Transition in the tunneling conductance of $YBa_2Cu_3O_{7-\delta}$ films in magnetic fields up to 32.4 T

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We studied the tunneling density of states in $YBa_2Cu_3O_{7-\delta}$ films under strong currents flowing along node directions. The currents were induced by fields of up to 32.4 T parallel to the film surface and perpendicular to the CuO_2 planes. We observed an interesting transition in the tunneling conductance at high fields where the gaplike feature shifts discontinuously from 15 meV to a lower bias of 11 meV, becoming more pronounced as the field increases. The effect takes place in increasing fields around 9 T and the transition back to the initial state occurs around 5 T in decreasing fields.

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I. INTRODUCTION

The order parameter of a *d*-wave superconductor has node lines located at angles $\theta_{\pm} = \pm\pi/4$, where θ is the angle between the quasiparticle momentum and the crystallographic [1,0,0] direction.[1] As a result, the tunneling density of states of a *d*-wave superconductor is significantly different from that of a conventional *s*-wave superconductor. In particular, it reveals the existence of low energy surface bound states, which are the origin of the zero bias conductance peak at pair breaking surfaces.[2,3] The high conductance at low bias, below the *d*-wave gap, is in sharp contrast with the low conductance in an *s*-wave superconductor at similar bias. The *d*-wave gap itself is marked in the tunneling density of states by a weak structure called the gaplike feature[3] (see Fig. 1). The zero bias conductance peak and gaplike feature are well identified in the tunneling density of states of high-T_c cuprates[4,5] and simultaneously observed when the surface roughness scale is smaller than the junction size.[5,6] It was predicted that a *d*-wave symmetry can be modified by a perturbation that creates a gradient of the order parameter. This is the case of a vortex core,[7] sample surface,[8] and currents.[9,10]

In this study we report measurements of the conductivity of $In/YBa_2Cu_3O_{7-\delta}$ (YBCO) junctions. Currents in the YBCO film are induced by applying magnetic fields, parallel to the surface and perpendicular to the CuO_2 planes. Films having (110) and (100) orientation are used, respectively, to induce nodal and antinodal currents.

The tunneling conductance changes remarkably for the (110) films in high magnetic fields-high currents in a domain that has not been investigated until now. The position of the gaplike feature shifts down discontinuously in increasing fields around 9 T and in decreasing fields around 5 T. We argue that these shifts are due to nodal surface currents induced by the applied field, with the field itself, possibly inducing a certain modification of the vortex state. No transition is observed when the field is parallel to the CuO_2 planes [Fig. 1(b)] or when the film has the (100) orientation [Fig. 1(c)]. In both cases there are no currents flowing along the nodal direction.

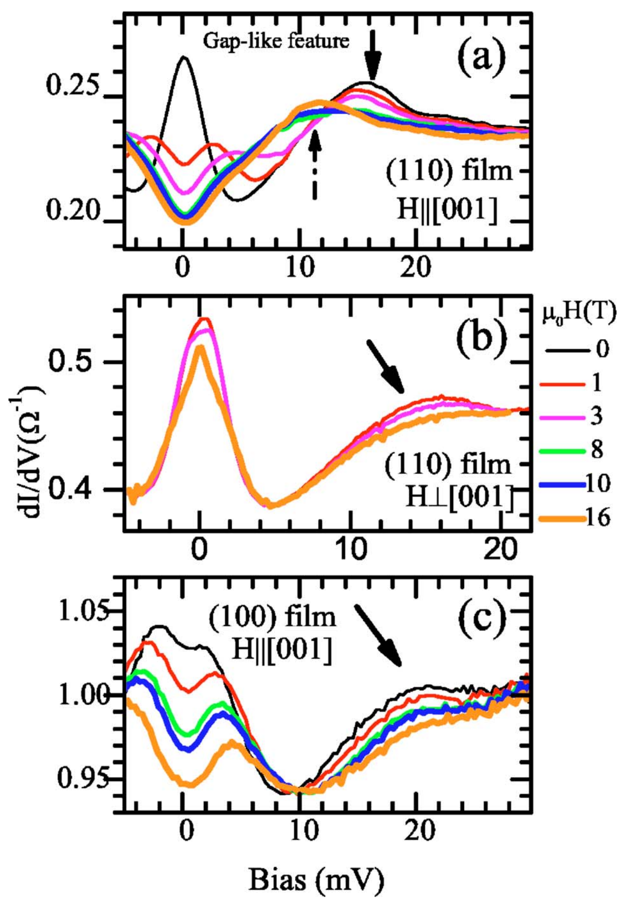

FIG. 1. (Color online) dI/dV vs bias voltage; magnetic field applied parallel to the films surface up to 16 T at 4.2 K. (a) A (110) in-plane orientated film at increasing field. The field is perpendicular to the CuO_2 planes (sample 1). (b) A (110) in-plane orientated film at increasing field. The field is parallel to the CuO_2 planes (sample 1). (c) A (100) in-plane orientated film. The field is perpendicular to the CuO_2 planes. Solid (dashed) arrows indicate the gaplike feature positions at low (high) fields. A remarkable change in the spectrum is observed at high fields only when the field is perpendicular to the CuO_2 planes and the nodal direction is normal to the film surface.

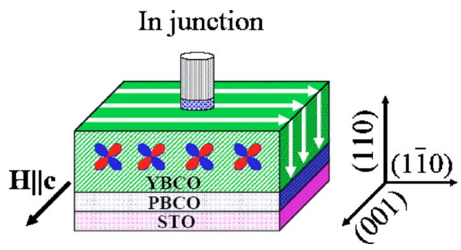

FIG. 2. (Color online) Schematic presentation of the measurement setup for the (110) films. Indium pads are pressed against the surface of the oriented thin film. The orientation of the film enables us to apply a magnetic field parallel or perpendicular to the CuO_2 layers while the field is kept parallel to the films' surface and perpendicular to the tunneling current.

II. EXPERIMENTAL RESULTS

Our oriented films were sputtered onto (110) $SrTiO_3$ and (100) $LaSrGaO_4$. All films have a critical temperature of 89 K (slightly underdoped). Tunneling junctions were prepared by pressing a freshly cut indium pad onto the films' surface.[12] These junctions are of high quality, as shown by their low zero-bias conductances below the critical temperature of the indium electrodes.[12] A schematic drawing of the crystallographic orientation and experimental setup is shown in Fig. 2.

Tunneling characteristics in (110) films at zero magnetic field exhibit the known zero-bias conductance peak and gaplike feature [Fig. 1(a)]. The magnetic field splitting of the zero-bias conductance peak was previously addressed.[4–6,12–14] We focus here on the field dependence of the gaplike feature at high bias. It shows a progressive, roughly linear, shift of the peak position from 17 to 15 meV as the field increases from 0 to 1 T. This initial decrease is followed by a flat region up to 6 T. If that field is not exceed and then reversed a hysteresis loop is described ending up with a flat region at low field. If the field is increased above 6 T the gaplike feature amplitude starts to shrink until, at 8 T, it cannot be identified anymore. In the range of 8–11 T a flat maximum develops between 10 and 15 meV. An 11 meV peak builds up with the field and is clearly identified above 11 T. Up to a field of 16 T, no detectable smearing of this peak occurs.

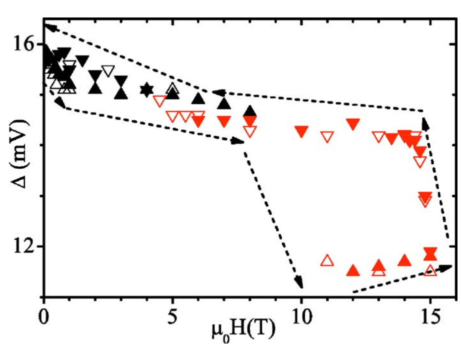

FIG. 3. (Color online) Gaplike feature position for sample 1 in increasing (△) and decreasing (▽) magnetic fields at 4.2 K. Data taken both for positive (full) and negative (hollow) field polarity. Black (red) represent the low (high) field state.

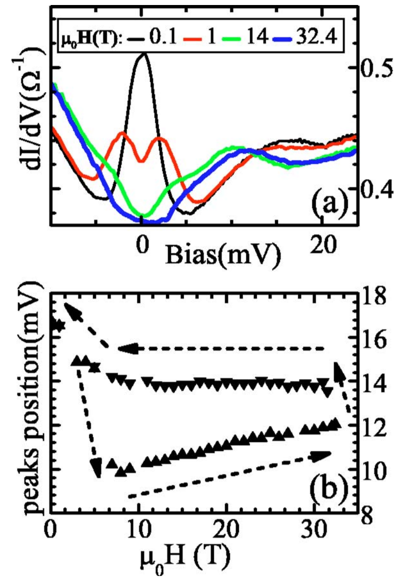

FIG. 4. (Color online) (a) *dIdV* vs bias voltage for sample 2 measured at 1.3 K in increasing magnetic fields. (b) Gaplike feature position in increasing (△) and decreasing (▽) fields.

Reducing the field from values larger than 11 T has another interesting effect. The 11 meV peak gradually shifts back to 14 meV as the field is reduced by about 1 T, for example from 15 to 14 T (Fig. 3) or from 32.4 to 31.5 T (Fig. 4(b)). In contrast to the 9 T field up transition, the shift back to 14 meV is *continuous*, which shows that the new peak at 11 meV is indeed a new gaplike feature rather than being related for instance to the split zero-bias conductance peak. By further reducing the field, the 14 meV peak shrinks while the 16 meV builds up below 5 T [Fig. 5(a)]. An analogous behavior is seen under field cooled conditions [Fig. 5(b)].

The overall variation of the gaplike feature peak position with respect to the applied field can be seen in Fig. 3. The jump in its position can be clearly observed in increasing fields above 8 T and decreasing fields lower than 6 T. The gradual increase of the 11 meV peak amplitude as the field is increased beyond 10 T (Fig. 6) suggests that it characterizes a different superconducting state.

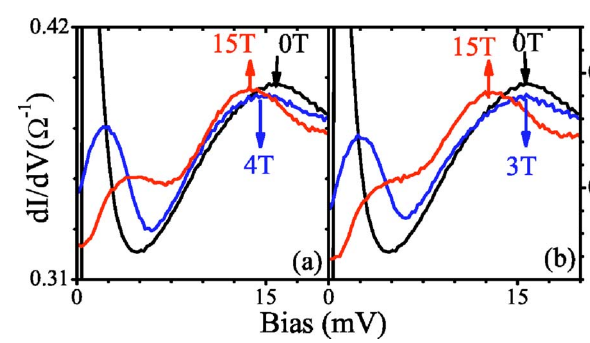

FIG. 5. (Color online) *dI*/*dV* vs bias voltage for sample 3 measured at 0.5 K. (a) Decreasing fields from 16 T. (b) Field cooled conditions. Note that the intermediate field peak conductance is lower than both the high and low field ones.

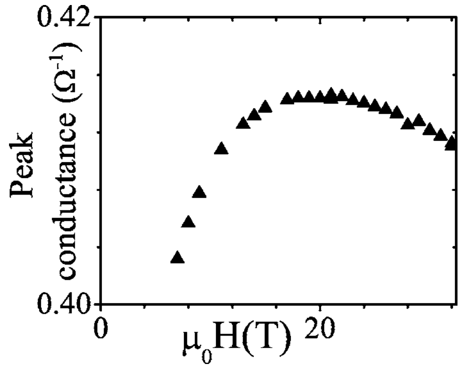

FIG. 6. 11 meV gaplike feature peak amplitude of sample 2 for increasing fields. The enhancement up to 20 T suggests that the high fields state has a stronger coherence peak.

III. DISCUSSION

The rapid change in the peak position upon field reversal [Figs. 3 and 4(b)] means that its position is affected by field induced currents. The strong difference between (100) and (110) oriented films, both showing a similar gaplike feature, presumably due to surface roughness,[6] indicates that these currents flow over a depth much larger than the surface roughness (a few tens of nanometers).

The Bean-Livingston barrier[15] can prevent the entry of vortices up to fields of the order of the thermodynamical critical field, H_c ($\sim$1 T for YBCO). The rapid initial decrease of the gaplike feature peak position from 16 meV down to 14 meV over that field range can be due to the delayed vortex entrance (see Fig. 3). We name the corresponding currents surface vortex currents, j_V. This is confirmed by the low field hysteresis loop, as there is no Bean-Livingston barrier in decreasing fields. This initial decrease is not observed in (100) oriented films where the currents at the surface flow along an antinodal direction. This decrease is therefore clearly due to nodal currents. The major question raised here concerns however the origin of the 11 meV peak seen in increasing fields above 10 T. It could be a current effect, or a field effect, or a combination of both.

In addition to the vortex surface currents, j_V, one should also consider. The Meissner screening current, j_M, and the Bean current j_B due to vortices pinned in the bulk. We showed[14] that by measuring the difference between field cooled and decreasing field splitting values of the zero-bias conductance peak (also due to the surface currents[6]), one can estimate the Bean critical current value. We found that j_B is roughly constant up to fields of 16 T and has a value of a few tens of MA/cm^2.

The surface current can be obtained by calculating the depth, d, of the vortex-core free area at the sample surface.[15] Its derivation is not affected by the d-wave symmetry and has to include the Bean current j_B. In the following the effect of the vortex surface current is neglected. Consider a semi-infinite superconductor in a uniform magnetic field H. The field inside, $b(x)$, is the solution of London's equation which has to match the boundary conditions $b(0)=H$, $b(d)=\tilde{B}$ and the vortex matter equilibrium condition $j(d)=j_B$, where $\tilde{B}$ is the local induction value. In the field range $H_{c1} \ll H \ll H_{c2}$ we have $d \ll \lambda$ and $j_B \ll j_M$:

$$d \approx \lambda\sqrt{2(H-\tilde{B})/H} + 4\pi j_B \lambda^2/cH, \qquad (1)$$

where λ is London's penetration depth. The same approximation results in $\tilde{B} \approx B$, where B is the equilibrium induction, $j \approx j_M(H)+j_B$ in increasing fields and $j \approx j_M(H)-j_B$ in decreasing fields, where

$$j_M = \frac{c}{4\pi\lambda}\sqrt{-8\pi HM} = \frac{c}{4\pi\lambda^2}\sqrt{\frac{\phi_0 H}{4\pi}\ln\frac{H_{c2}}{H}}, \qquad (2)$$

and ϕ_0 is the flux quantum. We find $j_M \sim 2.2\times10^8\ A/cm^2$ for $H=90$ kOe, $\lambda=1500$ Å, and $H_{c2}=1200$ kOe.

We emphasize that the contributions of j_V, j_M, and j_B may all be important for the interpretation of the experiment. The field reversal effect can be explained by j_B and/or j_V. After field reversal, j_B changes sign while j_V is negligible.[15]

We note that the progressive enhancement of the 11 meV peak in increasing fields (Fig. 6) suggests a transition to a different superconducting state. Any continuous reduction of the d-wave gap would not be accompanied by an enhancement of its gaplike feature peak amplitude.

The superconducting phase could be a different vortex state,[17] in such case the transition would be basically field induced. Alternatively, the new phase could appear due to strong nodal currents and possibly have an order parameter with a symmetry different from a pure *d wave*.[9,10]

A general difficulty in comparing our data to existing theories is that they have addressed only the small current limit.[9–11] We can only offer some speculations as to what a high current phase might be. In a previous publication[13] we discussed the zero-bias conductance peak field splitting in terms of a field-induced id_{xy} component. But we have found no correlation between the zero-bias conduction peak splitting and the gaplike feature position implying that their origins are different. For instance, after decreasing the field from 16 to 15 T, the position of the gaplike feature remains unchanged down to 5 T (see Fig. 3), but the zero-bias conductance peak splitting reduce from 4.2 to 2.5 meV (see Fig. 4 in Ref. 13). We speculate that surface currents on the coherence length scale could split the zero-bias peak,[6] but, as shown here, only currents on much larger length scale are affecting the position of the gaplike feature position.

The fact that we observe a regime where two gap features coexist, both in increasing and decreasing fields as well as in field cooled conditions, with a definite hysteresis, suggests a first order transition showing superheating and supercooling effects. To be specific, following the position and amplitude of the gaplike feature as a function of applied field we observed that the transition from low to high fields state takes place at 9 T (superheating) and back from the high to low fields at 5 T (supercooling).

The effect of reducing the low-lying density of states is independent on the high current-high field phase nature. As shown in Fig. 4(a), this is well beyond the field-current region where the zero-bias conductance peak vanished. A transition to an inhomogeneous state in the case of nodal currents was recently speculated about by Khavkine *et al.*[9] We also note that in very high fields the vortices nearest to the surface are located within a few coherence lengths, which may affect the tunneling conductance.[16]

A different explanation to the data would be that the remarkable transition in the tunneling conductance at 9 T in increasing fields is a vortex state transition, e.g., Bragg to vortex glass.[18] Such a transition is known to be irreversible as observed. The vortex state could modify the pinning and, hence, the total nodal current or its' effect on the order parameter. This could explain the large hysteresis observed at high fields. However, in contradiction to the high bias region, the low bias region which is also sensitive to total current via the Doppler shift mechanism,[6] does not show substantial hysteresis.

IV. SUMMARY

In conclusion, we have observed a transition in the tunneling conductance in high magnetic fields in YBCO (110) oriented films. A transition of the gaplike feature position and amplitude is present in both increasing and decreasing fields and under field cooled conditions for fields oriented parallel to the surface and perpendicular to the CuO_2 planes in such a way as to induce currents along nodal directions. We have proposed that the observed transition may be induced by these currents. In the high current state, the density of low energy states is reduced, possibly indicating the emergence of a component of the order parameter leading towards a fully gaped state. Alternatively, the changes in the tunneling characteristics may be due to a transition between two vortex states, having different gap values and sensitivity to nodal currents.

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