Magnetic imaging of Pearl vortices

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(Dated: March 22, 2002)

We have used scanning SQUID magnetometry to image vortices in ultra-thin \([\text{Ba}_{0.9}\text{Nd}_{0.1}\text{CuO}_{2+x}]_m/\text{CaCuO}_2 \) high temperature superconductor samples, with as few as three superconducting \(\text{CuO}_2 \) planes. The Pearl lengths (\(\Lambda = 2\lambda_L/d, \lambda_L \) the London penetration depth, \(d \) the superconducting film thickness) in these samples, as determined by fits to the vortex images, agree with those by local susceptibility measurements, and can be as long as 1 mm. The in-plane penetration depths \(\lambda_{ab} \) inferred from the Pearl lengths are longer than many bulk cuprates with comparable critical temperatures. We speculate on the causes of the long penetration depths, and on the possibility of exploiting the unique properties of these superconductors for basic experiments.

Vortices play a central role in many aspects of superconductivity. Not only do the dynamics of vortices determine many of the transport properties of type II superconductors, especially the high critical temperature cuprates, but vortices are also of more general interest, since as topological defects they are of great relevance, for instance, to phase transitions \([2,3] \). The formation of topological defects in phase transitions has even stimulated some analogies between cosmology, gauge theories and condensed matter physics \([4,5] \). Vortices in bulk type II superconductors were first predicted by Abrikosov in 1957 \([6] \), and have since been imaged by many different experimental techniques \([7] \). Vortices in thin superconductors \((d << \lambda_L, \text{ where } d \text{ is the superconducting film thickness and } \lambda_L \text{ the London penetration depth respectively}) \) were first described by Pearl \([8] \) (hence “Pearl” vortices). Pearl vortices have several interesting attributes. The field strengths \(h_z \) perpendicular to the films diverge as \(1/r \) at distances \(r << \Lambda \) in Pearl vortices, whereas in Abrikosov vortices the fields diverge as \(\ln(r/\lambda_L) \) \([9] \). Since in the Pearl vortex much of the vortex energy is associated with the fields outside of the superconductor, the interaction potential \(V_{\text{int}}(r) \) between Pearl vortices has a long range component \(V_{\text{int}} \sim \Lambda/r \) for \(r >> \Lambda \) \([9] \), unlike Abrikosov vortices, which have only short range interactions. The interaction between Pearl vortices \(V_{\text{int}} \sim \ln(\Lambda/r) \) for \(r << \Lambda \) leads to a Berezinskii-Kosterlitz-Thouless (BKT) transition which is cut off due to screening on a scale \(\Lambda \) \([1] \). The logarithmic interaction makes this system very similar to a Coulomb gas and ideal to study screening effects and renormalization in BKT transitions \([10] \). While superconducting vortices in films with thickness \(d \) comparable to the London penetration depth \(\lambda_L \) have been imaged using many techniques, to our knowledge the present work is the first to directly demonstrate experimentally the existence of Pearl vortices for \(d << \Lambda \), and is also the first to use scanning susceptibility measurements to determine penetration depths in superconductors.

In the present work, two different types of \([\text{Ba}_{0.9}\text{Nd}_{0.1}\text{CuO}_{2+x}]_m/\text{CaCuO}_2 \) (CBCO) structures were grown: a) the ultrathin \([\text{Ba}_{0.9}\text{Nd}_{0.1}\text{CuO}_{2+x}]_M/\text{CaCuO}_2 \) \(M \text{/N/M} \) structure which consists of only one superconducting infinite layer (IL) block \((N \text{ CaCuO}_2 \text{ unit cells}) \), sandwiched between two charge reservoir (CR) blocks \((M \text{ Ba-based unit cells}) \) and the similar \(M/N/M/N/M \) structure \((M=5 \text{ and } N=2) \); b) the thick \([\text{Ba}_{0.9}\text{Nd}_{0.1}\text{CuO}_{2+x}]_m/\text{CaCuO}_2 \) \(m \times n \text{ superlattice} \) structure which consists of \(S \) sequences \((S \geq 15) \) of the \([\text{Ba}_{0.9}\text{Nd}_{0.1}\text{CuO}_{2+x}]_m/\text{CaCuO}_2 \) supercells composed of \(m \text{ Ba-based and } n \text{ Ca-based unit cells} \). All the samples were grown on \((001) \) SrTiO\(_3 \) substrates, with nominally zero miscut angle, by Pulsed Laser Deposition (PLD), using a focussed KrF excimer pulsed laser source \((\lambda = 248 \text{ nm}) \) with energy areal density on the target surface of \(7 \text{ J/cm}^2 \) in a spot size of \(2 \text{ mm}^2 \). Two sintered powder targets, with a nominal composition of \([\text{Ba}_{0.9}\text{Nd}_{0.1}]\text{CuO}_2 \) and \(\text{CaCuO}_2 \), mounted on a multitarget system, were used. The substitution of 10% of the Ba atoms with trivalent Nd cations, even if not strictly necessary for superconductivity \([11,12] \), helped to find the right growth conditions by slightly decreasing the uncompensation of the electrical charge in the CR block. The growth temperature was about \(640^\circ \text{ C} \) and the molecular oxygen pressure was \(\approx 1 \text{ mbar} \). At the end of the deposition procedure, an amorphous protecting layer of electrically insulating \(\text{CaCuO}_2 \) was deposited on top of the film at a temperature lower than \(100^\circ \text{ C} \).

The SQUID microscope measurements were made at \(4.2 \text{ K} \) with the sample cooled and imaged in fields of a few mG, sufficient to trap several vortices in a \(200 \mu \text{m} \times 200 \mu \text{m} \) scan area. Two types of SQUID sensors were used: 1) magnetometers \([13] \) with either square pickup loops \(7.5 \mu \text{m} \) on a side, or octagonal pickup loops \(4 \mu \text{m} \) in diameter; and 2) SQUID susceptometers \([14] \) with a single turn field coil \(20 \mu \text{m} \) in diameter, with a square pickup loop \(8 \mu \text{m} \) across (see Fig. \([2] \)).
FIG. 1: SQUID microscope image and cross-sectional data (along the positions indicated by the dashed lines in (a,c)) of vortices trapped in two CBCO samples. The SQUID pickup loops were a square 7.5µm on a side (a,b) and an octagon 4µm on a side (c,d). The open symbols in (b,d) are the cross-sectional data; the solid lines in (b,d) are fits to Eq. 1. Scaled schematics of the pickup loops used appear in (a,c).

We have performed scanning SQUID microscopy (SSM) on various 5/2/5 monolayers and CBCO-\(m \times n\) samples, and as a function of the number of the CuO
planes. In all systems we have clearly observed Pearl vortices. This provides evidence of superconductivity complementary to traditional transport measurements [15] for the thinnest films. We show in Fig. 1 SSM images of vortices trapped in two typical samples. The SQUID pickup loops were a square 7.5µm on a side (a,b) and an octagon 4µm on a side (c,d). The open symbols in (b,d) are the cross-sectional data; the solid lines in (b,d) are fits to Eq. 1. Scaled schematics of the pickup loops used appear in (a,c).

TABLE I: Pearl lengths \(\Lambda\) of various CBCO samples. \(T_c\) is measured by standard four-probe techniques and refers to zero resistance. We estimate uncertainties in \(\Lambda\) of ±20% and of \(T_c\) of ±0.25K.

| Sample | Type   | Cells | \(d(\text{Å})\) | \(d_{IL}(\text{Å})\) | \(T_c(\text{K})\) | \(\Lambda(\text{µm})\) |
|--------|--------|-------|----------------|-----------------|----------------|-----------------|
| 1159   | 5/2/5  | 1     | 50             | 6.4             | 30             | 128             |
| 1151   | 5/2/5  | 1     | 50             | 6.4             | 35             | 205             |
| 1988   | 5/2/5/2/5 | 1 | 79          | 12.8           | 50             | 292             |
| 1984   | 5/2/5/2/5 | 1 | 79          | 12.8           | 50             | 490             |
| 1987   | 5/2/5/2/5 | 1 | 79          | 12.8           | 50             | 810             |
| 1985   | 2×2    | 12   | 182           | 76.8           | 78             | 25              |
| 1201   | 2×2    | 20   | 304           | 128            | 65             | 13.6            |
| 1108   | 2×2    | 28   | 426           | 179.2          | 70             | 12.7            |
| 1106   | 2×2    | 28   | 426           | 179.2          | 75             | 9.1             |
| 1171   | 5×2    | 15   | 426           | 96              | 60             | 14.2            |
to make it energetically favorable for the vortex flux to thread vertically through the superconducting layers, as opposed to escaping between the layers.

As expected, the Pearl lengths are longest for the thinnest CBCO films. Fig. 2 shows that the CBCO penetration depths $\lambda_{ab,h} = \sqrt{d/\Lambda}$ obtained assuming a homogeneous film (solid circles) are longer than for a number of hole-doped cuprates with comparable critical temperatures [21, 22, 23]. For example, optimally doped YBa$_2$Cu$_3$O$_{7-\delta}$ (Y-123), with a $T_c$ of 92K, has $\lambda_{ab} \sim 0.15\mu$m [24]. The highest $T_c$ CBCO sample (sample 1985, $T_c=78$K) has $\lambda_{ab,h} = 0.48\mu$m. Our samples span a wide range of Pearl lengths and sheet resistances per square. Detailed measurements of the latter are given elsewhere [11, 15]. The $2 \times 2$ superlattices have resistance per square values a factor of 10 lower than the metal-insulator limit in the $2 \times n$ superlattice series [11]. Since the mean free path in the high resistivity (but metallic, $n \sim 11$ or $5/2/5/2/5$) films can be no shorter than the width of a CuO$_2$ unit cell ($\sim 4\Lambda$), and since the normal state carrier sheet densities and effective masses should be similar within this series, this implies that the mean free paths in the $2 \times 2$ superlattices must be at least a few times larger than the in-plane coherence length ($\xi \sim 20\Lambda$), and that the Pippard correction for the effect of a finite mean free path $l$, $\lambda_{eff} = \lambda_L (1 + \xi/l)^{1/2}$, cannot be large. The London approximation ($\lambda^2 = m^*e^2/4\pi n^*\hbar^2$, [25], where $m^*$ is the effective mass of the charge carriers) may therefore be reasonable to evaluate the superfluid density for this type of structure. If we use the standard London expression and a reasonable value of $m^* = 5m_e$ [26], we obtain $n_s = 6.29 \times 10^{21}$ cm$^{-3}$ for optimally doped Y-123, as compared with $n_s = 6.28 \times 10^{20}$ cm$^{-3}$ for the highest $T_c$ CBCO sample (1985). The corresponding areal superfluid densities per plane $n_p = n_s d/N_p$ are $3.67 \times 10^{14}$ cm$^{-2}$ for optimally doped Y-123 and $3.2 \times 10^{13}$ cm$^{-2}$ for CBCO sample 1985 ($N_p$ is the number of superconducting CuO$_2$ planes). The superfluid densities for the CBCO samples are about a factor of 10 lower than for Y-123, although they have comparable $T_c$’s.

It has been proposed that the superfluid screening in films could be suppressed by proximity to the metal-insulator transition [27] or quantum fluctuations [28]. However the $2 \times 2$ superlattices have normal state resistances 10 times smaller than the metal-insulator critical resistance of $\sim 26k\Omega\text{cm}$ [11]. It appears that the penetration depths in these films are significantly larger than bulk cuprates with comparable $T_c$’s. This may mean that these compounds are more efficient at producing high $T_c$’s from a given superfluid density [24].

A clue to how this could come about comes from considering the layered structure of these films. If instead of assuming that the superfluid densities are homogeneously distributed, we assume instead that all of the superfluid density is localized in the IL layers, then $\lambda_{ab,IL} = \sqrt{d_{IL}\Lambda/2}$. In this case the calculated pen-

\[ h_z(k) = \frac{-4\pi^2IR}{c} J_1(kR)(1 - e^{-2kz} / (1 + k\Lambda)), \]

where $J_1(kR)$ is a Bessel function of the first kind. The solid line in Fig. 2(b) is obtained by numerically integrating the 2-D Fourier transform of Eq. 2 over the area of the pickup loop, for various values of $z$, and fit to the data by varying $\Lambda$. Figure 2(c) compares the values obtained for the Pearl lengths for a number of the CBCO samples using magnetometry and susceptometry methods. The two methods agree within experimental error over the range of Pearl lengths present. Since the fitting to the Pearl vortex images was done assuming each vortex has $\phi_0$ of total flux threading through it, rather than a fractional value [21], this agreement, especially in the $5/2/5/2/5$ sample means that the superconducting layers are sufficiently strongly Josephson-coupled when separated by a CR layer made of five BaCuO$_x$ unit cells.

Experimentally there continues to be some change, presumably because the tilt angle between the substrate and the sample decreases.

The 2-D Fourier transform of the $z$-component of the field in the pickup loop, with a current $I$ in a circular ring of radius $R$ oriented parallel to, and a height $z$ above a sample, is given by [10]

\[ h_z(k) = \frac{-4\pi^2IR}{c} J_1(kR)(1 - e^{-2kz} / (1 + k\Lambda)), \]
neous distribution of superfluid density). The crosses are ideal systems to test novel theories and concepts for devices (VQT and field effect experiments).

This work has been partially supported by the ESF projects “Pi-Shift” and “VORTEX”. The authors would like to thank G. Blatter, J. Guikema, V.G. Kogan, C.C. Tsuei and V. Kresin for useful discussions.

FIG. 3: Values of $T_c$ vs $\lambda_{ab}^{-2}$. The solid dots are the results for CBSCO, using $\lambda_{ab,h} = \sqrt{d\Lambda/2}$ (homogeneous distribution of superfluid density). The crosses are $\lambda_{ab,IL} = \sqrt{d_{IL}\Lambda/2}$ (superfluid density localized in the IL layers). The open symbols are recent results for a number of bulk hole-doped cuprates: La$_{2-x}$Sr$_x$CuO$_4$ (La-214) [21]; HgBa$_2$CuO$_{4+\delta}$ (Hg-1201); Bi$_2$Sr$_2$Ca$_{1-x}$Y$_x$Cu$_2$O$_{8+\delta}$ (Bi-2212) [22]. YBa$_2$Cu$_3$O$_{7-\delta}$ (Y-123) [23].

cetration depths (the crosses in Fig. 3) become comparable to the longest penetration depths reported for some cuprates: Although the average superfluid density in these films is low, the density in the IL layers might be higher, possibly promoting superconductivity at high temperatures.

We also note that the areal superfluid densities are about $2 \times 10^{14}$ cm$^{-2}$ for the 5/2/5 structures, making them ideal candidates for field effect experiments. The height of the surface barrier $E_o$ to formation of vortices is one of the crucial parameters to observe vortex quantum tunneling (VQT) [30]. $E_o$ is proportional to $\varphi_0^2/(8\pi^2\Lambda)$ and therefore inversely proportional to $\Lambda$: the larger the Pearl length, the lower the barrier height.

In conclusion, we have investigated vortex matter in ultrathin [Ba$_{0.9}$Nd$_{0.1}$CuO$_{2+x}]_m/[CaCuO$_2)_n$ systems using scanning SQUID magnetometry and susceptometry. We have given the first experimental evidence for Pearl vortices in the regime $d \ll \lambda_l$. This can be considered the closest attempt yet to investigate vortices in 2-dimensional systems (vortices of zero length). This experiment proves that extreme regimes (ultrathin films) are experimentally accessible through SSM and opens up several prospects of broad interest, especially if we consider that these topological defects may have analogies in other fields of physics. These measurements identify systems with very long penetration depths and relatively high $T_c$. This represents a further step to experimentally isolate the properties important for superconductivity in high-$T_c$ compounds. Finally, these systems potentially represent ideal systems to test novel theories and concepts for devices (VQT and field effect experiments).

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