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Precision measurement of the in-plane penetration depth $\lambda_{ab}(T)$ in $YBa_2Cu_3O_{7-\delta}$ using grain-boundary Josephson junctions

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We have determined the temperature dependence of the *ab*-plane penetration depth λ_{ab} in epitaxial $YBa_2Cu_3O_{7-\delta}$ films by measuring the magnetic-field dependence of the critical current of $YBa_2Cu_3O_{7-\delta}$ bicrystal grain-boundary Josephson junctions. Using this dc technique the change of the penetration depth with varying temperature has been measured between 4.2 and 60 K with a resolution of 0.2 Å. We found a linear $\lambda_{ab}(T)$ dependence at temperatures below about 10 K. This linear dependence is consistent with lines nodes of the gap function.

One of the key issues in the study of the high-temperature superconductors (HTS) is the question whether the superconducting state is something other than the conventional *s*-wave BCS pairing state. It is well known that the study of the temperature dependence of the magnetic-field penetration depth $\lambda(T)$ allows one to reveal important information on the pairing state in superconductors.[1–3] At low temperatures, the increase $\Delta\lambda(T)=\lambda(T)-\lambda(0)$ of the penetration depth above its zero temperature value is a measure of the thermally excited quasiparticles. Therefore, the temperature dependence $\lambda(T)$ for $T\rightarrow 0$ reflects the low-lying quasiparticle excitations of a superconductor and provides information regarding the pairing state in the material. For $T\ll T_c$ in *s*-wave BCS theory $\Delta\lambda(T)$ is given by[4]

$$\frac{\Delta\lambda(t)}{\lambda(0)}\simeq\left(\frac{\pi\Delta(0)}{2k_BT}\right)^{1/2}\exp\left(-\frac{\Delta(0)}{k_BT}\right). \tag{1}$$

The exponential dependence for small T is a consequence of the energy gap Δ which is nonzero on the hole Fermi surface. Conversely, for pairing states with point or line nodes on the Fermi surface one expects a power law $\Delta\lambda(T)\propto T^p$.[2] It has been shown that all possible non-*s*-wave pairing states of superconductors with tetragonal or orthorhombic symmetry and spherical or cylindrical Fermi surface have line nodes in the gap giving rise to $\Delta\lambda(T)\propto T$. In general, other powers are possible due to impurity scattering[3,5] as well as other types of nodes.[2] Since a low temperature $\Delta\lambda(T)$ varies slowly with temperature, accurate experimental techniques are required to distinguish between the possible $\Delta\lambda(T)$ dependences. Measurements of $\Delta\lambda(T)$ yield information on the magnitude of the superconducting order parameter. We note that there also is a growing number of approaches probing the phase of the order parameter (for a recent review see, e.g., Ref. 6).

Several methods have been used so far to measure $\lambda(T)$. On the one hand, μSR (Ref. 7) and magnetization measurements[8] can be performed on bulk samples and give accurate values of the absolute magnitude of λ. However, these methods are not precise enough to measure small changes $\Delta\lambda(T)=\lambda(T)-\lambda(0)$ at low temperatures. On the other hand, microwave techniques such as the measurement of the resonant frequency of microstrip and parallel plate resonators[9–12] formed from HTS thin films allow the precise measurement of $\Delta\lambda(T)$ but are less accurate in determining the absolute value of λ. The same is true for the cavity perturbation method which allows the precise measurement of $\Delta\lambda(T)$ using single crystals.[13,14] In contrast to the microwave techniques in this paper we report on a dc method allowing the measurement of $\Delta\lambda(T)$ of thin film samples with the high precision of about 0.2 Å.

The measurement of $\Delta\lambda(T)$ reported here is based on the measurement of the magnetic-field dependence of the critical current $I_c(H)$ of [001] tilt bicrystal grain-boundary Josephson junctions (GBJ's).[15] The geometry of [001] tilt bicrystal GBJ's together with the relevant length scales is shown in Fig. 1. The magnetic field is applied parallel to the *c* axis of the epitaxial YBCO film forming the GBJ. Since the thickness d of the film usually is small compared to the Josephson penetration depth λ_J,[17] bicrystal GBJ's represent quasi-one-dimensional Josephson junctions. It has been shown recently that high quality $YBa_2Cu_3O_{7-\delta}$ GBJ's have good spatial homogeneity of the critical current density J_c on a μm scale and behave as ideal overdamped Josephson junctions.[15,16] The $I_c(H)$ dependence of a perfectly homogeneous GBJ with width $W\ll\lambda_J$ is given by the well-known Fraunhofer diffraction pattern,

$$I_c(H)=I_c(0)\frac{\sin\pi\Phi/\Phi_0}{\pi\Phi/\Phi_0}. \tag{2}$$

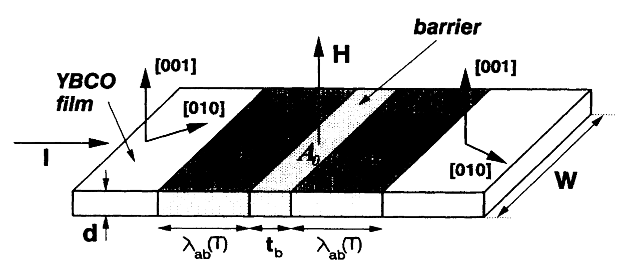

FIG. 1. Sketch of the geometry of a [001] tilt bicrystal grain-boundary Josephson junction formed by a *c*-axis oriented $YBa_2Cu_3O_{7-\delta}$ film. Typical length scales: $t_b\sim 20$ Å, $d\sim 200$ μm, $W\sim 5$ μm, $\lambda_{ab}(0)\sim 150$ nm.

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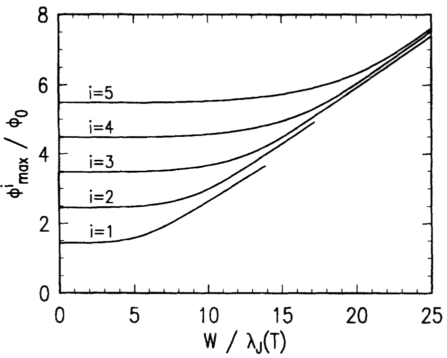

FIG. 2. Calculated magnetic flux value $\Phi^i_{\max}$ of the maximum of the first to fifth sidelobe of the $I_c(H)$ dependence as a function of the temperature dependent reduced width $W/\lambda_J(T)$ of a bicrystal GBJ.

Here, Φ_0 is the flux quantum and $\Phi = HA_{\mathrm{eff}}$ the magnetic flux linked into the effective GBJ area A_{eff} by the applied field H. It is evident from Fig. 1 that A_{eff} is composed of a temperature independent part $A_0 = Wt_b$ and a temperature dependent part $A_1(T) = 2W\lambda_{ab}(T)$. Here, λ_{ab} is the ab-plane penetration depth and t_b the thickness of the barrier of the GBJ. For YBCO-GBJ's t_b typically is a few nm and $\lambda_{ab}(0) \simeq 150$ nm.[18] According to Eq. (2) the maximum of the ith sidelobe of the $I_c(H)$ dependence is given by the constant flux $\Phi^i_{\max}$ close to $(i+1/2)\Phi_0$ linked into A_{eff}. Due to the temperature dependent value of A_{eff} this constant flux is generated by the temperature dependent magnetic field $H^i_{\max}(T) = \Phi^i_{\max}/A_{\mathrm{eff}}(T)$. It can be shown easily that

$$\frac{\Delta\lambda_{ab}(T)}{\lambda_{ab}(0)} = \frac{-\Delta H^i_{\max}(T)}{H^i_{\max}(T)}\left(1 + \frac{A_0}{2W\lambda_{ab}(0)}\right), \qquad (3)$$

with $\Delta H^i_{\max}(T) = H^i_{\max}(T) - H^i_{\max}(0)$ and $\Delta\lambda_{ab}(T) = \lambda_{ab}(T) - \lambda_{ab}(0)$. Since $t_b \ll \lambda_{ab}(0)$, the temperature independent term $A_0/2W\lambda_{ab}(0)$ in Eq. (3) usually can be omitted. Hence by accurately measuring $H^i_{\max}(T)$ the temperature dependence of $\Delta\lambda_{ab}/\lambda_{ab}$ can be determined with high precision and compared to the theoretical predictions. We note that in contrast to the microwave techniques commonly used for the measurement of $\Delta\lambda_{ab}(T)$ so far, our method represents a dc technique.

In many cases the conditions required for the validity of Eq. (2), namely $W/\lambda_j \leq 1$ and the spatial homogeneity of J_c, are difficult to satisfy. First, for YBCO-GBJ's we have $\lambda_J \sim 1$ μm at low temperatures.[15] Therefore, the small junction condition ($W \leq \lambda_J$) required for the validity of Eq. (2) is difficult to meet and large junction effects have to be taken into account. In contrast to the small junction case, for $W > \lambda_J$ the flux value $\Phi^i_{\max}$ corresponding to the maximum of the ith sidelobe of the $I_c(H)$ curve no longer is constant but depends on the reduced junction width $W/\lambda_J(T)$.[17] Since λ_J and, hence, W/λ_J varies with temperature, $\Phi^i_{\max}$ depends on temperature and Eq. (3) can no longer be applied. Therefore, it seems to be difficult to accurately extract $\lambda_{ab}(T)$ from the measurement of $H^i_{\max}(T)$. However, a detailed numerical analysis based on Ref. 19 shows that this is not the case. In Fig. 2 we have plotted the calculated values of $\Phi^i_{\max}$ versus $W/\lambda_J(T)$. Figure 2 clearly shows that for large i the peak value $\Phi^i_{\max}$ becomes about independent of $W/\lambda_J(T)$ over a considerable range of reduced junction width. That is, for constant junction width $\Phi^i_{\max}$ becomes independent of T as in the small junction case. In our experiments we choose i large enough to stay in the horizontal part of the $\Phi^i_{\max}$ vs $W/\lambda_J(T)$ curve for the temperature range of the measurement. In this way the systematic error due to large junction effects can be kept below the experimental resolution.

Next we discuss the impact of spatial inhomogeneities of J_c. In general, the critical current density of GBJ's is not perfectly homogeneous due to imperfections of the barrier. This results in deviations from the ideal $I_c(H)$ dependence. However, also in the case of spatially inhomogeneous J_c, the maxima of the resulting $I_c(H)$ dependence are given by temperature independent flux values $\Phi^i_{\max}$, which, however, in contrast to the homogeneous case, now may deviate considerably from $(i+1/2)\Phi_0$. With $\Phi^i_{\max}(T) = \text{const}$, $\Delta H^i_{\max}(T)$ again is determined only by $\Delta\lambda_{ab}(T)$. That is, Eq. (3) is still valid and $\Delta\lambda_{ab}(T)$ can be derived in the same way as for a GBJ with perfectly homogeneous J_c. Finally, we note that we have to deal with considerable flux focusing factors in the GBJ geometry. However for the temperature range of our experiments and for the dimensions of our GBJ's we always have $Wd < \lambda^2_{ab}$. In this case we have a flux focusing factor of $k \simeq 1.2W/d$,[20] which is independent of temperature and, according to Eq. (3), does not affect the determination of $\Delta\lambda_{ab}(T)$. The exact value of the flux focusing factor, however, is required to derive the absolute value of λ_{ab}.

The fabrication and the electrical transport properties of high quality $YBa_2Cu_3O_{7-\delta}$ bicrystal GBJ's have been reported in detail elsewhere.[15] For our experiments we only used 24° [001] tilt GBJ's which typically have a critical current density $J_c \sim 10^5$ A/cm^2 at 4.2 K corresponding to a Josephson penetration depth of about 1 μm. The $I_c(H)$ dependence of the GBJ's was measured using a maximum critical current detector, which allows us to measure I_c at a rate larger than 1000/sec.[21] The $I_c(H)$ dependence is obtained by slowly varying H and measuring I_c continuously. The high measuring rate allows us to use signal averaging techniques. The magnetic field applied parallel to the grain-boundary plane (see Fig. 1) typically was of the order of several gauss. It was generated by a coil placed directly on top of the sample. All measurements were performed in a magnetically shielded cryostat to reduce ambient magnetic fields.

In order to determine $H^i_{\max}$ the $I_c(H)$ dependence was measured in a small field interval ΔH around the maximum of the ith sidelobe starting at 4.2 K. Typically more than 10^4 measurements of I_c were taken within this interval. The measured data were fitted to a polynom of fourth to sixth order to accurately determine the maximum $H^i_{\max}$ of the ith sidelobe. Then the temperature was increased and this procedure was repeated at different temperatures up to a maximum temperature T_{up} to obtain $H^i_{\max}(T)$. Of course, we measured $H^i_{\max}(T)$ for different values of i, i.e., for different sidelobes. Typical experimental results are shown in Fig. 3, where we have plotted the temperature dependence of $H^i_{\max}$ for different values of i. The data were obtained for a 5

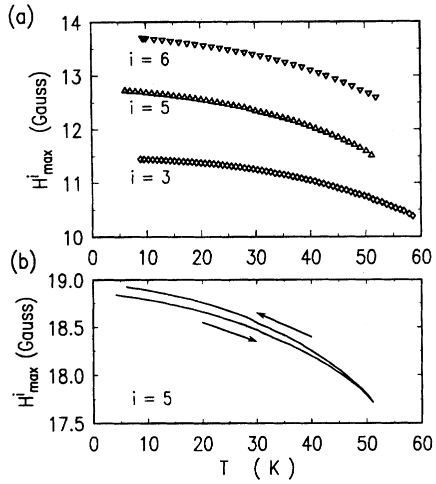

FIG. 3. Temperature dependence of H^i_{max} for different values of i (a). The curves for $i=5$ and 6 are displayed vertically by -6 and -9 G, respectively. In (b) we show the $H^i_{max}(T)$ dependence recorded for increasing and decreasing temperature as indicated by the arrows.

μm wide YBCO-GBJ. The $H^i_{max}(T)$ curves were measured several times both for increasing and decreasing temperature. In this way we could check to what amount magnetic flux is creeping into the epitaxial YBCO film away from the grain boundary during the temperature sweep. Since the flux creep rate increases about exponentially with temperature, the amount of flux trapped in the film is negligibly small at low temperature and becomes significant with increasing temperature. Going back to low temperatures again the magnetic flux usually stays trapped in the film. Since the trapped flux causes a small change of magnetic field at the grain boundary, the $H^i_{max}(T)$ curves recorded for increasing and decreasing temperature are slightly shifted against each other. A typical example is shown in Fig. 3(b). The shift is observed to increase with the applied magnetic field and the upper limit T_{up} of the temperature scan. Since the amount of trapped flux stays constant after once going from low to high temperature we only used the $H^i_{max}(T)$ curves recorded for decreasing temperature for evaluating $\Delta\lambda_{ab}(T)$. For $T_{up} \leq 20$ K the creep effects become so small that the shift of the $H^i_{max}(T)$ curves for increasing and decreasing T becomes unmeasurably small. We also emphasize that the shape of the $I_c(H)$ dependence stays completely unaffected by the flux trapped in the film, although it is slightly shifted along the H axis.

Using the measured $H^i_{max}(T)$ dependences we can determine $\Delta\lambda_{ab}(T)/\lambda_{ab}(0)$ according to Eq. (3). We note that for some samples a significantly reduced magnitude of $\Delta H^i_{max}(T)/H^i_{max}(T)$ was measured. This could be correlated to the presence of nonsuperconducting precipitates at the grain boundary. These precipitates result in a large value of $A_0/2W\lambda_{ab}(0)$ that no longer can be neglected in Eq. (3) and has to be taken into account evaluating $\Delta\lambda_{ab}(T)/\lambda_{ab}(0)$. In Fig. 4(a) we show a typical experimental result together with the prediction of Eq. (1). At low temperatures the experimental data clearly deviate from the s-wave BCS result. Reasonable agreement with the BCS temperature dependence only

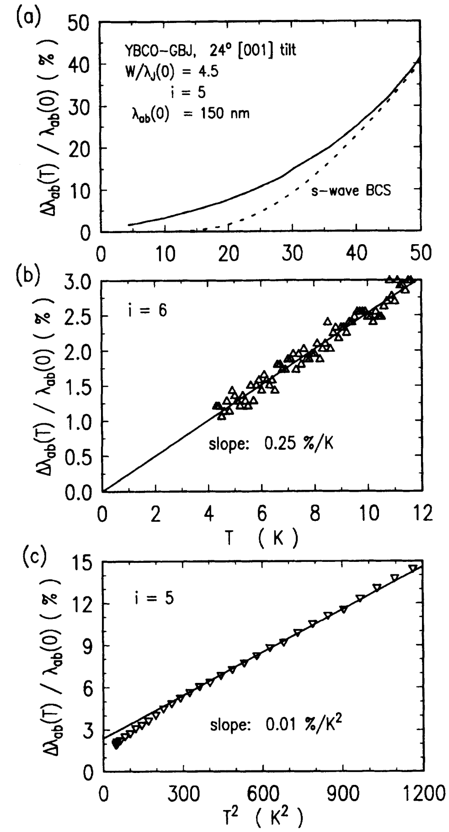

FIG. 4. (a) $\Delta\lambda_{ab}(T)/\lambda_{ab}(0)$ versus temperature. Also shown is the s-wave BCS dependence (broken line) according to Eq. (1). In (b) and (c) the low temperature part of $\Delta\lambda_{ab}(T)/\lambda_{ab}(0)$ is plotted versus T and T^2, respectively. The lines represent linear fits to the data.

is obtained above about 50 K. In Figs. 4(b) and 4(c) the low temperature part of $\Delta\lambda_{ab}(T)/\lambda_{ab}(0)$ is replotted versus T and T^2, respectively. Below about 10 K we clearly observe a linear temperature dependence which is changing to a quadratic dependence between about 10 and 15 K. The slope in the quadratic regime [see Fig. 4(c)] is about $0.01\%/K^2$ in good agreement with microwave experiments.[9,11] The zero temperature value $H^i_{max}(0)$ is obtained by linearly extrapolating the measured $H^i_{max}(T)$ dependence to $T=0$ K. Since the flux focusing factor k is not precisely known the measured value of $H^i_{max}(0)$ allows us to give only an order of magnitude estimate for the absolute value of $\lambda_{ab}(0)$. Therefore, in Fig. 4 we used the value $\lambda_{ab}(0) \simeq 1500$ Å given in the literature.[13] However, the experimental resolution for the relative change of the penetration depth is as high as 0.2 Å and, hence, comparable to that of high precision microwave results.[10]

For all YBCO-GBJ's we observed a linear $\Delta\lambda_{ab}(T)/\lambda_{ab}(0)$ dependence with a slope of about 2.5×10^{-3} K^{-1} below 10 K. This is in full agreement with the results reported in Refs. 13 and 14 for $YBa_2Cu_3O_{7-\delta}$ single crystals. However, our result is clearly different from the T^2 dependence found in several high precision microwave studies of thin film samples.[9,11,12] In this context we note that Ma *et al.*[11] observed deviations from the T^2 dependence towards a flatter dependence at temperatures below about 10 K in their microwave penetration depth measurements. The origin of the different low temperature dependences of $\lambda_{ab}(T)$ obtained in different experiments performed with different samples is still unclear. Recent experiments on doped YBCO single crystals[11] suggest that the linear T-dependence would be intrinsic to pure samples whereas the T^2 dependence would be due to defects in agreement with recent theoretical calculations.[5] Since the density of defects usually is high in thin film samples, a T^2 dependence is expected in experiments performed with such samples. Although this argument holds for most microwave experiments, it is in clear contradiction to our result which, in contrast, is obtained by a dc measuring technique. Therefore, we believe that such an argument about the effects of scattering cannot be regarded as definitive. Possibly there is some influence of the copper-oxygen chains on the electrodynamic response of YBCO causing different results in microwave and dc experiments.

In conclusion, we performed a high resolution measurement of $\Delta\lambda_{ab}(T)$ in epitaxial $YBa_2Cu_3O_{7-\delta}$ films using a dc measuring technique. We observed a linear $\Delta\lambda_{ab}(T)$ dependence below about 10 K in $YBa_2Cu_3O_{7-\delta}$ thin-film samples which is changing to a quadratic dependence above about 15 K. The linear low temperature dependence of the in-plane penetration depth is consistent with line nodes in the gap function. Our results agree with those obtained with single crystals, however, they are clearly different from the T^2 dependence found in microwave studies of thin-film samples. In order to clarify this discrepancy a more thorough study of the effect of disorder on the microwave properties of thin-film samples seems to be necessary.

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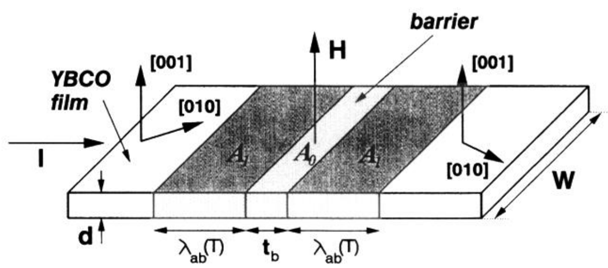

FIG. 1. Sketch of the geometry of a [001] tilt bicrystal grain-boundary Josephson junction formed by a c-axis oriented $YBa_2Cu_3O_{7-\delta}$ film. Typical length scales: $t_b \sim 20$ Å, $d \sim 200$ μm, $W \sim 5$ μm, $\lambda_{ab}(0) \sim 150$ nm.