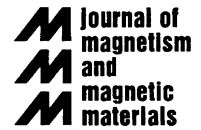




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Fabrication and superconducting properties of nanostructured SFS contacts

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Abstract

Superconducting hybrid structures of submicrometer size utilizing high-melting transition metals such as Nb or Ta can be fabricated in ultra-high vacuum by means of a non-organic evaporation mask (Si_3N_4) of high thermal and mechanical stability. We report on the magnetic and superconducting properties of mesoscopic superconductor/ferromagnet/superconductor (SFS) junctions realized in a Nb/Cu/Co/Cu/Nb multilayer (ML). Below the superconducting transition temperature, the magnetic hysteresis loop shows a contribution from the strongly pinned magnetic flux of the superconducting Nb layers. Electrical transport measurements perpendicular to the layered structure clearly demonstrate a Josephson coupling between the Nb layers through the 5-nm thick ferromagnetic Co film. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Electronic transport; Mesoscopic systems; Proximity effect

Electron-beam lithography has become a powerful tool for the fabrication of submicrometer electronic devices. Complicated hybrid structures can be created in a single vacuum run by the shadow evaporation-technique, where the materials are deposited under various angles of the vapor beam with respect to the substrate which is covered by a suspended shadow-mask. However, vapor deposition of high-melting superconducting metals such as Nb or Ta in ultra-high vacuum (UHV) gives rise to an excessive degassing of the usually used organic mask resist PMMA or PMMA/MA because of the high thermal load. This leads to a deterioration of the superconducting properties for lateral sample dimensions below $1\ \mu\text{m}$.

In order to avoid these limitations we use an *nonorganic* Si_3N_4 mask. Briefly, our technique is based on a heterostructure consisting of a silicon substrate covered by an 800-nm thick SiO_2 spacer layer and an Si_3N_4 layer for the suspended mask [1]. The pattern is

written by e-beam lithography into a sacrificial PMMA layer and is transferred into the nitride layer by ion-plasma etching. Afterwards, the SiO_2 is wet-chemically underetched. The quality and purity of the Nb in the vicinity of the shadow mask is proven by the high superconducting transition temperature $T_c = 8.4\ \text{K}$ and small transition width $\Delta T_c \approx 30\ \text{mK}$ of 50-nm thick Nb wires without a relevant size-dependence down to a wire width of 250 nm [1].

Here we focus on the preparation of planar SFS microjunctions which are presently attracting considerable interest [2–4]. The exceptional feature of an SFS contact is a sign change of the superconducting order-parameter difference (π phase-shift) for certain values of the ratio d_F/ξ_F , where d_F is the thickness of the F interlayer and ξ_F is the (complex) penetration depth of the Cooper pair amplitude \mathcal{F} in the F layer. \mathcal{F} has an oscillatory component along the normal of the SF interface due to the interference of the spin-split $k_{F\uparrow}$ and $k_{F\downarrow}$ electrons forming the pairs. The oscillatory behavior of \mathcal{F} should appear in the thickness dependence of the critical current $I_c(d_F)$ [5,6] of an SFS Josephson contact. Experimental evidence for the existence of a π -junction in SF and SFS contacts with

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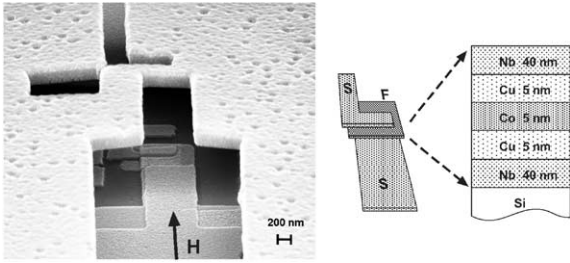


Fig. 1. Left: TEM micrograph of a microstructured Nb/Cu/Co/Cu/Nb-ML. Right: Schematic of the electrode configuration and of the multilayer stacking sequence.

diluted ferromagnetic layers has been reported recently [3,4]. However, in concentrated ferromagnets the modulus of the decay length $|\zeta_F|$ is of the order of 1–2 nm. Therefore, the F layer has to be extremely thin with a correspondingly small resistance. This makes transverse transport measurements difficult unless the junction area is of mesoscopic size.

Nb/Cu/Co/Cu/Nb microjunctions were prepared by e-beam evaporation in UHV at room temperature [7] (Fig. 1). A very small contact area 360×460 nm [2] was achieved by evaporating the layers under three different angles through the Si_3N_4 -mask. The electrode configuration ensures that the two S electrodes are clearly separated by the Co interlayer without any shortcuts. The Co layer is free of detectable pin holes as inferred from the absence of the Nb (167 eV) and Cu (918 eV) lines in the Auger spectrum taken in situ after Co deposition.

Magnetic hysteresis loops of an unstructured SFS multilayer with identical layer thicknesses were measured by means of a vibrating sample magnetometer with the magnetic field H oriented in the film plane. At a temperature $T = 10$ K, well above $T_c \approx 7$ K of the ML, a coercive field $\mu_0 H_c = 5.3$ mT and a saturation magnetization close to the bulk value of Co ($\mu_0 M_{\text{Co}} = 1.8$ T) were measured (Fig. 2a). The coercivity of the $1 \times 1 \mu\text{m}^2$ Co interlayer in the microstructured SFS sample may be slightly higher because of finite size effects. At $T = 1.8$ K $< T_c$ the magnetic saturation is considerably shifted along the M axis depending on the sweep direction of the magnetic field (Fig. 2b). This is attributed to the contribution of the superconducting Nb layers which is seen more clearly from the difference of the $M(H)$ data as shown in Fig. 2c.

The magnetic flux-density experienced by the Nb layer in contact with the Co layer is estimated to $B_{\text{eff}} = \mu_0 \times [H + M_{\text{eff}}(H)]$, where $M_{\text{eff}} = M_{\text{Co}} d_{\text{Co}} / d_{\text{eff}}$ and $d_{\text{eff}} \approx 49$ nm is the effective thickness of the junction barrier, see below. Hence, B_{eff} is governed by the large magnetization of the Co layer $M_{\text{eff}} = 0.18$ T, in addition to the applied field. M_{eff} has to be compared with typical values of the lower and upper critical field of a 40-nm

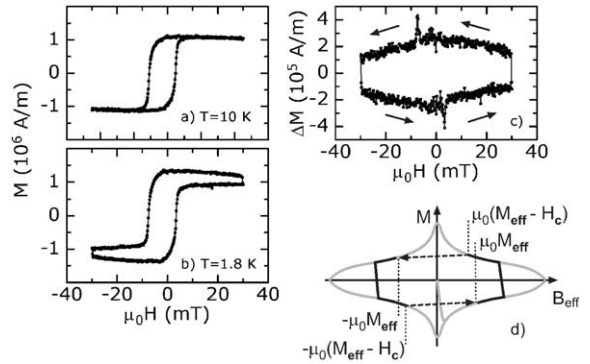


Fig. 2. $M(H)$ loops of a Nb/Cu/Co/Cu/Nb-ML (not microstructured) (a) above and (b) below $T_c \approx 7$ K. (c) Difference plot $\Delta M(H) = M(10 \text{ K}, H) - M(1.8 \text{ K}, H)$. Arrows indicate the field sweep direction. (d) $M(H)$ dependence of the S layer (with strong pinning) in contact with F, see text.

thick Nb film, $\mu_0 H_{c1} \approx 50$ mT and $\mu_0 H_{c2}^{\parallel} \approx 2.5$ T, respectively. This means that for $T \ll T_c$ the Nb layer is always in the mixed state between H_{c1} and H_{c2} due to the Co magnetization. Furthermore, thin Nb films deposited at room temperature have a very strong pinning of magnetic flux, i.e. a very small Meissner effect. The magnetization curve of such a type-II superconductor is schematically drawn in Fig. 2d (gray curve). Everytime, when the Co magnetization switches its direction in the applied field, the superconductor experiences a sudden change of magnetic flux (broken line), which gives rise to the sharp peaks in $\Delta M(H)$ around the coercive field of ± 5 mT (Fig. 2c).

On the microstructured samples, electrical transport measurements were done in an RF-shielded ^3He cryostat. From the $R(T)$ behavior a transition temperature $T_c^j \approx 4.7$ K of the junction and a normal-state resistance of 1.8Ω were determined. The inset of Fig. 3 shows the current–voltage dependence of the junction at $T = 2.1$ K characteristic for a Josephson coupling between the S layers via the 5-nm thick ferromagnetic Co layer. At $T = 0.3$ K a well defined critical current $I_c \approx 8 \mu\text{A}$ is observed which vanishes above T_c^j . $I_c(0.3 \text{ K})$ is much smaller than the Kulik–Omelyanchuk result of $I_c(0) \approx \pi \Delta(0) / 2eR_N \approx 3$ mA for SNS junctions which indicates the strong pair-breaking effect by the Co interlayer. Unlike in the experiment of Ryazanov et al. [4] we do not observe a transition from a “0”-state to a “ π ”-state in the $I_c(T)$ behavior but a monotonic decrease of I_c with increasing T . However, this is expected for a concentrated ferromagnet where the exchange energy is much larger than $k_B T$.

Fig. 3 shows the characteristic interference pattern of I_c in a magnetic field H applied parallel to the junction with pronounced and relatively regular oscillations of I_c . However, a quantitative analysis shows deviations when

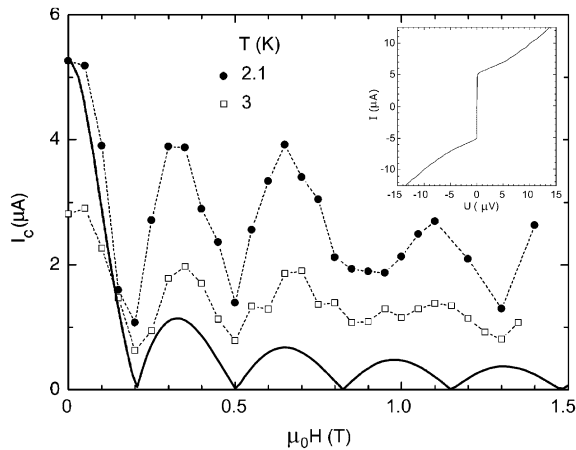


Fig. 3. $I_c(H)$ of the microstructured SFS junction at different temperatures $T < T_c$. Solid line is a Fraunhofer fit including the contribution of the Co layer magnetization to the enclosed flux. Inset: current–voltage characteristics at $T = 2.1$ K.

compared to an ideal Fraunhofer pattern. These cannot be ascribed to screening effects, because the Josephson penetration-depth of the junction ($10 \mu\text{m}$ at $T = 0.3$ K) is much larger than the junction size. The first minimum of the interference pattern is found at $\mu_0 H \simeq 0.2$ T, while the following minima are separated by 0.3 T. This can be explained in the same manner as above by taking the contribution of the Co layer magnetization to the magnetic flux Φ in the junction into account. The solid line is a Fraunhofer pattern calculated for a single Josephson junction including M_{eff} . For the present sample the effective thickness of the

junction depends very weakly on the magnetic penetration depth $\lambda(0) \simeq 90$ nm and is given by $d_{\text{eff}} = 2\lambda \tan h[(d_{\text{Nb}} + d_{\text{Co}})/(2\lambda)] + d_{\text{Co}} \simeq 49$ nm. This results in a cross-section of $460 \text{ nm} \times 49 \text{ nm}$ exposed perpendicular to the field and an expected magnetic field period of $\Delta(\mu_0 H) = 92$ mT which is substantially smaller than the experimentally observed value $\Delta(\mu_0 H) = 320$ mT. This could be related to the stray fields of the Nb layer on the nitride mask in $1 \mu\text{m}$ distance from the junction. Such stray fields can be avoided in future samples designed to allow for a mask lift-off.

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References

- [1] T. Hoss, C. Strunk, C. Schönenberger, *Microelectron. Eng.* 46 (1999) 149.
- [2] O. Bourgeois, P. Gandit, A. Sulpice, J. Claussy, J. Lesueur, X. Grison, *Phys. Rev. B* 63 (2001) 64517.
- [3] T. Kontos, M. Aprili, J. Lesueur, X. Grison, *Phys. Rev. Lett.* 86 (2001) 304.
- [4] V.V. Ryazanov, V.A. Oboznov, A. Yu. Rusanov, A.V. Veretenikov, A.A. Golubov, J. Aarts, *Phys. Rev. Lett.* 86 (2001) 2427.
- [5] Z. Radovic, M. Ledvij, L. Dobrosavljevic-Grujic, A.I. Buzdin, J.R. Clem, *Phys. Rev. B* 44 (1991) 759.
- [6] A.I. Buzdin, M. Kuprianov, *JETP Lett.* 53 (1991) 321.
- [7] T. Hoss, C. Strunk, C. Sürgers, C. Schönenberger, *Physica E*, in press.