# Expansion of a superconducting vortex core into a diffusive metal


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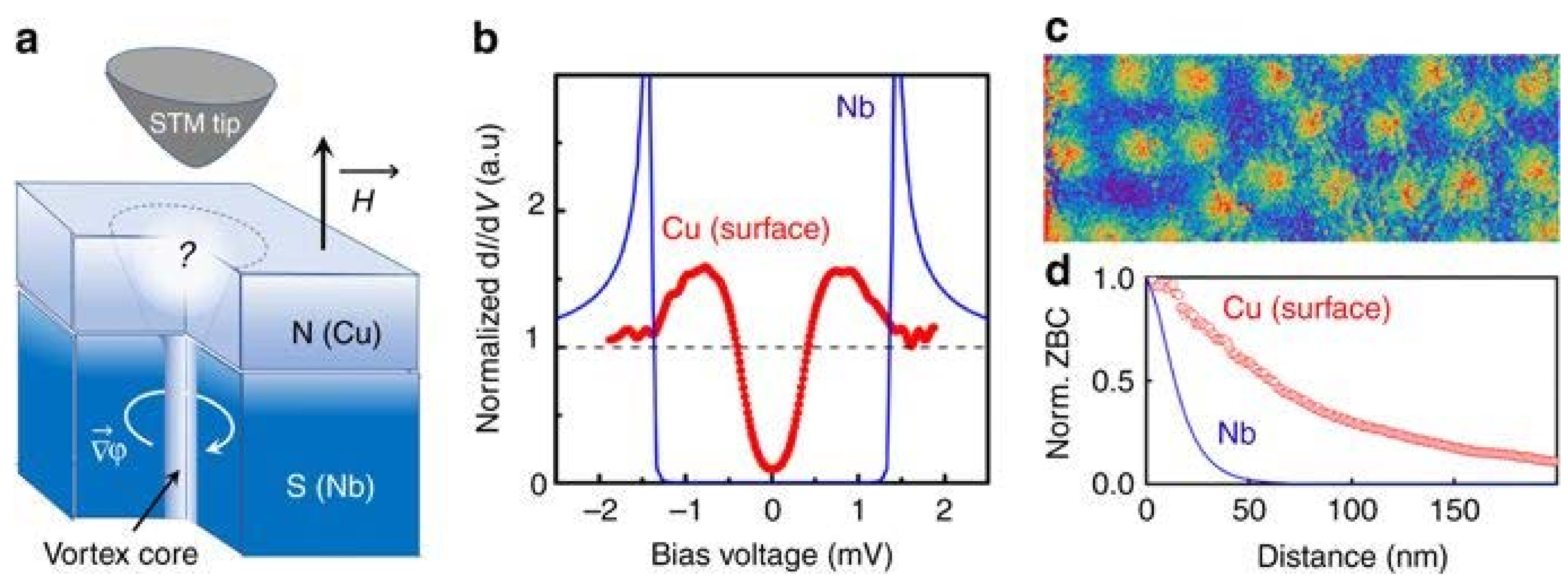
## Introduction

We report on the experimental observation of vortices on the surface of a 50nm-thick layer of Cu in the hybrid structure Cu/Nb with ultra-low temperature Scanning Tunneling Spectroscopy (STS). In the studied samples the non-superconducting Cu-layer acquires superconducting correlations due to the proximity effect with 100nm-thick superconducting Nb. To avoid the oxidation at Cu-surface and allow STS, the samples were *ex-situ* grown on SiO2/Si in the reverse order, i. e. Cu was deposited directly on the substrate. Nb was deposited on Cu. The samples were then introduced to the UHV STM chamber and cleaved *in-situ*. The structural analysis showed that, upon cleavage, the samples break at Cu-SiO2 interface, thus exposing fresh Cu surface.

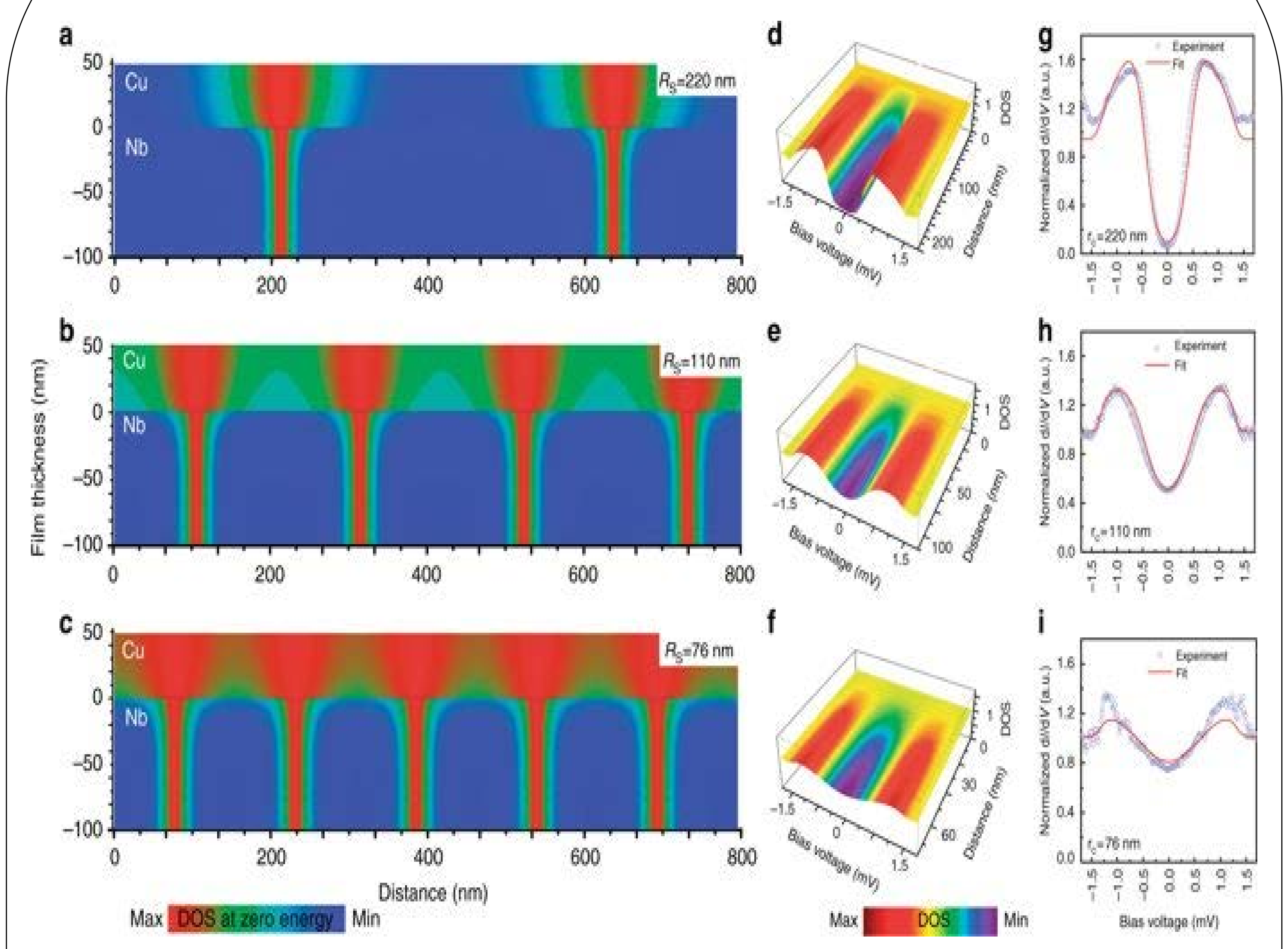
The presence of the proximity effect at the surface of Cu was first evidenced by observation of a proximity gap in the tunneling conductance spectra dI(V)/dV, in clear relation to the value of the superconducting gap of bulk Nb. The evolution of the proximity spectra with temperature was also studied in the range (0.3-4.2) K. Upon application of an external magnetic field, spatial variations of the tunneling conductance spectra were observed. These variations appear in the detailed STS map as round nm-size spots, in which centers the proximity gap vanishes. The density of spots rises continuously with magnetic field; it corresponds perfectly to the expected density of Abrikosov vortices in Nb. We identify the observed spots as proximity induced vortices in the normal Cu. On the basis of our STS data, we have determined the size and shape of the proximity vortex cores, and evaluated the coherence length in Cu. Independent numerical calculations of the quasiparticle spectra in S-N hybrids within the Usadel equation formalism were performed and found in agreement with experimental findings.

## Scanning tunneling spectroscopy experiment



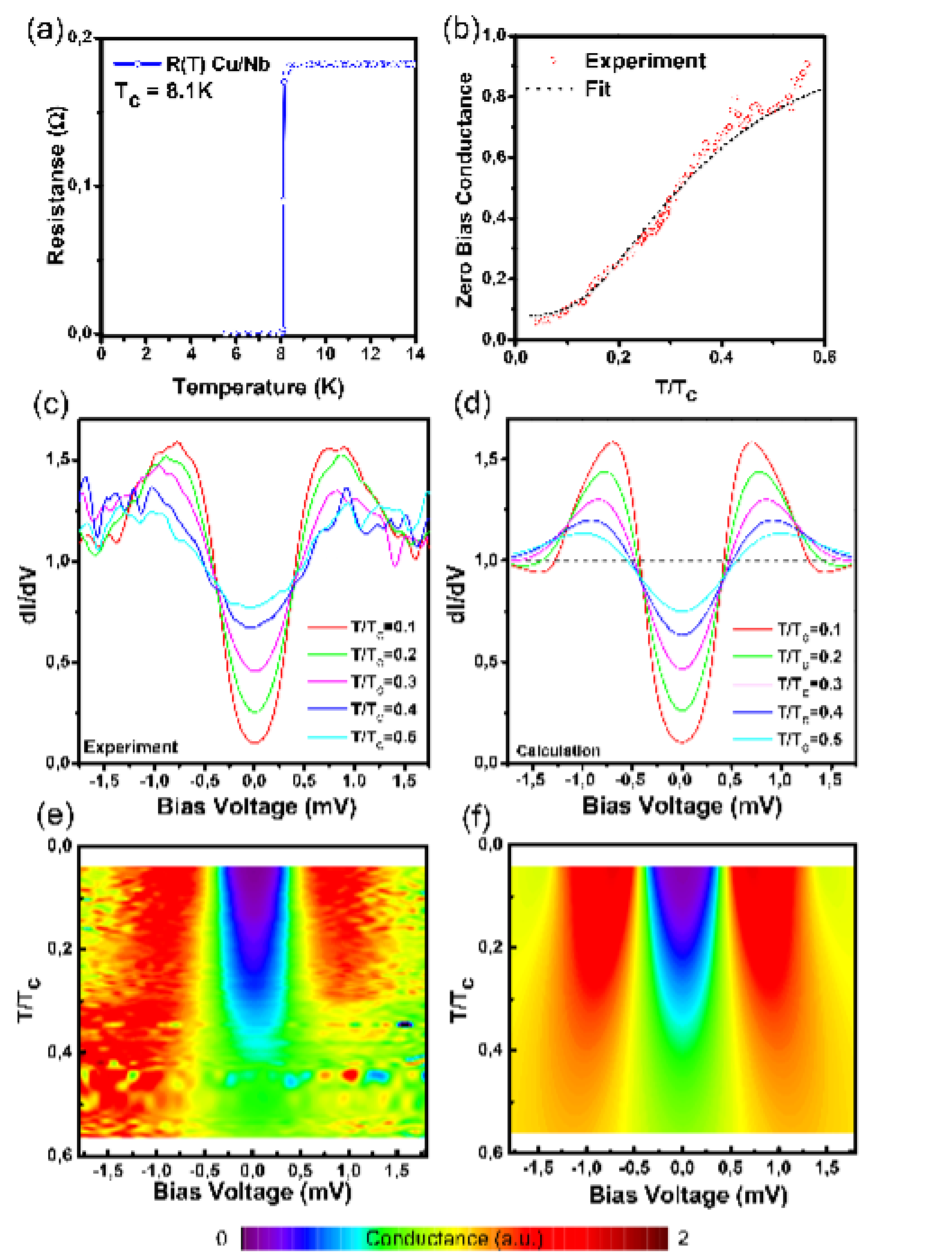

**a** Local tunneling characteristics are probed at the surface of 50 nm thick Cu-film backed with a 100 nm-thick Nb. Superconducting vortices are created in Nb by applying an external magnetic field perpendicularly to Cu/Nb interface; **b** Red data points: tunneling conductance d$I$($V$)/d$V$ spectrum measured at Cu-surface exhibits a minigap $\delta_{Cu} \simeq 0.5$ meV; it is three times smaller than the superconducting gap $\Delta_{Nb} \simeq 1.4$ meV in the d$I$($V$)/d$V$ spectrum of Nb (blue line); the observed excitations inside the minigap are due to a non-zero residual magnetic field (see the discussion in the main text); **c** 800 nm × 250 nm color-coded ZBC d$I$/d$V$($V$ = 0) map acquired in the magnetic field of 120 mT reveals proximity vortices; **d** Radial variation of the ZBC from the vortex center defines the vortex core profile (red data points). The minigap vanishes in the vortex cores; blue line-expected radial ZBC evolution at the Abrikosov vortex core in Nb-film

## Calculated local DOS inside Cu/Nb-bilayer



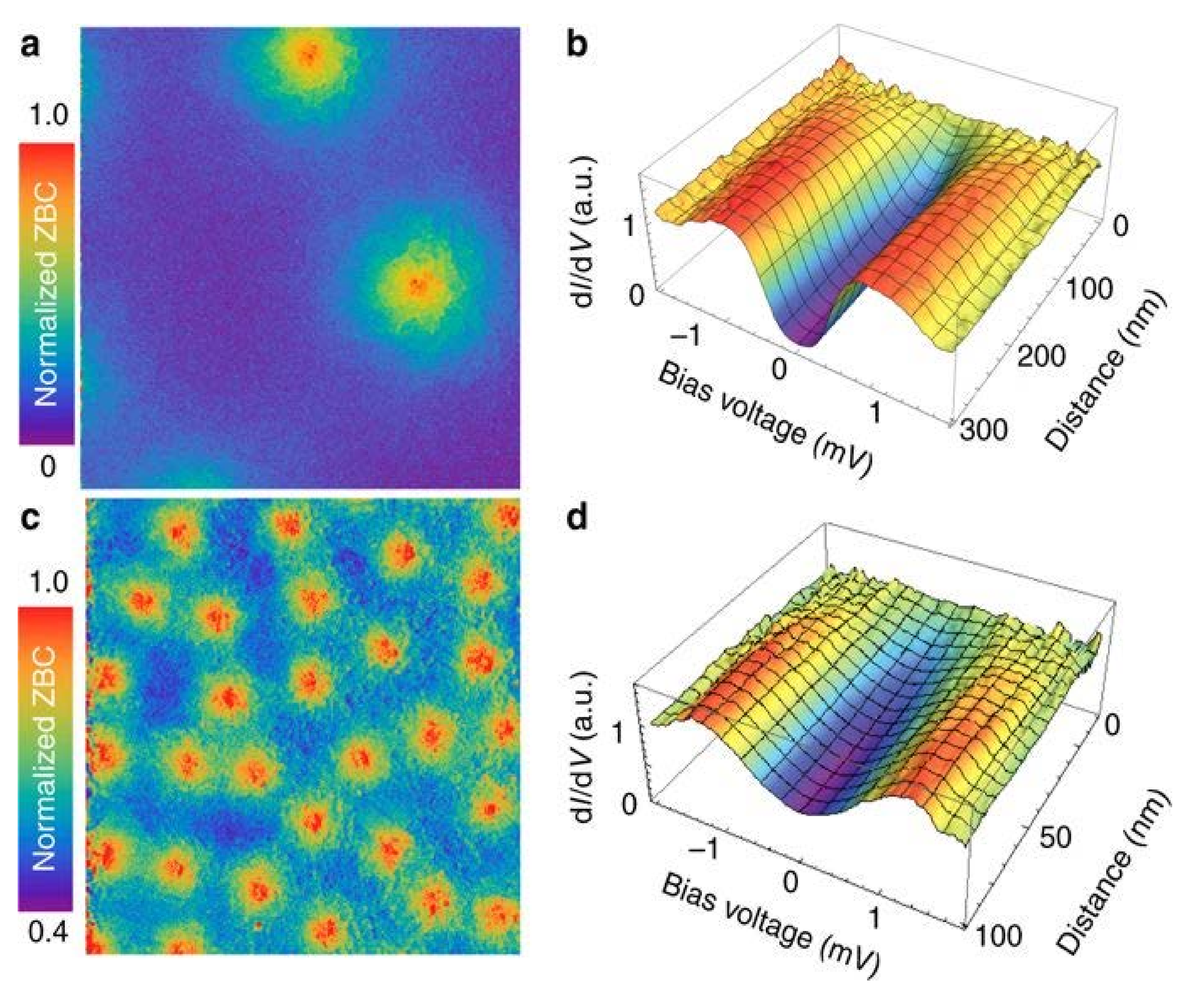

(a–c) Color-coded zero-bias DOS ($r$, $z$) maps calculated for three different magnetic fields 5, 55, and 120 mT, respectively. (d–f) Calculated 3D-plot of the radial evolution of the tunneling DOS in the vicinity of the proximity vortex cores; the magnetic fields are the same as in (a–c). (g–i) Dots: experimental tunneling spectra acquired away from the vortex cores at three magnetic fields as in (a–c). Lines: DOS fits calculated at the edge $R_S$($H$) of the circular vortex lattice unit cell.

## Sample characterization and minigap temperature dependance



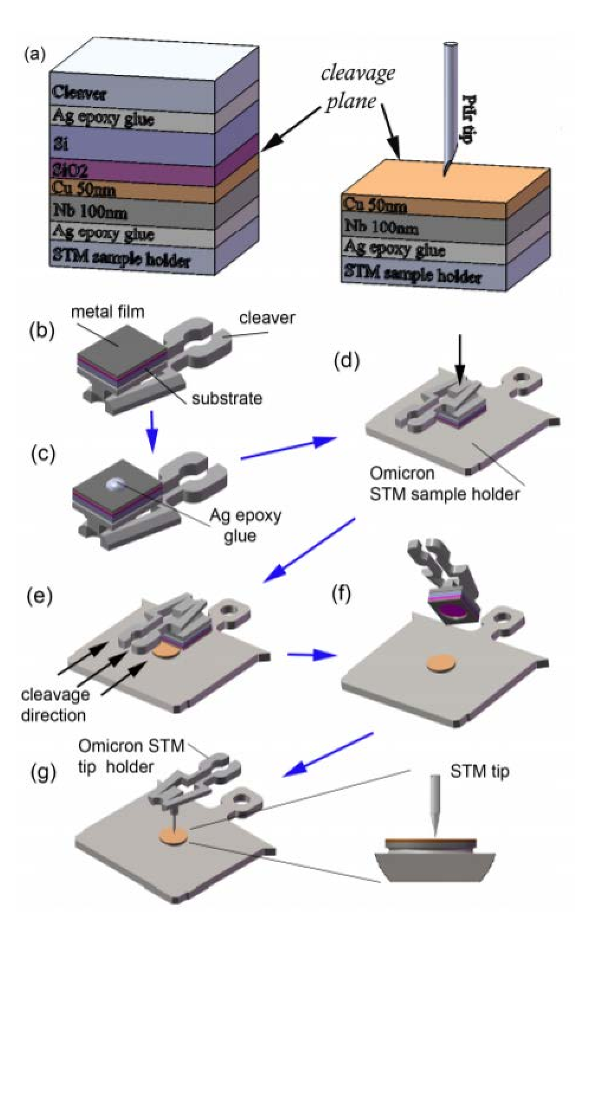

(a) - resistive transition of the studied Nb/Cu bilayer to a superconducting state; (b) - dots: temperature evolution of the zero-bias tunneling conductance measured by STM/STS at Cu-surface; dashed line - fit by Usadel theory: (c) - experimental dI/dV spectra measured at different temperatures; (d) - best fits of the data in (c) using Usadel model; (e) and (f) - the same as in (c) and (d) but presented as continuous color-coded plots.

## Overlap of proximity vortex cores




**a**, **c** 800 nm × 800 nm ZBC maps acquired at 300 mK in magnetic fields of 5 and 55 mT, respectively. **b**, **d** Radial evolution of the tunneling conductance spectra in the vicinity of the proximity vortex cores. The applied magnetic fields are the same as in **a**, **c**. Due to their large cores, the proximity vortices strongly overlap already at low fields, H≪HNbc2≃4H≪$H_{c2}^{Nb}$≃4 T

## Sample preparation




(a) - a schematic representation of the sample before and after cleaving and STM tip orientation; (b-g) - schematic cleaving process