Superfluid Density Measurements of Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ Films from Optimal Doping to Strong Underdoping

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Abstract. Temperature dependence of superfluid densities $n_s(T) \propto \lambda^{-2}(T)$ of underdoped Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ (Bi2212) films are measured. Transition temperature of these films varies from 80K near optimal doping to 12K for severely underdoped ones. T-dependence of superfluid density gradually loses its sharp downward curvature with underdoping. Similar behaviour seen in YBa$_2$Cu$_3$O$_{7-\delta}$ suggests that this is a universal phenomenon in underdoped cuprates.

1. Introduction

Underdoped cuprates, with its unusual proximity to antiferromagnetism and mysterious pseudogap behavior, become a major research frontier in recent years. Uemura [1] observed a universal linear relationship between superfluid density $n_s(T)$ and transition temperature $T_c$. Later this is explained by the importance of thermal phase fluctuation [2] because of its low superfluid density on the underdoped side. However, recent measurements on both severely underdoped crystals [3, 4] and thin films [5] reveal a sublinear relationship between $T_c \propto n_s(0)^\alpha$, with $\alpha \sim 1/2$, clearly violates Uemura’s observations and indicates a 3D quantum critical point (QCP) that means there is still a decent coupling between conducting CuO$_2$ planes. Also in these severely underdoped YBCO crystals and films, signature of thermal phase fluctuations totally disappears [3 - 5], although underdoped YBCO is much more anisotropic than optimal doped YBCO. Here we choose to study underdoped Bi-2212 films because of its extremely anisotropic nature. [6, 7] This can help us clarify the dimensional nature of cuprates and see if the unusual observations above are universal among all the cuprates.

2. Film fabrication

Bi2212 films are fabricated by both Pulsed Laser Deposition (PLD) and sputtering using MgO and LaAlO$_3$ substrates respectively. All the films are about 100 nm thick. All the films are epitaxial and phase pure from XRD measurements. FWHM values of rocking curves of films are usually 0.3-0.4 degrees, regardless of growth methods and doping levels. Underdoped films with lower $T_c$ tends to have a slightly larger c-axis lattice constant compared to films near optimal doping. This is consistent with YBCO data. [8] A wide range of doping level has been achieved by tuning deposition and postannealing oxygen pressure. Transition temperature varies from 12K to 80K.

3. Superfluid density measurements

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Superfluid densities are measured by a two-coil mutual inductance apparatus. The film is sandwiched between two coils, and the mutual inductance between these two coils is measured at a frequency $\omega/2\pi = 50$ kHz. The measurement actually determines the sheet conductivity, $Y \equiv (\sigma_1 + i\sigma_2)d$, with $d$ being the superconducting film thickness and $\sigma$ being the conductivity. Given a measured film thickness, $\sigma$ is calculated as: $\sigma = Y/d$. The imaginary part, $\sigma_2$, yields the superfluid density through a low frequency measurement of: $\omega\sigma_2 \equiv n_s e^2/m$, which is proportional to the inverse penetration depth squared: $\lambda^{-2}(T) \equiv \mu_0\omega\sigma_2(T)$, where $\mu_0$ is the permeability of vacuum. The dissipative part of the conductivity, $\sigma_1(T)$, has a peak near $T_c$, whose width provides an upper limit on the inhomogeneity of $T_c$. Measurements are taken continuously as the sample warms up so as to yield the hard-to-measure absolute value of $\lambda$ and its $T$-dependence.

4. Results and discussions

Temperature dependences of superfluid densities of underdoped Bi2212 films (red/pink curves for sputtered films and blue curves for PLD films) are shown in Fig.1. A wide range of doping has been achieved with highest transition temperature $T_{c,max} \sim 80$K and lowest transition temperature $T_{c,min} \sim 12$K $<0.2* T_{c,max}$. This gives us unprecedented access to the evolution of superfluid density, both the magnitude and $T$-dependence, as the doping level is lowered to where superconductivity is almost vanished. Little peaks near $T_c$ indicates all the films have decent sharp transition with transition width $<2$K (not shown, for clarity purposes).

Let us start with the films near the optimal doping. Superfluid density has a wide range of linear temperature dependence at low $T$. At the first thought, this can be explained by d-wave pairing symmetry with nodes. However, as a well-known effect, impurity scattering tends to change this linear dependence to quadratic $T$-dependence, which is true for our previous studied YBCO films. It is hard to believe these Bi-2212 films are cleaner than their YBCO counterparts although resistivity data are not available for these films. Then we turned to another explanation, thermal phase fluctuation will give superfluid density a linear $T$-dependence that deviates from its mean field behaviour. This is possible given relatively low superfluid densities in these films. At higher temperatures, there is a Kosterlitz-Thouless-like sharp downturn near $T_c$. This downturn is absent in superfluid data from previous crystal microwave measurements. [9, 10] We think this is because they need to pick a value for superfluid density at $T = 0$K but as it is shown recently that superfluid density changes rapidly near optimal doping. [11] The microwave data will show a much more downturn near $T_c$ if they chose a larger penetration depth. For 2-D superconductors, Kosterlitz-Thouless theory predicts the downturn occurs where vortex-antivortex unbind at $\lambda^{-2}(T) = 8\mu_0 kT/d\Phi_0^2$, where $\Phi_0$ is flux quanta and $d$ is the distance between individual superconducting layers. If we treat every CuO_2 bilayer in Bi-2212 as an independent entity with distance $d=15.35$ Å between them, KT theory gives a line that is a little before where the actual downturn happens. Our previous YBCO study shows this downturn actually happens
where we treat the whole film thickness as the 2D parameter $d$ in KT theory. [5] This indicates there is
decent coupling between CuO$_2$ bilayers in YBCO. This is certainly not the case for Bi2212 (otherwise
the KT theory line will be way down to the x-axis). Distance between neighbouring CuO$_2$ bilayers in
Bi2212 is 15.35Å, much larger than ~6 Å, that of YBCO. This probably leads to a much more
anisotropic nature of Bi2212. We found this downturn occurs closer to the line where we use $d = 30.7$
Å, the unit cell size of Bi2212. The reason behind it is still unknown.

As Bi2212 films are underdoped, a clear trend is that this sharp downturn get smeared out and
eventually disappeared for film with $T_c \sim 40K$, about half of $T_c,max$. As $T_c$ is further reduced, $T$-
dependence of superfluid density becomes roughly linear all the way to $T_c$ without any significant
curvature. Because the downward curvature at higher temperatures is usually an indication of thermal
phase fluctuations, here we conclude that thermal fluctuations disappeared for those heavily
underdoped Bi2212 films. Because these severely underdoped films are close to a quantum critical
point where superconductivity disappears, we think this linear T-dependence of superfluid density all
the way to $T_c$ is an indication of quantum fluctuations. Similar observations have been made in
underdoped YBCO crystals, [3] although instead of a sharp downturn near $T_c$ for optimal doping, they
observed 3D-XY behaviour. [12] The disappearances of curvature at higher temperatures have been
explained By Franz [13] that the temperature range for thermal phase fluctuations shrinks near a QCP
and probably cannot be observed by experiments.

5. Conclusion.
T-dependence of superfluid density in underdoped Bi2212 films is measured with $T_c$ varying from
15K to 80K. Near optimal doping, we observed a KT-like sharp downturn near $T_c$ which indicates the
significance of 2D thermal phase fluctuations. As films are undoped, this curvature gradually
disappears and gives away to a quasi-linear T-dependence all the way to $T_c$ which probably indicates
quantum fluctuations.

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