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Overdamped Josephson junctions for digital applications

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Abstract

An interesting feature of Superconductor - Normal metal - Superconductor - Josephson junctions for digital applications is due to their non-hysteretic current-voltage characteristics in a broad temperature range below T_c . This allows to design Single-Flux-Quantum (SFQ) cells without the need of external shunts. Two advantages can be drawn from this property: first the SFQ cells can be more compact which leads to a more integrated solution towards nano-devices and more complex circuits; second the absence of electrical parasitic elements associated with the wiring of resistors external to the Josephson junctions increases the performance of SFQ circuits, in particular regarding the ultimate speed of operation. For this purpose Superconductor - Normal metal - Insulator-Superconductor Nb/Al-AlO_x/Nb Josephson junctions have been recently developed at INRiM with aluminum layer thicknesses between 30 and 100 nm. They exhibit non-hysteretic current-voltage characteristics with RnI_c values higher than 0.5 mV in a broad temperature range and optimal Stewart-McCumber parameters at 4.2 K for RSFQ applications. The main features of obtained SNIS junctions regarding digital applications are presented.

Keywords: Josephson Junctions; self-shunted junctions; SNIS; RSFQ; superconducting electronics; tunnel barrier

1. Introduction

Josephson junctions have been widely used since several decades in different applications whenever ultimate sensitivity or, more generally, performance, is required. This is the case for instance for heterodyne mixers in the millimeter and submillimeter range [1,2] where Josephson junctions act as a non-linear analog device. Josephson junctions are also used in digital mode in the so-called energy-efficient superconductive digital electronics, or Rapid-Single-Flux-Quantum (RSFQ) electronics [3,4], used to process signals at very high clock rates, in the 100 GHz range, with very low power consumption about 100,000 times lower than its semiconductive counterpart. So far such analog or digital electronics make use of low- T_c superconductors based more often on Superconductor-Insulator-Superconductor (SIS) Nb/Al-AlO_x/Nb junctions operating at liquid helium temperature, but also sometimes on NbN/MgO/NbN [5] or NbN/AlN/NbN [6] SIS junctions. This last choice based on the NbN superconductor is motivated by the need to work at slightly higher temperature (around 10K) to reduce the overall cost associated with cryogenic cooling. For digital applications, where non-hysteretic current-voltage characteristics are necessary for operation [3], a resistive shunt is inserted in parallel with each SIS Josephson junction. Though this technique is widely used, including for the most complex circuits [4] that can comprise more than 10,000 devices with current densities of around 10 kA/cm² [7], it limits the ultimate integration of the technology as the wiring of the parallel resistor occupies typically an area of four times the junction area. It also adds some parasitic inductance that limits the ultimate switching frequency of the shunted device [8]. To bring a solution, self-shunted Josephson junctions, for

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which the tunnel barrier is resistive, are an attractive alternative, also of interest for future ac voltage standards. Several solutions have been used in the past based on NbN/TiN/NbN, NbN/TiS₂/NbN, NbN/TaN/NbN or NbN/NbN_x/NbN Superconductor-Normal metal-Superconductor (SNS) junctions [9-14]. Some junctions like the ones based on TaN material placed at the limit of the metal-insulator transition, are currently studied to evaluate their reproducibility for complex circuits since they have the advantage to operate in the 10K temperature range [12]. Another alternative was based on Superconductor-Insulator-Normal metal-Insulator-Superconductor (SINIS) junctions [15,16] that led to circuits with several thousands Josephson junctions. Nevertheless the characteristic voltage of these junctions is not high enough for future digital circuits. More recently, another approach was proposed, it is based on the replacement on the aluminum oxide insulating barrier of niobium junctions by a poor conductor at the limit of the metal-insulator transition, namely NbSi [17-18], resulting in self-shunted SNS junctions. It led to the successful test of the first digital circuits with such a technology [19]. In this work we propose an alternative process based on Superconductor - Normal metal - Insulator-Superconductor (SNIS) where the normal metal is an aluminum layer with increased thickness compared to SIS junctions, and the insulator is the usual aluminum oxide. This process combines the reproducibility of unshunted technological processes with the possibility to operate at higher temperature than 4.2K, resulting from the proper engineering of the barrier properties at the desired temperature, located in the 5-7 K range.

2. Technological process for SNIS junctions

The overdamped Nb/Al-AlO_x/Nb SNIS Josephson junctions have been recently developed at INRIM and exhibit high values of critical current density and characteristic voltage, making them appealing both for metrology and digital electronics.

SNIS Josephson junctions are fabricated starting from the well-known SIS trilayer process [20] by oxidizing in-situ, and without breaking the vacuum, the aluminum barrier in pure oxygen. The thickness of the aluminum metal layer and the oxidation time, properly trimmed, are able to determine the peculiar internal shunt of a SNIS junction and a transition from a hysteretic to a non-hysteretic current-voltage I-V characteristics. This transition has been also observed by increasing the temperature of operation [21, 22].

SNIS junctions can be fabricated trimming a wide range of electrical parameters, showing critical current density values J_c from less than 1 kA/cm² up to 105 kA/cm². The critical voltage $V_c=I_cR_n$ can be easily tuned from 0.1 to 0.7 mV at 4.2 K, for a typical SNIS junction of 5x5 μm² size realized by optical lithography.

Satisfying the demand of reducing Josephson junction dimensions down to sub-micron scale, necessary for proper operation of superconducting digital devices when current densities are higher, recent results have been obtained concerning the realization of sub-micron SNIS junctions [23]. The effective area has been defined exploiting a nanolithographic technique based on Electron Beam Lithography (EBL) by using a FEI Quanta 3D ESEM FEG equipped with a J. C. Nauty NPGS pattern generator.

A proper scaling of junction current densities has been observed and quantized Shapiro steps have been measured also at the temperatures of about 7 K, confirming the interest to be employed at temperature above 4.2 K in a cryocooler set up.

3. Specific capacitance, critical voltage and McCumber parameter of self-shunted Josephson junctions

Digital superconductive electronics circuits are usually designed so the current-voltage characteristics is non hysteretic while the critical voltage is maximum. This corresponds to a Stewart-McCumber parameter β_c found experimentally in the range of 1 to 3 [24]; this range is optimum for RSFQ electronics applications. To this regard, the value of the intrinsic capacitance plays a major role, since a too high value reduces the ultimate critical voltage, hence reduces the ultimate speed of the circuit. Several SNIS junctions have been resonated with a parallel inductive stub in order to determine this capacitance, which has been found to be in the range of 180 to 480 fF/μm² [24]. The lowest values have been found for a temperature of 4.2 K and are about a factor of 3 higher than the ones of Nb/Al-AlO_x/Nb SIS junctions. Nevertheless critical current densities of SNIS junctions can be higher, as mentioned in the former paragraph, than the ones of SIS junctions. This counterbalances the capacitance trend. As a result the critical voltage can reach 0.55 to 0.7 mV [24] which corresponds to the state-of-the-art for externally-shunted technological processes [7], without the need of external shunts.

An interesting feature of the SNIS junctions are their ability to still present good performance when temperature is increased up to 7K. Conventional SIS junctions show a sharp decrement of the electrical parameters above 4.2 K, associated to a strong temperature dependence, which comes from a steep behavior of the $I_c(T)$ curve above $0.5T_c$ in

the Ambegaokar-Baratoff theory, where T_c is the critical temperature of the superconducting film. The replacement of the bottom superconducting electrodes by a Superconductor/Normal metal S/N bilayer leads to a more gentle curve in this temperature interval [25], as seen in figure 1. Indeed, it has been shown experimentally [26] and theoretically [27] that the superconducting order parameter in a N layer of thickness dN comparable with the thickness dS of a S film first rapidly decreases with temperature and then, at T close to $T_c/2$ becomes flat up to a nearest vicinity of T_c . Changing the ratio dN/dS modifies T_c and, hence, leads to the possibility of engineering the thermal stability of the Josephson SNIS devices.

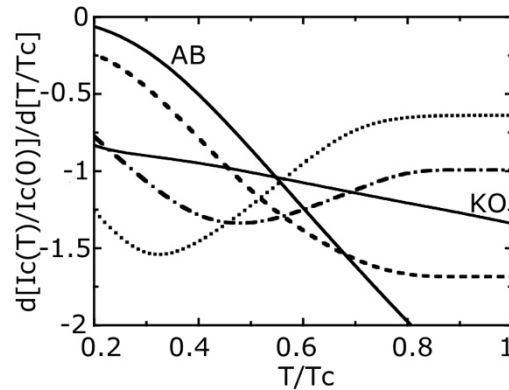


Fig.1. Normalized temperature derivative of the critical current of conventional SIS junctions that follow the Ambegaokar-Baratoff theory (AB curve) and of SNS junctions explained by the Kulik-Omelyanchuk theory (KO curve). Same variations for SNIS devices with $\gamma_{\text{eff}} = 2, 10,$ and 20 (dashed, dashed-dotted, and dotted lines respectively). γ_{eff} is proportional to the ratio of Al to Nb in the S/N bilayer.

4. Perspectives based on a multilayer process including a ground plane

Applications of such SNIS devices for digital RSFQ circuits require the reduction of sizes of junctions in the $1\text{-}\mu\text{m}$ size range [23] in order to be able to produce junctions with critical currents in the $100\text{-}300\ \mu\text{A}$ range. Moreover it is necessary to develop a multilayer technology with a ground plane in order to guide on the circuit voltage pulses produced by self-shunted Josephson junctions. These steps are currently being implemented at INRIM. A cross-section of the process under development is shown in figure 2.

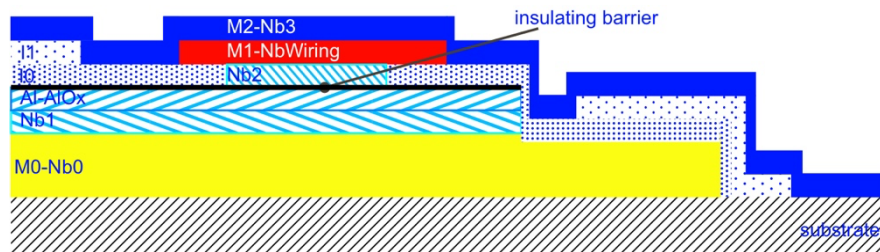


Fig.2. Multilayer process with self-shunted SNIS junctions implemented for RSFQ applications

As a result we plan to operate circuits with self-shunted SNIS junctions either at 4.2K with a typical characteristic voltage of $0.55\ \text{mV}$, but also at about $6\ \text{K}$ with a reduced critical voltage in the $0.3\ \text{mV}$. The expected performance in this last case is the one of an RSFQ process based on process with current densities of $1\ \text{kA}/\text{cm}^2$, with the advantage of a higher temperature that relaxes the cryogenic constraint for specific applications. In all cases the Stewart-McCumber parameter stays in the ideal range, comprised between 1 and 3.

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