PHYSICAL REVIEW B **67**, 184501 (2003)

Campbell penetration depth of a superconductor in the critical state

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(Received 3 November 2002; published 1 May 2003)

The magnetic penetration depth $\lambda(T,H,j)$ was measured in the presence of a slowly relaxing supercurrent j. In single crystal $Bi_2Sr_2CaCu_2O_8$ below approximately 25 K, $\lambda(T,H,j)$ is strongly hysteretic. We propose that the irreversibility arises from a shift of the vortex position within its pinning well as j changes. The Campbell length depends upon the ratio j/j_c where j_c is the critical current defined through the Labusch parameter. Similar effects were observed in other cuprates and in an organic superconductor.

DOI: 10.1103/PhysRevB.67.184501 PACS number(s): 74.25.Ha

Many measurements have shown that the character of vortex pinning in BSCCO changes qualitatively in region of 20–30 K.[1–7] The second magnetization peak disappears and the critical current increases sharply. The Larkin pinning length[8] becomes comparable to the interplanar spacing implying that vortex pancakes are pinned individually $(0-D$ pinning) rather than as components of an elastic string. In this region the ac susceptibility measured in a zero-field cooled (ZFC) sample differs markedly from that obtained in a field cooled (FC) sample.[5] ZFC samples represent a non-equilibrium flux profile and the small signal response of such a system is not fully understood.[9,10] In this paper we report measurements of the penetration depth in both FC and ZFC samples. Our measurements show strong hysteresis and memory effects but are not in the limit of strong driving fields where the ac field itself can induce new vortex phases.[11] We propose that the hysteretic ZFC response can be understood as a generalized Campbell penetration depth $\lambda_C(B,T,j)$ that depends upon the slowly relaxing supercurrent j as well as the curvature of the pinning potential as parametrized by j_c. We compare data in $Bi_2Sr_2CaCu_2O_8$ (BSCCO, $T_c \sim 92$ K) to measurements in electron-doped $Pr_{1.85}Ce_{0.15}CuO_4$ (PCCO, $T_c \sim 24$ K), an organic superconductor $\beta''-(ET)_2SF_5CH_2CF_2SO_3$ (β''-ET, $T_c \sim 5$ K) (Ref. 12) and Nb ($T_c \sim 9.3$ K). The penetration depth was measured with an 11 MHz tunnel-diode driven LC resonator[13,14] mounted in a ^{3}He refrigerator. An external dc magnetic field $(0-7$ kOe) was applied parallel to the ac field (~ 5 mOe). The oscillator frequency shift $\Delta f = f(T) - f(T_{\mathrm{min}})$ is proportional to the ac susceptibility and, therefore, to the change in penetration depth $\Delta\lambda = \lambda(B,T) - \lambda(B,T_{\mathrm{min}})$ via $\Delta f = -G\Delta\lambda$, where G is a calibration constant.[13,14] For an ac magnetic field along the c axis, only ab-plane rf screening currents are excited. Although this results in a much smaller ac Lorentz force on vortices, it removes complications from interplane currents. The absence of c-axis currents is demonstrated by the zero field data in BSCCO. We obtain a linear change $d\lambda_L/dT \approx 11$ Å/K in good agreement with earlier measurements and indicative of a d-wave superconductor.[15–17] Any significant tilt of the ac field would generate c-axis currents and give a much larger value of $d\lambda_L/dT$. The total penetration depth in the mixed state is $\lambda^2 = \lambda_L^2 + \lambda_{\mathrm{vortex}}^2$ where λ_L is the London penetration depth and $\lambda_{\mathrm{vortex}}$ the contribution from vortex motion. A comprehensive expression for $\lambda_{\mathrm{vortex}}$ has been derived by several authors.[21–23] At low temperatures and frequencies well below the pinning frequency (of order GHz in cuprates), $\lambda_{\mathrm{vortex}}$ reduces to the Campbell pinning penetration depth $\lambda_C^2 = \phi_0 B/4\pi\alpha$.[19] Here ϕ_0 is the flux quantum and α is the Labusch parameter.[20] Our measurements give $\alpha > 10^3$ dyne/cm^2 for temperatures below 25 K, so the maximum vortex excursion due to the ac current is less than 5 Å. This value is well within the range of individual pinning wells (of order a coherence length or more), justifying our assumption of small oscillations. Figure 1 presents $\lambda(B,T)$ for a BSCCO single crystal as the temperature was cycled. After zero field cooling (ZFC) to 1.5 K, the dc field was

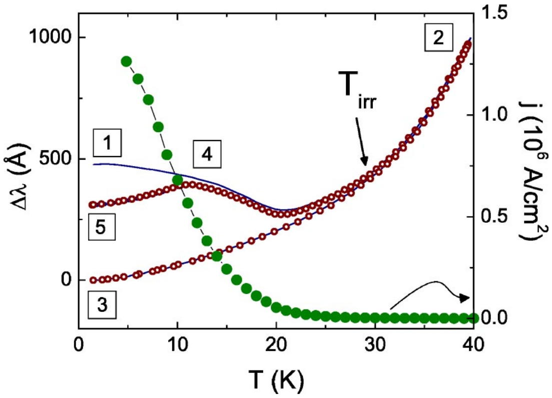

FIG. 1. Experiment 1: BSCCO crystal ZFC to 1.5 K and $H_{\mathrm{dc}} = 260$ Oe applied. The signal followed curve $1 \rightarrow 2 \rightarrow 3$. Experiment 2: BSCCO crystal ZFC to 12 K and $H_{\mathrm{dc}} = 260$ Oe applied. Sample was then cooled and warmed following the path $4 \rightarrow 5 \rightarrow 4 \rightarrow 2 \rightarrow 3$. The right axis shows current density estimated from the irreversible magnetization.

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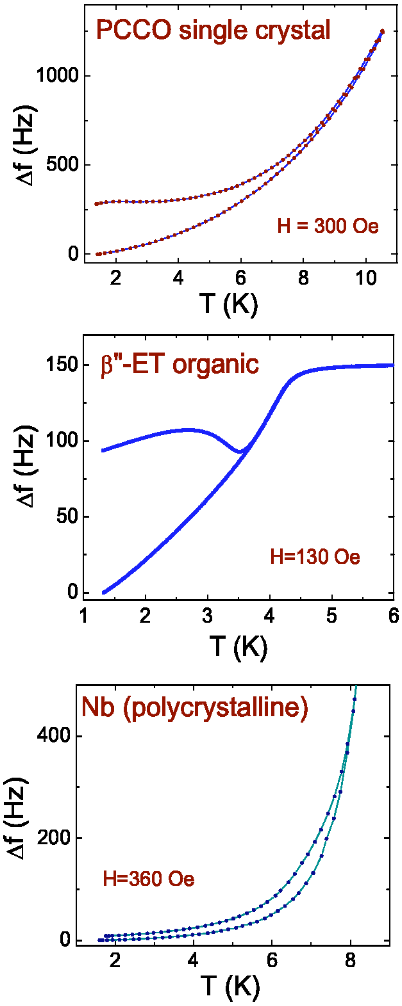

FIG. 2. FC and ZFC frequency shift (proportional to penetration depth) in single crystals of PCCO, β''-ET, and polycrystalline Nb.

ramped from $0\rightarrow-7$ kOe$\rightarrow$260 Oe. This procedure ensured that the entire sample was filled with vortices, but nonuniformly. The sample was then warmed ($1\rightarrow2$) during which λ first decreased and then increased again. (If the initial magnetizing field of -7 kOe is not applied, the penetration depth versus temperature looks nearly the same as in Fig. 1, but with a weak maximum near 2 K. This may come from portions of the sample where no vortices exist which screen more effectively.) During this phase of the cycle j relaxes as the flux distribution becomes more uniform. On the same plot we show the screening current j measured on the same sample, in the same field in a SQUID magnetometer. j was determined from the irreversible component of magnetization and applying the Bean model. j measured in this way is considerably different from j_c owing to strong flux creep in the cuprates. Once the temperature exceeds $T_{\mathrm{irr}}\sim25-30$ K, j relaxes more rapidly and the flux profile becomes uniform. Subsequent cooling and warming traces ($2\rightarrow3\rightarrow2$) were perfectly reversible and represent the penetration depth of a uniform flux profile. This reversible curve was identical to that obtained in a field-cooled (FC) experiment and we refer to them interchangeably. The hysteresis between points 1 and 3 in Fig. 1 corresponds to a change in rf magnetization of $\leqslant10^{-7}$ emu, which is at the detectability limit of commercial magnetometers.

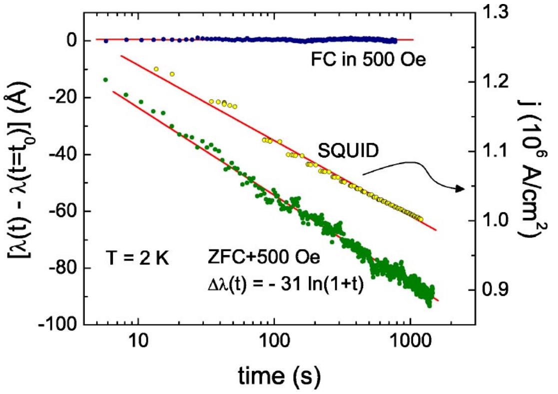

FIG. 3. Time-logarithmic relaxation of the ac penetration depth after application of a 500 Oe magnetic field at 2 K (lower curve) and after FC in 500 Oe (upper curve) in single crystals of BSCCO. Right axis refers to the relaxation of the current j obtained from the magnetization measurements.

In Fig. 2 we show similar measurements in the electron-doped cuprate PCCO ($\gamma=30-80$), an organic superconductor β''-ET ($\gamma=400-800$),[18] and polycrystalline Nb ($\gamma=1$). Together with BSCCO ($\gamma=300-400$), these materials span a wide range in transition temperature and anisotropy γ. All three anisotropic superconductors show nonmonotonic ZFC temperature dependence, represented by the top curve in each panel. By contrast, in Nb and in YBCO (also measured but not shown, $\gamma=6-8$) λ(ZFC) always increases monotonically with temperature. Returning to Fig. 1, although the pinning changes dramatically near 25 K, the change in the penetration depth is observable only in the ZFC curve. The FC curve is perfectly smooth. Goffman *et al.*[3] reported measurements of the transverse susceptibility (ac field along the ab plane) at very low frequencies that *did* show a sharp increase in screening below 22 K. This feature disappeared at kHz frequencies,[3] which is consistent with our data at 11 MHz. We now focus on the ZFC behavior. Figure 3 shows the time dependence of various quantities. The topmost curve shows λ when the sample field was cooled to 2 K in $H_{\mathrm{dc}}=500$ Oe. Relaxation is negligible. When the sample was zero field cooled and then 500 Oe applied, λ and j showed logarithmic relaxation. This correspondence suggests that in a ZFC state, the penetration depth should have a direct functional relationship to j. This is confirmed in Fig. 4 where we compare λ measured at the same final value of field but with two entirely different flux profiles. The solid symbols correspond to the initial application (at 1.5 K) of a -7 kOe magnetizing field, as before, while the open symbols correspond to a $+7$ kOe magnetizing field. Both fields were then returned to $H=+260$ Oe before the temperature sweep began. The distribution of B throughout the sample was entirely different for these two starting conditions, as shown schematically. However, within a critical state picture, the magnitude of dB/dx and thus j remains the same for these two distributions. The fact that λ vs T was unchanged for the two starting conditions is strong evidence that j and not B is the determinant of the penetration depth in the non-

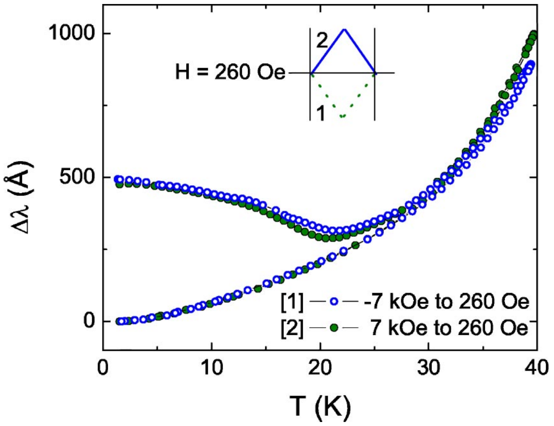

FIG. 4. Comparison of $\Delta\lambda(T)$ for flux entry and exit for BSCCO single crystal. Closed symbols: magnetic field was ramped up from -7 kOe to $+260$ Oe (flux entry). Open symbols: field was ramped down from $+7$ kOe to $+260$ Oe (flux exit) and the sample was warmed and then cooled. Schematics shows the corresponding profiles of vortex density.

uniform state. Some implicit dependence of the Labusch constant upon B could account for minor differences between the curves at higher temperatures. Based on these results, we propose the following model for $\lambda_C(B,T,j)$ in a superconductor with a non-uniform flux profile. The supercurrent j biases vortices away from equilibrium through the Lorentz force $F_L = j\times\phi_0/c$. The Campbell depth is then determined by the curvature of the pinning potential well at the biased position. For a pinning potential $V(r)$ the vortex displacement r_0 is found from $dV/dr = F_L$. The maximum force determines the critical current $j_c = c\alpha_0 r_p/\phi_0$, attained at the range of the pinning potential r_p. The effective Labusch constant $\alpha(j)$ is then determined from $\alpha(j) = d^2V/dr^2|_{r=r_0}$. For example, consider the form $V(x) = \alpha_0(T)x^2(1-x/3)/2$, for which the volume pinning force saturates. Here $x = r/r_p$ is a dimensionless vortex displacement. This potential has been used to analyze the quantum tunneling of vortices.[24] The supercurrent j biases the vortex segment to a new position $x_0 = 1-\sqrt{1-j/j_c}$ where the local curvature is $\alpha(j) = \alpha_0\sqrt{1-j/j_c}$. The change in curvature produces a j dependence to the Campbell depth

$$\lambda_C^2 = \frac{\phi_0 B}{4\pi\alpha(j)} = \frac{\phi_0 B}{4\pi\alpha_0}\,\frac{1}{\sqrt{1-j/j_c}} = \frac{\lambda_C^2(j=0)}{\sqrt{1-j/j_c}}. \qquad (1)$$

The model predicts that $\lambda_C(\mathrm{ZFC}) > \lambda_C(\mathrm{FC})$ since $j=0$ in the FC case. This conclusion remains true for other pinning potentials such as $V(x) = \alpha_0 x^2(1-x^2/6)/2$.[25] As Fig. 2 shows, $\lambda_C(\mathrm{ZFC}) > \lambda_C(\mathrm{FC})$ in all materials studied. The model also predicts that j/j_c, and not B explicitly, determines the nonequilibrium component of the penetration depth, as shown in Fig. 4. Rodriguez *et al.*[5] have previously reported a difference in the ac susceptiblity between FC and ZFC samples of BSCCO. Their data look similar to ours, although they observed hysteresis only when the ac field was *parallel* to the conducting planes, inducing both ab-plane and c-axis currents. They also worked at considerably larger ac field amplitudes. They attributed the nonmonotonic ZFC curve to a c-axis critical current that was nonmonotonic with temperature in the critical state. This effect presumably occurs only in highly anisotropic materials such as BSCCO. We found nonmonotonic ZFC curves only in the highly anisotropic materials studied (BSCCO, PCCO, and β''-ET) so two dimensionality clearly is important as those authors emphasize. However, our model involves no c-axis currents and shows that the current biasing effect predicts $\lambda_C(\mathrm{ZFC}) > \lambda_C(\mathrm{FC})$ as observed. The precise shape of the ZFC curve depends upon how rapidly j relaxes during the sweep and the thermal history of the sample, so it is not a basic property of the superconductor. For example, in Fig. 1, if we ZFC only to 12 K instead of 1.5 K, the maximum in λ occurs at point 4, i.e., the lowest temperature achieved on the initial cooldown. We then trace the path $4\rightarrow5\rightarrow4\rightarrow2\rightarrow3$. Despite being in a nonequilibrium state, the system retains perfect memory in its passage from point 4 to 5 and back to 4.

There is, in principle, another contribution to the measured penetration depth. If a small amplitude ac field is applied in the presence of a relaxing flux profile, the current-dependent activation energy $U(j)$ is modulated in time. This was shown to produce a universal resistivity that depends only upon the time since the establishment of a critical state and sample dimensions.[9,10] This, in turn, gives rise to an additional time dependent contribution to the penetration depth. In our measurement, the ac field is present at all times, before and after the critical state is established, so the effective waiting time is not well defined. In any case, for waiting times much larger than our inverse frequency (10^{-7} sec) this contribution would be negligible. (For experiments at much lower frequencies it will be more important.) We note that these calculations of a universal vortex resistivity ignore the harmonic response of the vortex lattice and so cannot, in principle, account for the Campbell depth that dominates our signal.

In conclusion, we propose a current biasing effect to explain the difference between FC and ZFC measurements of the Campbell penetration depth in a variety of superconductors. The supercurrent j biases vortices to a new position in the pinning potential and the Campbell depth measures the local curvature, which depends upon j/j_c.

We thank V. Geshkenbein, J. R. Clem, A. Koshelev, and V. Vinokur for useful discussions. Work at UIUC was supported by NSF Grant No. DMR 0101872. Work at USC was supported by the NSF/EPSCoR under Grant No. EPS-0296165. Work at Sherbrooke was supported by CIAR and NSERC. Work at UT was supported by the Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology. Research at Argonne was supported by DOE, Office of Basic Energy Sciences, Division of Materials Sciences, under Contract No. W-31-109-ENG-38.

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