Josephson junctions with centered step and local variation of critical current density

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Abstract—Superconductor-insulator-ferromagnet-superconductor (SIFS) Josephson tunnel junctions based on Nb/Al$_2$O$_3$/NiCu/Nb stacks with a thickness step in the metallic NiCu interlayer were fabricated. The step height of a few 0.1 nm was defined by optical lithography and controlled etching of both Nb and NiCu layers. Experimentally determined junction parameters by current-voltage characteristics and Fraunhofer pattern indicate a uniform NiCu thickness and similar interface transparencies for etched and non-etched parts. The critical current diffraction pattern was calculated and measured for stepped junctions having the same ground phase difference but different critical current densities in both halves. The measured data show a good agreement with simulations.

Index Terms— Ferromagnetic materials, Josephson junctions, Superconducting device fabrication, Thin films

I. INTRODUCTION

THE Josephson junction (JJ) is considered as the work horse in superconducting electronics. They are based on two weakly coupled superconducting electrodes via a constriction, e.g., made up by a normal metal or a tunnel barrier and are routinely applied in ultra-high sensitive SQUID (Superconducting Quantum Interference Devices) magnetometers, or the voltage standard [1]. Especially Nb/Al$_2$O$_3$/Nb tunnel junctions attract considerable interest as the fabrication of high density Nb-based Josephson circuits with promising small parameters spreads is possible. With the advent of high-quality magnetic tunnel junctions one decade ago, new so far unexplored devices are now under development which combine both fabrication techniques by advanced multilayers of superconducting (S), insulating (I) and magnetic (F) materials. These superconducting spintronic devices were in the focus of recent research activities, like so called 0–π Josephson junctions [2], [3] where the type of coupling (0 or π) is related to the local thickness of the stepped F-layer barrier in the junction. In this work stepped JJs with variation of critical current densities, but same coupling, are discussed.

Generally, for a variety of JJs a non-uniform critical current density $j_c$ is desirable, e.g., for tunable superconducting resonators, toy systems for magnetic flux pinning or magnetic-field driven electronic switches being similar to SQUIDs.

The first considerations [4] of non-uniform $j_c$’s were caused by technological drawbacks leading to a variation of the effective barrier thickness by either fabrication [5] or illumination of light-sensitive barriers [6]. JJs with periodic spatially modulations of $j_c$ were intensively studied regarding the pinning of fluxons [7]–[9], the spectrum of electromagnetic waves [10], [11] or their magnetic field dependencies [12]. Experimentally, a modulation of $j_c$ was done by lithographic insertion of defects such as i) insulation stripes ($j_c = 0$) [13], [14], microshorts ($j_c$ increased) or microresistors ($j_c$ decreased).

The properties of JJs depend on geometrical (width, length, thickness) and the physical (dielectric constant $\epsilon$, specific resistance $\rho$, magnetic thickness $\Lambda$ and $j_c$) parameters. When tailoring $j_c$ all other parameters should be unchanged to facilitate calculations and avoid further inhomogeneities in the system. These conventional methods for changing $j_c$ necessarily modify either $\epsilon$ or $\rho$.

In this paper a new method is used to gradually modify $j_c$ in one half of the junction. The fabrication technology presented (see Fig. 1) permits the controlled change of only the interlayer thicknesses $d_1$ and $d_2 = d_1 + \Delta d$, i.e., the local $j_c$, while keeping both $\epsilon$ and $\rho$ constant. The magnetic field dependence of the critical current is measured for several stepped junctions and compared to simulations.

II. EXPERIMENT

The deposition and patterning of the stepped junctions was performed by a four level photolithographic mask procedure [15], [16]. The SIFS stack were deposited by a magnetron sputter system. Nb and NiCu were statically deposited, whereas Al was deposited during sample rotation and at much lower deposition rates to obtain very homogeneous and uniform films.

After the deposition of the Nb as cap layer and subsequent lift-off the complete SIFS stack, without steps in F-layer yet, was obtained. The part of the JJ that was supposed to have a larger thickness $d_2 = 5$–7 nm was protected by photoresist, see Fig. 1. It was shown that SF$_6$ reactive ion etching provides an excellent chemistry for low-voltage anisotropic etching of Nb with high selectivity towards other materials [17] and the photoresist. The inert SF$_6$ was dissociated in a RF-plasma and the fluor reacted with niobium $5F + Nb \rightarrow NbF_5$. The volatile NbF$_5$ was pumped out of the etching-chamber. When SF$_6$ was used as process gas all non-metallic etching products such as fluorides and sulfides from the top-layer of the NiCu-layer had to be removed by subsequent argon etching.

The patterning process of the step is depicted in Fig. 1(a)–(c). The key points were a) selective reactive etching of Nb, b) argon etching of NiCu to define $d_1 = d_2 - \Delta d F$ and c) subsequent in situ deposition of Nb.

The Nb cap layer was removed by reactive dry etching using SF$_6$. A few 0.1 nm of NiCu were Ar ion etched at a very

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The uniformity of the supercurrent transport in a Josephson junction can be judged qualitatively from the $I_c(H)$ pattern. The magnetic field $H$ was applied in-plane and along one junction axis. The magnetic diffraction pattern depends in a complex way on the current distribution over the junction area [19] and the effective junction length. The ideal pattern of a short ($L_1 + L_2 \leq \lambda J$) JJ with Josephson penetration depth $\lambda J$ is symmetric with respect to both polarities of the critical current and the magnetic field and has completely vanishing $I_c$ at the minima. Asymmetry, irregularity or current offsets in $I_c(H)$ indicate a non-uniform current transport over the interlayers. If the JJs are flux-free, this non-uniformity can be located in both the insulating and ferromagnetic layers as well as at the interfaces.

Transport measurements were made in a liquid He dip probe using low-noise home made electronics and room-temperature voltage amplifier. The critical current was determined by a voltage criteria of 3 $\mu$V.

### III. Results and Discussion

Three different types of junctions are discussed: being either fully etched or not-etched (so-called reference JJs) and half etched (stepped JJs) (Fig. 1 d). From the current-voltage characteristic (IVC) and magnetic field dependence of critical current $I_c(H)$ of the reference JJs one can estimate parameters for the stepped junction, such as the ratio of symmetry $\Delta = j_2/j_1$, where $j_1 = j_c(d_1)$ and $j_2 = j_c(d_2)$, and the quality of the etched and non-etched parts.

| Table I | Etching parameters of Nb and NiCu. The rates were determined by profiler measurements. |
|---------|-----------------------------------------------------------------------------------------|
|         | partial pressure [mbar] | power density [W/cm²] | etching rate [nm/s] |
| SF₆ on Nb | $15 \cdot 10^{-3}$ | 0.6 | $\sim 1$ |
| SF₆ on NiCu | $15 \cdot 10^{-3}$ | 0.6 | $<0.001$ |
| Ar on NiCu | $5 \cdot 10^{-3}$ | 0.6 | $\sim 0.01$ |

The low rate to avoid any damaging of the NiCu film under the surface and to keep a good control over the step height, see etching rates in Table I. The etching was stopped when the F-layer thickness was reduced down to the thickness $d_1$ and subsequently Nb was deposited as cap-layer. The complete etching and subsequent Nb deposition was done in-situ. The chip contained stacks with the new NiCu thicknesses $d_1$ (uniformly etched), $d_2$ (non-etched) and with step in the F-layer thickness $\Delta d_F$ ranging from $d_1$ to $d_2$ as depicted in Fig. 1(d).

The junction mesas were defined by aligning the photo mask on the optically visible step-terraces, followed by Ar ion-beam etching of the upper Nb, NiCu and Al layers. The length of both junctions halves $L_1$ and $L_2$ are within the lithographic alignment accuracy of 1 $\mu$m. The etching was stopped after the complete etching of the $Al_2O_3$ tunnel barrier. Afterwards the mesas were insulated by SNEAP (Selective Niobium Etching and Anodization Process) [18]. In the last photolithographic step the wiring layer was defined. After a short argon etch to remove the contact resistance the thick Nb wiring was deposited.
The phase-field relation for maximum peak and the appearance of periodic minima of $\phi$ can be found in Ref. [22].

The general analytical form of $\phi$ was normalized to the maximum value $c \phi(0)$ and decreases for smaller values of $j_2$. $I_c(h)$ becomes that of a junction with half the width and uniform magnetic flux penetration due to different conduction of the magnetic field. In the short $J_J$ limit and measurements were done at 4.2 K.

**1) Calculated $I_c(h)$ of stepped $J_J$:** The magnetic diffraction pattern $I_c(H)$ of a $J_J$ depends on its $j_i$ profile, see Ref. [19]. The analytic solution for a short stepped junction with centered step $(L_1 = L_2 = L/2)$ and different critical current density $j_1$ and $j_2$ in both halves is given by

$$I_c(h) = w \left[ \int_0^{L/2} j_1 \sin \left( \phi_0 + \frac{hx}{L} \right) dx + \int_0^{L/2} j_2 \sin \left( \phi_0 + \frac{hx}{L} \right) dx \right]$$

where $\phi_0$ is an arbitrary initial phase, $h = 2\pi \lambda_c \mu_0 LH/\Phi_0$ the normalized magnetic flux through the junction cross section, $\lambda$ the magnetic thickness of junction and $w$ the junction width. The phase-field relation for maximum $I_c$ is reached for

$$\phi_0 = \arctan \left[ \frac{\sin \left( \frac{\pi}{4} \right) \cdot (j_1 + j_2)}{2 \sin^2 \left( \frac{\pi}{4} \right) \cdot (j_2 - j_1)} \right].$$

The general analytical form of $I_c(h)$ for multi-step junctions can be found in Ref. [22]. The calculated $I_c(h)$ for various ratios of $\Delta = j_2/j_1$ are depicted in Fig. 3a. Characteristic features are the centered maximum peak and the appearance of periodic minima of $I_c(h)$. The depths of the odd-order minima depend on the asymmetry ratio $\Delta$ and decrease for smaller values of $j_2$. $I_c(h)$ is completely vanishing at the even-order minima.

**2) Measured $I_c(H)$ of stepped $J_J$:** The measured $J_J$s are in short limit, $I_c = 0.5 \cdot j_1 A$ for $j_2 = 0$. The corresponding $I_c(h)$ pattern becomes that of a junction with half the width and uniform $j_c = j_1$.

It can be seen that for smaller $\Delta$ i) the oscillation period changes to the double value by comparing the $I_c(H)$ for $\Delta = 1$ and $\Delta = 0.25$, ii) the depth of the odd-order minima decreases and iii) the maximum critical current $I_c(0)$ is reduced.

The slight asymmetry of some $I_c(H)$ pattern, for example at the first side-maxima of the $\Delta = 0.45$ sample, and in consequence the deviation to simulation can be explained by a modification of the magnetic flux penetration due to different...
magnetic states in both halves [23]. Recently, it was shown by the author that remanent magnetization of F-layer can lead to strong deviation of the expected $I_c(H)$ pattern [24]. Here, the weak magnet NiCu was used as interlayer. However, as both halves are in the $\pi$ coupled state the magnetic properties of F-layer can not be neglected. The difference in F-layer thickness for both halves even facilitates some variation of the local magnetic configuration. Nevertheless, the fair agreement of measurement and simulation in Fig. 3 b) shows the good reliability of the step formation procedure.

IV. CONCLUSIONS AND OUTLOOK

As conclusion, SIFS Josephson junctions were fabricated with a well-defined step by local etching of the ferromagnetic interlayer. The etched and not-etched SIFS junctions differ only by F-layer thickness. No inhomogeneities can be seen in the current transport characteristics of the etched junctions. Magnetic field transport measurements on stepped junctions have a good correlation with the simple analytical model.

As an outlook, the use of a non-magnetic stepped layer avoids the modifications of magnetic cross-section by intrinsic magnetic remanence, and may help to further improve the consistence of $I_c(H)$ measurement with simulation. Replacing the optical lithography with electron beam lithography may enhance the lateral accuracy of the step down to the dimension of e-beam resist. The patterning of stepped JJs allows free lateral placement of well-defined $j_c$'s and/or local coupling regimes within a single junction. JJs with varying $j_c$ and planar phase could be used for devices with special shaped $I_c(H)$ pattern [19], toy systems for flux pinning or tunable superconducting resonators. The stepped junctions can be realized in Nb based JJs with any interlayer material, which is chemically stable towards the reactive etching gas. The patterning process could be adjusted to all thin film multilayer structure providing that the reactive etching rates of the layer materials differ, e.g., it can be applied to other metallic multilayer systems such as magneto-resistance devices (GMR/TMR elements) where a local variation of magnetic properties may enhance their functionality.

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