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The superconductor proximity effect in Au–$YBa_2Cu_3O_{7-\delta}$ bilayer films: the role of order parameter anisotropy

O. Millo[a,*], I. Asulin[a], A. Sharoni[a], O. Yuli[a], G. Koren[b]

[a]*Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel*
[b]*Department of Physics, Technion—Israel Institute of Technology, Haifa 32000, Israel*

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Abstract

Scanning tunneling spectroscopy of Au–$YBa_2Cu_3O_{7-\delta}$ bilayers reveals proximity effect features that reflect the anisotropic $d_{x^2-y^2}$-wave order parameter in $YBa_2Cu_3O_{7-\delta}$ (YBCO). No proximity effect takes place at the (001)YBCO–Au interface, manifesting the quasi two-dimensional nature of the order parameter. Proximity gaps are induced in the gold primarily via (100)YBCO facets, and their size decays exponentially on a scale of ~30 nm, in good agreement with estimations for the dirty limit. In the nodal (110)YBCO–Au interface, the proximity effect manifests itself by the penetration of Andreev bound states into the gold. The corresponding zero bias conductance peaks are nearly constant in magnitude for Au layers thinner than 7 nm, and then decay abruptly with Au thickness, vanishing above 10 nm, on the scale of the (ballistic) mean free path.

Keywords: High temperature superconductors; Proximity effect; Scanning tunneling microscopy; Tunneling spectroscopy

1. Introduction

When a normal metal (N) is brought into good electrical contact with a superconductor (SC), superconducting properties may be induced in N and weakened at the SC side of the interface, a phenomenon known as the proximity effect (PE) [1]. This effect has been thoroughly studied, and is well understood by now, for proximity systems involving 'conventional' isotropic (s-wave) SCs. The mechanism leading to the penetration of SC order parameter into N is the Andreev reflection [2]: Upon impinging on the N–SC boundary from the N side, a hole-like quasi-particle is retro-reflected as an electron-like quasi-particle with inverse momentum and spin, while destroying a Cooper pair in the SC. By this, naively speaking, Cooper pairs leak from the SC side into the N side of the SC–N interface. The penetration length, namely, the normal coherence length ξ_N, is essentially the range over which the electron and hole maintain phase-coherence. In the case of a diffusive metal (the 'dirty limit') ξ_N is equal to the thermal length, $\xi_N = (\hbar D/2\pi k_B T)^{1/2}$, where D is the diffusion coefficient in N [1]. At the SC side, the order parameter (pair amplitude) recovers back to its bulk value over a length scale of the order of ξ_S, the BCS coherence length. Scanning tunneling spectroscopy (STS) performed via the scanning tunneling microscope (STM) can yield direct and detailed information on the evolution the SC order parameter as a function of distance from the N–SC interface, as demonstrated by various groups, including ours [3–5].

For an anisotropic d-wave superconductor, such as the high temperature (cuprate) superconductor $YBa_2Cu_3O_{7-\delta}$ (YBCO), the crystallographic orientation of the SC surface at the N–SC interface can modify significantly the PE. Indeed, Josephson coupling was observed in high temperature SC–N–SC junctions only for transport parallel the *a–b* plane, but not when it was along the *c*-axis [6], implying that Cooper pairs leak into N only along the CuO_2 planes. In this paper we summarize our recent STS studies of the PE in YBCO–Au bilayer films, in which some fundamental unresolved questions related to the PE involving a d-wave SC are addressed. One such issue is the symmetry of the proximity-induced order parameter in N, for which some theoretical calculations attribute s-wave symmetry [7]. Another fundamental problem is related to the PE in junctions involving the nodal (110)YBCO surface (on which SC order parameter is, in effect, suppressed [7]).

* Corresponding author. Tel.: +972 2 6585670; fax: +972 2 6586784.
E-mail address: milode@vms.huji.ac.il (O. Millo).

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A clear picture of the spatial variation of the local density of states (DOS) in the vicinity of these junctions, in particular the (possible) penetration of the Andreev bound states (ABS) [8] into the N layer has not yet been established.

2. Experimental details

The (001)YBCO–Au and (110)YBCO–Au bilayers were grown by laser ablation deposition on (100)$SrTiO_3$ and (110)$SrTiO_3$ wafers, respectively. The details of the growth procedure can be found in Refs. [9–11]. The (epitaxial) YBCO films (~50 nm thick) were optimally doped (or slightly underdoped), showing sharp (0.5 K wide) SC transitions at temperatures ranging between 88 and 90 K. The Au layer was deposited onto the YBCO film in-situ, without breaking the vacuum, to ensure good electrical contact.

The (001)YBCO (*c*-axis) films consisted of nearly square-shaped crystallites, of 50–100 nm lateral size and 10–15 nm in height, which had relatively large (100) side facets [9]. This crystalline structure was clearly observed, yet somewhat smeared, under the Au layers (up to 50 nm thick). The Au films displayed a granular morphology with surface grains of ~10 nm in lateral size and rms height roughness of up to 1.5 nm (see Fig. 1). The (110)YBCO films revealed 40×100 nm^2 elongated crystallite structures, about 4 nm in height. Here too, this structure was clearly visible under the gold layers, which showed a similar surface morphology as described above (see image in Fig. 3).

Tunneling spectra (d*I*/d*V* vs *V* characteristics, proportional to the local DOS) were obtained by numerical differentiation of the *I–V* curves that were measured in correlation with the topography by momentarily disconnecting the feedback loop. About 10 curves were acquired at each position to assure data reproducibility

3. Results and discussion

Our main finding on the (001)YBCO–Au bilayer system is that the local value of the gap induced in the Au via the PE depends on the distance from an interface with a (100) YBCO facet (taking into account also the Au film thickness), and not on the gold-film thickness by itself (see Fig. 1(b)). Fig. 1(c) presents a series of tunneling spectra acquired sequentially along a line such as marked by the arrow in Fig. 1(a). It is evident that the gap size reduces with increased distance from the crystallite edge, and at the same time the zero bias conductance increases. As discussed above, such edges typically expose the (100) YBCO surface. Note that the maximal observed gap, just at the edge −6.7 meV, is still much smaller than the 18–20 meV gaps measured on the bare YBCO films. This is consistent with the presence of the Au layer that determines a minimal

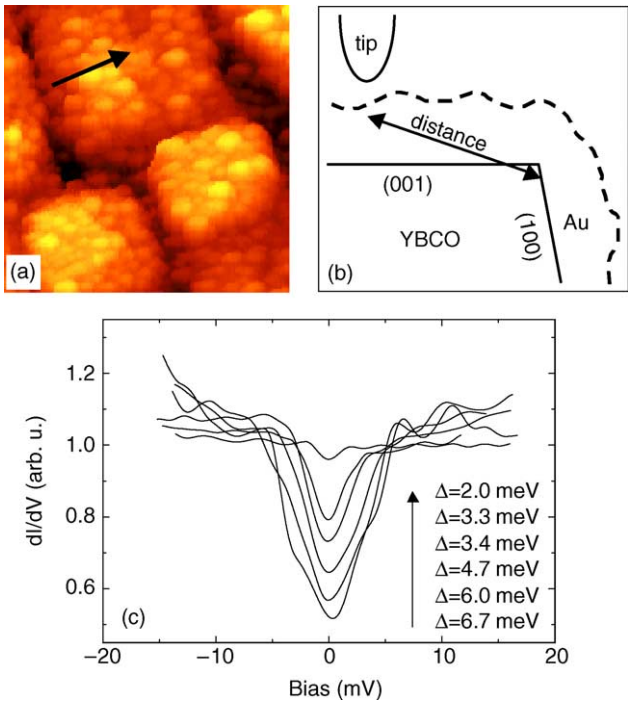

Fig. 1. (a) Topographic STM image (140×140 nm^2) of an YBCO film coated by a (nominally) 30 nm thick Au layer. (b) Schematic of the measurement configuration, showing the STM tip, the Au layer and the underlying YBCO crystallite, with labeled facets. The double-sided arrow shows the relevant distance that governs the size of the proximity-induced gap. (c) A typical measurement showing the decrease of the gap with increasing distance from a (100) facet at an YBCO crystallite edge. The tunneling spectra were measured sequentially along a line such as shown in (a). The gap sizes are denoted, from 6.7 meV (near the crystal edge) to 2 meV (the smallest detectable gap).

distance from the N–SC interface, corresponding to the Au film thickness (see Fig. 1(b)), 30 nm in this case. At larger distances from the edge, even for thinner gold layers, the gap structure practically vanished (due to the increase of the zero bias conductance it was hard to detect gap values much smaller than 2 meV).

Fig. 2 displays an accumulation of proximity gaps measured on the gold surface as a function of the distance to the closest (100)YBCO–Au interface (solid squares). This distance was determined from the distance to the crystallite edge, measured from the STM topographic images, taking into account the nominal thickness of the gold film (that in many cases was larger than the lateral distance to the crystallite edge). The solid line represents a best fit to the standard exponential decay form of the gap, $\Delta(x)=\Delta_0\exp(-x/\xi_N)$. This fit was obtained for $\xi_N\approx29$ nm, and an interface gap value $\Delta_0\approx15$ meV (solid circle in Fig. 2). The value extracted for the penetration depth is very close to that estimated for 'conventional' proximity systems in the dirty limit, $\xi_N=(\hbar D/2\pi k_B T)^{1/2}$, assuming that the elastic mean free path in the gold film is governed by grain boundary scattering, thus $l_N\sim10$ nm, with the Fermi velocity in gold taken from the literature, $\sim1.4\times10^6$ m/s.