrode is of "electron-confinement" shape (see the text).
[b] For SISN- and SIN-partial junctions, respectively.