Real space visualization of thermal fluctuations in a triangular flux-line lattice

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New Journal of Physics 12 (2010) 033022 (14pp)
Received 28 October 2009
Published 12 March 2010
Online at http://www.njp.org/
doi:10.1088/1367-2630/12/3/033022

Abstract. The temperature-dependent properties of a triangular flux-line lattice (FLL) in the low-flux density regime were investigated by evaluating the imaged flux-line (FL) size and the lattice regularity observed in real space utilizing magnetic force microscopy (MFM). At low temperatures, pinning by randomly distributed point defects in the anisotropic type-II superconductor Bi\textsubscript{2}Sr\textsubscript{2}CaCu\textsubscript{2}O\textsubscript{8+δ} results in curved FLs and lateral disorder within the FLL (Bragg glass). Above 30 K, depinning of pancake vortices (PVs) leads to straightening of FLs and a better-ordered lattice. Evaluation of the temperature-dependent imaged FL size allows us to determine the stiffness of the potential, in which FLs in the lattice are caged due to mutual repulsion between them. At 54.1 K, far below melting temperatures reported so far, thermal fluctuations plus the lateral force exerted by the scanning tip facilitate decoupling of PVs near the surface and the image contrast exhibit a liquid-like behavior. Our analysis demonstrates the ability of MFM to obtain three-dimensional information on the arrangement of PVs.

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1. Introduction

Magnetic fields can penetrate type-II superconductors in the form of vortices. Their cores of radius $\xi$ (the coherence length of the Cooper pairs) are normal conducting. A magnetic field, corresponding to one quantum flux $\Phi_0 = 2 \times 10^{-15}$ Tm$^2$, threads the vortex core and is screened from the surrounding superconducting phase by circular supercurrents, which decay on the length scale of the London penetration depth $\lambda$. In the highly anisotropic superconductor Bi$_2$Sr$_2$CaCu$_2$O$_8$ (BSCCO), the Cooper pairs, and therefore the vortices as well, are confined to the copper oxide double planes, which are separated along the crystal $c$-axis by a distance $s > \xi$ (BSCCO: $s = 1.54$ nm and $\xi \approx 1$ nm). If located in neighboring planes, these so-called pancake vortices (PVs) attract each other magnetostatically and via Josephson tunneling of Cooper pairs. Hence, they align along the $c$-axis to build up flux lines (FLs). On the other hand, PVs within the same plane repel each other. Consequently, FLs as a whole also repel each other and arrange themselves in a triangular flux-line lattice (FLL). Its lattice constant $a_\Delta$ depends on the flux density $B$ ($a_\Delta = 4/\sqrt{3} \sqrt{\Phi_0/B}$).

It has been realized that the discrete nature of FLs results in a strong susceptibility to thermal fluctuations, leading to a rich variety of vortex phases in the $B$–$T$-phase diagram of BSCCO and similar high-temperature superconductors (see, e.g. [1, 2] for reviews). For example, indirect volume-averaging transport and magnetization measurements revealed regularly ordered or glassy solid-like phases as well as liquid-like phases in BSCCO. The Bitter decoration method has been frequently applied to determine the range of translational as well as orientational order of FLLs and to discuss the role of pinning in real space (see, e.g. [3] for a more recent review). However, with this technique one cannot directly see the influence of thermal fluctuations on an individual FL, because the FLL is observed ex situ and decoration at elevated temperatures (above 4.2 K) is difficult. Furthermore, it is impossible to obtain information in the liquid state, i.e. if the PVs are decoupled and do not form FLs. Here, we report a real space visualization of the impact of thermal fluctuation on the alignment of PVs in individual FLs and on the regularity of the whole FLL by means of temperature-dependent magnetic force microscopy (MFM) experiments. We will demonstrate that a thorough evaluation of MFM images allows us to analyze the regularity of an FLL in the...
$ab$-plane and to infer the degree of ordering along the $c$-axis as well. Moreover, it is also possible to detect an MFM signal if PVs in adjacent layers are decoupled and hence do not form FLs.

2. Magnetic force microscopy applied to superconductors

MFM has proven its ability to detect [4]–[7] and manipulate [8, 9] individual FLs. This in situ real space imaging technique utilizes a cantilever of spring constant $c_z$ with a ferromagnetic tip at its free end to sense the magnetostatic interaction between tip and sample at a fixed height $h$ above the surface. For our experiments, data acquisition was performed using the frequency modulation technique [10]. In this mode of operation, the amplitude $A$ of the oscillating cantilever is kept constant and the frequency shift $\Delta f$, i.e. the deviation from the resonance frequency $f_0$ of the free cantilever, is a measure of the interaction strength. Details of the instrumentation (Hamburg design) and the MFM imaging mode can be found in [11].

For the following, it is important to know that MFM senses the force gradient $\partial F/\partial z = 2c_z\Delta f/f_0$ of the magnetostatic interaction between a ferromagnetic tip and the stray field emanating from FLs. Hence, for intervortex distances larger than $\lambda$, FLs in MFM images appear as circular objects with radii of the order of $\lambda$. Note that BSCCO is highly anisotropic resulting in different London penetration depths $\lambda_{ab}$ and $\lambda_c$ ($a$, $b$ and $c$ denote the corresponding crystallographic-axis of BSCCO). In our case, FLs are aligned along the $c$-axis, hence $\lambda_{ab} \approx 200 \text{ nm}$ is relevant to interpret our MFM images. For simplicity, we will use $\lambda_{ab} \equiv \lambda$ throughout this paper. If the magnetic polarization of the tip and the FL polarity are parallel, the magnetostatic interaction is attractive and FLs display brightly in images. Clem [12] showed that the magnetic field of an isolated PV in an anisotropic layered superconductor decays exponentially perpendicular to the surface with a decay length of $\lambda$. Therefore, the information depth of MFM is of the order of $\lambda$. Hence, in BSCCO more than 100 near surface PVs contribute to the signal stemming from one FL. As a consequence of the long range of the magnetostatic interaction, MFM data also contain information about the alignment of PVs within an FL.

It should be noted that in contrast to typical transport and magnetization measurements our experimental set-up is not optimized for temperature-dependent studies, but for in situ real space imaging with high spatial resolution. Thus, we could only record a limited number of data sets at different temperatures. However, as a local probe technique it does not suffer from artifacts, which have been reported for conventional volume-averaging methods [13].

3. Tip and sample preparation

For MFM imaging, iron was evaporated in situ on to commercially available standard silicon sensors ($f_0 \approx 200 \text{ kHz}, c_z \approx 40 \text{ nm}$). Typical data acquisition parameters were $A \approx 30 \text{ nm}$ and $h \approx 30 \text{ nm}$. To achieve out-of-plane magnetic sensitivity and to obtain a localized magnetic stray field, only one side face of the pyramidal tip was coated with about 5 nm of iron. Iron thickness and imaging parameters were chosen to obtain a detectable MFM signal without disturbing the genuine arrangement of FLs.

Platelet $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8+\delta$ single crystals ($T_c \approx 88 \text{ K}$), grown by the floating zone method, were investigated. One sample was not further treated (as-grown sample) and only contained intrinsic point defects like oxygen vacancies [14]. A second sample, used for reference

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4 Literature values for the London penetration depth at zero temperature $\lambda_0$ range from 180 to 270 nm.
(a) MFM image of randomly distributed FLs in the irradiated sample after field cooling. Since the flux density of about 2 mT corresponds to the matching flux density $B_m$, the distribution of FLs reflects the random distribution of columnar defects. They act as strong and coherent pinning sites, which result in straight FLs. This arrangement of FLs is characteristic for a Bose glass. (b) MFM image of a regular triangular FLL obtained after field cooling in the as-grown sample. The flux density corresponds to about 3 mT. Intrinsic randomly distributed pinning sites result in curved FLs and the absence of perfect long-range (see also figure 3(b)). Both features are characteristic for a Bragg glass. (c) Red and blue lines correspond to circular line sections (see footnote 5) across an FL in (a) and (b), respectively. The imaged FL radius $R_{FL}$ is significantly larger in (b). The two sketches depict why curved FLs appear broader in MFM images than straight ones.

measurements, was irradiated with heavy uranium ions parallel to the crystal $c$-axis to produce randomly distributed columnar defects (irradiated sample). The ion dose corresponded to a flux density of about 2 mT, the so-called matching flux density $B_m$. FLs were introduced into both samples by slow field cooling (within 1 h from above $T_c$ down to $T = 5.1$ K). The field cooling flux density $B_{FC}$ was chosen such that the mean distance between FLs was much larger than $\lambda$ (low-flux density regime). The resulting arrangement of FLs is displayed in figure 1 for both samples and analyzed with respect to the role of pinning for the imaged FL size. The as-grown sample was studied further to investigate the impact of thermal fluctuations on the vertical
alignment of PVs as well as on the lateral regularity of the FLL. The temperature-dependent series is shown in figure 2.

4. Experimental results

Figure 1 compares the arrangement of FLs in the irradiated (a) and the as-grown (b) sample. In both cases the FLs are well separated. However, in the irradiated sample FLs are randomly
distributed, while they form a triangular FLL in the as-grown sample. The two circular line sections displayed in figure 1(c) clearly reveal that the imaged FL size is smaller for the irradiated sample (red curve).

To investigate the impact of thermal fluctuations on the FLs in the FLL, the same area of the as-grown sample was imaged at different temperatures. The starting condition after initial field cooling is shown in figure 2(a). Thereafter, the temperature was increased stepwise toward $T_c$. After each step, the FLL was imaged; cf figures 2(b)–(f). The imaged FL size clearly increases with temperature. However, the FLL remains intact (all FLLs are surrounded by six neighbors) until the FLL contrast disappears at 54.1 K. To analyze our image data, we determined the FL radius $R_{FL}$ (half-width at half-maximum of profiles across the FLs), the lattice parameter $a_{\Delta}$ using Delaunay triangulation and its standard deviation $\sigma_{a_{\Delta}}$.

The temperature dependence of the FL radius $R_{FL}(T)$ is plotted in figure 3(a). Upon increasing the temperature, $R_{FL}$ increases monotonically. Initially, $R_{FL}$ increases only slightly from 183 nm (5.1 K) to 207 nm (23.2 K). Thereafter, a much steeper increase to 271 nm at 34.5 K can be observed until $R_{FL}$ has nearly doubled to about 352 nm at 49.7 K. At 54.1 K, the typical FLL contrast is absent. However, horizontally, i.e. along the fast scan direction, small contrast modulations are still visible. Note that the disappearance of the contrast happens far below $T_c$ and also far below typically reported melting temperatures $T_m$ for such a low flux density [15]–[17].

As expected, $a_{\Delta}$ remains constant as long as the FLL is visible. However, its standard deviation $\sigma_{a_{\Delta}}$, displayed in figure 3(b), exhibits a peculiar temperature dependence. As sketched in the inset, this quantity is a measure of the lattice regularity, because the spread of the FL-separation $a_{\Delta}$ becomes larger, if translational and orientational disorder within the $ab$-plane of the FLL increases. Below $T \approx 30$ K, $\sigma_{a_{\Delta}}$ decreases only slightly (from 66 nm at 5.1 K to 65 nm at 23.2 K), but above $T \approx 30$ K the decrease is significantly stronger (from 63 nm at 34.5 K to 59 nm at 38.1 K), which indicates that the regularity of the FLL becomes better with increasing temperatures. Interestingly, the stronger decrease of $\sigma_{a_{\Delta}}$ occurs in the same temperature regime where $R_{FL}$ exhibits a much stronger increase with temperature than before. If the temperature is increased further toward $T_c$ the decrease of $\sigma_{a_{\Delta}}$ turns into a sudden steep increase to about 92 nm at 49.7 K before the FLL contrast finally disappears at 54.1 K.

5. Data evaluation and discussion

In the following, we evaluate the influence of pinning on the alignment of PVs within an FL. Thereafter, the temperature-dependent data are discussed with respect to the ordering of PVs along the $c$-axis and within the $ab$-plane in the presence of disorder and thermal fluctuations. Particular emphasis is placed on the imaging mechanism, which allows extraction of information about the three-dimensional structure of FLLs, and the effect of the scanning tip on the genuine arrangement of PVs and FLs.

5.1. Bose glass, Bragg glass and pinning

We first analyze the random arrangement of FLs at 5.1 K in figure 1(a). After irradiation with uranium ions, the sample possesses columnar defects that are randomly distributed in the

5 From the center of a circular object all line sections of length $r$ on the circumference are radially averaged. The result is the circular line section.
Figure 3. (a) Temperature dependence of the imaged FL radius \( R_{\text{FL}}(T) \). Data points are taken from figures 2(a)–(e). Below depinning at \( T_D \approx 30 \text{ K} \) the small broadening is due to the temperature dependence of \( \lambda = \lambda(T) \). Curves 1 to 3 represent three different models for \( \lambda(T) \) (see main text). Curve 4 is the best linear fit for the two data points below \( T_D \). After depinning, thermal fluctuations are much stronger, resulting in a \( \sqrt{T - T_D} \)-dependence represented by curve 5.

(b) Temperature dependence of the standard deviation \( \sigma_{\Delta} \) of the mean FL distance \( a_{\Delta} \). It is a measure of the lattice regularity, as sketched in the inset (dots with gray discs mark the positions of pinned PVs, black circles represent the arrangement of PVs in a perfectly ordered lattice). After depinning at \( T_D \approx 30 \text{ K} \) the lattice becomes significantly better ordered. At 49.7 K, just before the typical FLL contrast disappears, the FLL becomes strongly disordered.

\( ab \)-plane. However, along the trajectory of each ion, i.e. the \( c \)-axis of the layered crystal, all defects within a column are coherently aligned. These columnar defects provide strong pinning sites. Thus, if \( B_{\text{FC}} \lesssim B_m \), all FLs are located at columnar defects. The presence of intrinsic defects is irrelevant, because they act as much weaker pinning sites. Hence, the random arrangement of FLs in the \( ab \)-plane of the irradiated sample \( (B_{\text{FC}} \approx B_m) \) reflects the random
distribution of columnar defects and PVs within each FL are coherently aligned along the $c$-axis. This situation is known as the Bose-glass state.

In the as-grown sample, cf figure 1(b), only intrinsic defects are present. For pinning of PVs in BSCCO, the most relevant defects are believed to be randomly distributed oxygen vacancies in the CuO-layers [14]. They are randomly distributed in all the three dimensions and act as weak pinning sites. In the low flux density regime, the interaction between FLs is very small, because for separations larger than $\lambda$, the repulsion between FLs decays exponentially with distance. In this situation, even weak pinning sites introduce significant disorder into the system, because they attract PVs. Of course, PVs still tend to form FLs. However, to accommodate the pinning sites, the somewhat elastic FLs are no longer straight, but curved [2, 18].

Since MFM is sensitive to many layers with PVs, the envelope of all laterally shifted PVs contribute to the imaged FL radius. Therefore, curved FLs will appear broader than straight ones, as sketched in the insets of figure 1(c). Indeed, the circular line section (see footnote 5) in figure 1(c) shows that the FL radius in the Bose glass state with straight FLs is smaller than for the curved FL in the as-grown sample. The difference measured at half-width at half-maximum between the red and blue curves is about 30 nm. On an FL segment of a length of the order of $\lambda$, i.e. the information depth of MFM, this corresponds to a displacement of more than 15% away from equilibrium positions of the PVs without pinning sites. It should be noted that without any pinning FLs are perfectly straight as well. Therefore, our finding that $R_{FL}$ in the as-grown sample is larger than in the irradiated sample strongly indicates that pinning at intrinsic defects occurs and is indeed relevant in our case.

Curved FLs are not the only evidence for the presence of randomly distributed point-like pinning sites. They show up in the lattice regularity as well. No defects in the FLL, e.g. FLs with 5 or 7 nearest neighbors, are visible in figure 2(a). However, the standard deviation $\sigma_{a_\Delta}$ of 66 nm, which corresponds to about 7.5% of $a_\Delta$, demonstrates that the FLL does not exhibit perfect long-range order in the $ab$-plane. How randomly distributed pinning sites lead to positional disorder is sketched in the inset of figure 3(b). PVs (and hence FLs) are slightly displaced from the equilibrium positions, if pinning sites are nearby. As a result $a_\Delta$ exhibits a Gaussian distribution of width $\sigma_{a_\Delta}$. A larger $\sigma_{a_\Delta}$ indicates more disorder. Note further that the difference in radius of $\approx 30$ nm (60 nm for the diameter) between straight and curved FLs, cf figure 1(c), corresponds well with the measured $\sigma_{a_\Delta} \approx 66$ nm at 5.1 K.

To summarize, we can infer that the presence of point-like weak pinning sites are relevant in our as-grown sample at 5.1 K in the low-flux density regime. Their random distribution leads to disorder in the $ab$-plane, as well as along the $c$-axis. The resulting absence of perfect long-range order is characteristic for a Bragg glass [19].

5.2. Potential landscape, temperature and lattice regularity

Figure 3(a) clearly shows that $R_{FL}(T)$ behaves distinctly differently below and above the temperature regime around 30 K, i.e. from 5.1 to 23.2 K the increase is only 13%, while it increases by 31% between 23.2 and 34.5 K. Interestingly, Dewhurst and Doyle [20] reported magnetization measurements on BSCCO samples, which revealed a clear feature in the derivative of the magnetic moment as a function of temperature at about 32 K. They interpreted this feature as being indicative of a depinning transition. We also performed such magnetization measurements (the data are not presented here). Analyzing our data in the same manner also revealed such a feature, but at a slightly lower temperature of about 30 K. If the different
Figure 4. Simplified one-dimensional energy landscape of a single PV. It is given by the superposition of a wide cage potential at \( r_0 \) and a localized off-center narrow pinning potential at \( r_p \). Bright and dark gray shaded areas indicate the size of \( \lambda \) and the broadening \( \Delta r_{th} \) due to thermal fluctuations, respectively. The MFM signal from one PV stems from a region with radius \( r_{PV} = \lambda + \Delta r_{th} \).

(a) Below the depinning temperature, \( T_D \), the PV is located at \( r_p \) and the narrow pinning potential restricts the thermal fluctuation \( \Delta r_{th} \) to a range much smaller than \( \lambda \). Hence, thermal broadening is negligible and \( r_{PV} \approx \lambda \). An FL formed by pinned PVs is curved (see sketch), because the distances between \( r_0 \) and \( r_p \) are not identical in every layer. (b) Above the depinning temperature, \( T_D \), the thermal fluctuations are limited by the much wider cage potential. Since MFM averages over the fast movement of all PVs within one FL, the thermal broadening is significant. Moreover, after depinning the equilibrium position of all PVs in an FL are located at \( r_0 \). Therefore, the FLs become straighter (see sketch).

The temperature behavior is related to a depinning transition, it will be very informative to examine the corresponding temperature dependence of the standard deviation \( \sigma_{\Delta a} \). As discussed above, this quantity is a measure of the lattice regularity. A nonzero value for \( \sigma_{\Delta a} \) in figure 2(a) is a consequence of the presence of randomly distributed pinning sites. Below \( \approx 30 \text{ K} \), the decrease in \( \sigma_{\Delta a} \) is tiny, but above \( \approx 30 \text{ K} \) the decrease is significant, meaning that the positional order within the FLL increases.

At first sight this finding is counterintuitive, because higher temperatures, i.e. increased thermal fluctuations, usually lead to more disorder in a system. However, a depinning transition can explain the significant reduction of \( \sigma_{\Delta a}(T) \) above 30 K, as well as the peculiarly different temperature dependence of \( R_{FL}(T) \) in the same temperature regime.

To understand the broader appearance of FLs after depinning, one has to consider the potential landscape for a PV surrounded by other PVs near a point-like weak pinning site. Owing to the mutual repulsion between PVs within the same CuO-layer, each PV is caged in a potential minimum formed by the six surrounding PVs. A simplified one-dimensional potential landscape of a PV is displayed in figure 4. In a first approximation, the cage potential is parabolic with a curvature \( k_{c,PV} \) and centered at \( r_0 \), i.e. \( E_{c,PV} = \frac{1}{2} k_{c,PV} (r - r_0)^2 \). The width of the cage potential \( E_{c,PV} \), given by \( k_{c,PV} \), depends on the flux density. In addition, pinning sites are present, which
Figure 5. Liquid-like behavior of decoupled PVs. (a) MFM image of a point-like feature, probably a still-pinned FL segment. (b) Circular line section (see footnote 5) around the point-like feature. The contrast pattern resembles a standing wave pattern.

alter the cage potential locally. The pinning potential $E_p$, which stems from a localized point defect, is characterized by its depth $E_{p,0}$ below the minimum of the cage potential. As for the cage potential, it can be approximated by a parabola, but with a different curvature $k_p$. For atomic-scale defects like oxygen vacancies its range $u$ is of the order of 1 nm. Since vortex cores in BSCCO are of similar size ($\xi \approx 1$ nm), such defects can act as pinning sites. Beyond this range, the pinning strength decays quickly to zero, i.e. $E_p = \frac{1}{2}k_p(r - r_p)^2 - E_{p,0}$ for $r \leq u$ and $E_p \approx 0$ for $r > u$. In the low-flux density (as in our case), $E_{c, PV}$ is certainly much wider than $E_{pin}$, i.e. $k_{c,PV} \ll k_p$. The superposition of $E_{c,PV}$ and $E_p$ is sketched in figure 5.

The energy $E_D$ needed for depinning depends not only on $E_{p,0}$ but also on the distance between $r_p$ and $r_0$, i.e. between equilibrium position $r_0$ and the location of the pinning site $r_p$, i.e. $E_D = \frac{1}{2}k_{c,PV}(r_p - r_0)^2 + E_{p,0}$. Therefore, even if one type of pinning site with a well-defined pinning strength $E_{p,0}$ dominates, e.g. oxygen vacancies, a certain distribution of depinning energies exists. Such a distribution of depinning energies explains the steady decrease of $\sigma_{\Delta \lambda}$ with increasing temperature. However, the distribution is not very wide, because in the low-flux density regime many more pinning sites than PVs are present. Hence, the actual pinning positions $r_p$ after slow field cooling are mostly relatively close to the equilibrium position $r_0$. Consequently, the depinning transition is relatively sharp as indicated by the distinctive feature found in volume-averaging magnetization data.

Although the MFM signal of one FL contains contributions from all PVs in the FL up to a distance of the order of $\lambda$ below the surface, it is sufficient for the time being to restrict the discussion regarding contrast formation to the behavior of a single PV. As explained in section 2, the MFM signal of one PV stems from a region with radius $r_{PV} = \lambda$. However, this is only exact for an immobile PV, i.e. at $T = 0$ K. For $T > 0$ K, the position fluctuates around its equilibrium position. The timescale of such thermal fluctuations is much faster than the data acquisition time (typically a few milliseconds per image point for MFM). Therefore, the MFM signal is averaged over a region of radius $r_{PV} = \lambda + \Delta r_{th}$, where $\Delta r_{th}$ is the range of the thermal fluctuations around the equilibrium position.

At a given temperature $T$, the available thermal energy $E_{th}$ is of the order of $\frac{1}{2}k_B T$ ($k_B$ is the Boltzmann constant). The magnitude of $\Delta r_{th}$ depends on the width of the potential in which the PV is trapped. As long as $E_{th}$ is smaller than $E_D$, the movement of the PV is confined by the narrow pinning potential. Thus, $\Delta r_{th} \ll \lambda$, and the MFM signal stems to a
very good approximation from a region with radius $\lambda$; cf figure 4(a). If the pinning potential is very narrow, $\Delta r_{th}$ does not increase significantly for higher temperatures. However, above the depinning temperature $T_D$, i.e. if $E_{th} > E_D = \frac{1}{2}k_B T_D$, the PV can move freely across the localized pinning site. Now the thermal fluctuations are limited by the much wider cage potential; cf figure 4(b). As a result, $\Delta r_{th}$ is not negligible and $r_{PV} = \lambda + \Delta r_{th}$ is significantly thermally broadened.

Depinning of individual PVs also shows up in the appearance of individual FLs and the FLL. With increasing temperature, more and more PVs within an FL are located at their equilibrium position $r_0$. Hence, the FLs become straight and the FLL becomes better ordered. We cannot directly detect this straightening in the $R_{th}(T)$-plot, because the resulting decrease of $R_{th}$ is masked by the thermal broadening. However, the increased long-range positional order results in the significant decrease of $\sigma_{th}$ at elevated temperatures.

Next, we check the qualitative picture given above in a more quantitative manner by analyzing the $R_{th}(T)$-plot in figure 3(a). Below $T_D$, the imaged FL size $R_{FL}$ is determined by $\lambda$. Since $\lambda$ is temperature dependent, $R_{FL}$ should exhibit the same temperature dependence, because $R_{FL}(T) \propto \lambda(T)$. For conventional isotropic type-II superconductors, the temperature dependence according to the two-fluid model is given by $\lambda(T) = \lambda_0/\sqrt{1 - (T/T_c)^{1/4}}$, where $\lambda_0$ is the London penetration depth at 0 K. However, for $d$-wave superconductors like BSCCO, different temperature dependencies have been proposed for temperatures sufficiently below $T_c$, i.e. $\lambda(T) = \lambda_0(1 + \alpha T^\beta)$ with $\beta = 1$ or 2. Assuming $R_{FL}(T) \propto \lambda(T)$ and $\lambda_0 \propto R_0$ corresponding fits are included in figure 4(a) as curves 1 to 3: (i) a two-fluid model; (ii) $\alpha = 3.92 \times 10^{-3} K^{-1}$, $\beta = 1$; (iii) $\alpha = 9.03 \times 10^{-5} K^{-2}$, $\beta = 2$. The values for curves 2 and 3 are taken from torque magnetometry measurements by Waldmann et al [21] for materials with a $T_c$ close to its optimal $T_c$ of about 90 K ($\beta = 1$) and for materials with a significantly reduced $T_c$ ($\beta = 2$), respectively.

None of the models describe the experimental data correctly over the whole temperature range. Below $T_D$, curve 2 ($\beta = 1$, for an optimal $T_c$) fits best, which is in agreement with our relatively high $T_c$. If we use the two data points below $T_D$ to determine $\alpha$ from a linear fit ($\beta = 1$; see curve 4), its value of $7.5 \times 10^{-3} K^{-1}$ is very close to the one found by Waldmann et al [21]. Since only two data points are below $T_D$, the other models cannot be excluded. However, the temperature-dependent behavior of $R_{FL}$ below $T_D$ can be satisfactorily explained by the temperature dependence of $\lambda$.

Above $T_D$, all models for $\lambda(T)$ fail to explain the MFM data, because additional broadening by thermal fluctuations is not considered in these models. If we assume a parabolic cage potential, the additionally thermal broadening $\Delta R_{th}$ should exhibit a $\sqrt{T}$-dependence, i.e. $\Delta R_{th} = \sqrt{k_B(T - T_D)/k_{c,FL}}$. Note that $k_{c,FL}$ cannot be identified with $k_{c, PV}$, which was introduced for a single PV, because the MFM signal stems from an FL segment with a length of the order of $\lambda$. Similarly, $\Delta R_{th}$ denotes the thermal broadening of the FL-segment of length $\lambda$ sensed by MFM, which, in general, will be different from $\Delta r_{th}$, the thermal broadening of a single PV.

After depinning, the PVs of each FL probe their potential landscape stemming from the PVs in the surrounding FLs. This can be utilized to determine the effective stiffness $k_{c,FL}$ of the cage potential for an FL segment of length $\lambda$. To fit the $R_{FL}(T)$ data above $T_D$, we take a linear temperature dependence of $\lambda$ into account as well as thermal fluctuations within the cage potential for one FL, i.e. $R_{FL}(T) = R_0(1 + \alpha T) + \sqrt{k_B(T - T_D)/k_{c,FL}}$. For $\alpha$, we use the value from the best fit in the regime below $T_D$, i.e. $\alpha = 7.5 \times 10^{-3} K^{-1}$ (curve 4) and $R_0 = R_{FL}$ at $T = 5.1 K$. Thus, $k_{c,FL}$ is the only free parameter. The fit with $k_{c,FL} = 1.8 \times 10^{-3} N m^{-1}$ clearly

New Journal of Physics 12 (2010) 033022 (http://www.njp.org/)
shows that the temperature dependence of the imaged FL size $R_{FL}(T)$ can be directly related to thermal fluctuations, which become significant after depinning. As mentioned before, the magnitude of the thermal broadening depends on the width of the cage potential, i.e. on the flux density $B$. For higher flux densities, the interaction between FLs starts to dominate over thermal effects, because the cage potential becomes narrower, i.e. $k_{c,FL}$ becomes larger. Note also that below $T_D$, a similar formula applies, i.e. $\Delta r_{th} = \sqrt{k_B T/k_p}$. However, since $k_p \gg k_{c,FL}$, $\Delta r_{th}$ is negligibly small compared to the effect due to the temperature dependence of $\lambda$ itself, these tiny thermal fluctuations do not show up in our data.

5.3. Decoupling of pancake vortices

If the temperature is further increased, the thermal energy will surpass the coupling energy between PVs in neighboring layers. Hence, the disappearance of the typical FLL contrast at 54.1 K could be interpreted in terms of a melting transition. Randomly relative positions of mobile PVs in adjacent CuO-layers are consistent with the observed smeared out contrast in MFM images visible in figure 2(f). According to the Lindemann criterion, melting occurs when the thermal displacement is some fraction of the lattice constant, i.e. $\Delta r_{th} = c_L a_\Delta$, where $c_L \approx 0.1–0.2$ is the Lindemann parameter. Thus, for $a_\Delta = 866$ nm, the FLL is expected to melt, if $\Delta r_{th} \approx 87–173$ nm. Indeed, at 49.7 K, $\Delta r_{th}$ reaches about 100 nm. Moreover, at this temperature, we found a point-like feature shown in figure 5(a), which could be a still pinned FL segment. The ring-like structures around it, clearly visible in the circular line section (see footnote 5) of figure 5(b), can be interpreted as decoupled PVs, which locally form a standing wave pattern. It should be noted that these features are rare, i.e. we observed one in an area of about 20 $\mu$m $\times$ 20 $\mu$m.

However, data recorded with other techniques in the low-flux density regime for BSCCO suggest a melting temperature $T_m$ much closer to $T_c$ ($\approx 88$ K for our sample) than 54.1 K [15]–[17]. Therefore, the features in figures 3(f) and 5 cannot be simply identified with the vortex liquid phase observed with other experimental techniques. More likely, the decoupling of PVs is not exclusively a consequence of large thermal fluctuations. Additionally, dragging due to the magnetostatic attraction between PVs and tip could also play a significant role. It has been pointed out by Wadas et al [23] that lateral magnetostatic forces during MFM imaging could also lead to a depinning of FLs. We reported that FLs can be moved along antiphase boundaries due to the stray field of a magnetic tip [8]. Moreover, we determined experimentally the magnitude of the lateral force between an MFM tip and an FL by analyzing force spectroscopy data [22]. Recently, MFM tips were deliberately utilized to bend FLs away from their equilibrium positions without actually depinning them [9]. Therefore, it is likely that shearing forces exerted by the horizontally scanned tip on the FLL, together with thermal fluctuations, can decouple the PVs near the surface, resulting in the observed horizontal contrast modulations. This occurs even at temperatures far below the thermodynamic melting transition, but only in the vicinity of the tip. PVs outside the scanned area and PVs in the bulk are not affected.

The onset of the proposed shearing can already be observed at 49.7 K in figure 2(e). For this temperature $\sigma_{a_\Delta}$ behaves against the trend, i.e. it becomes very large (about 92 nm) instead of becoming smaller (cf discussion in the previous section). Although the FLL is still clearly visible, individual FLs appear less well defined than before, e.g. some appear ‘squeezed’ and others are elongated. This is a clear sign that lateral forces start to distort the genuine FLL.
structure. Furthermore, after recooling down from 54.1 to 5.1 K the FLL recondensates, but becomes significantly more disordered ($\sigma_{a_\perp} = 94$ nm) than was the case after the initial field cooling; cf figure 2(a). In fact, after recondensation $\sigma_{a_\perp}$ is very close to $\sigma_{a_\perp} = 92$ nm measured at 49.1 K just before the FLL contrast disappeared. This increased disorder after recondensation strongly indicates a true tip-induced decoupling of PVs and not just a very strong bending of intact FLs.

It should be mentioned that we never observed a tip-induced FL cutting within a regular lattice. This phenomenon has been reported in a highly anisotropic YBCO-sample [24] with a somewhat irregular arrangement of FLs. Interestingly, we also found cut FLs in BSCCO samples with randomly distributed columnar defects, which prevent the formation of a regular FLL.

6. Summary

In summary, we visualized in real space the interplay between pinning, thermal fluctuations and ordering of PVs within the $ab$-plane and along the $c$-axis. This remarkable three-dimensional sensitivity is possible because MFM detects the long-range magnetostatic force from PVs up to a depth of the order of $\lambda$ below the surface.

We found that the temperature dependence of the FL radius $R_{FL}(T)$ and the lattice regularity, represented by $\sigma_{a_\perp}(T)$, as well as volume averaging magnetization data, indicate a depinning of PVs at about 30 K. The transition is sharp enough to show up as a distinctive feature in the magnetization data. However, the steady decrease of $\sigma_{a_\perp}(T)$ with increasing temperatures suggests a certain distribution of depinning energies. Below $T_D$ pinning of PVs results in curved FLs and prevents perfect long-range lateral order (Bragg glass). Above $T_D$ the lattice becomes more regular and the imaged FL radius increases mainly due to thermal broadening. Utilizing depinned FLs as probes, we were able to determine the stiffness of the cage potential $k_{c,FL}$ felt by an FL segment of length $\lambda$ to about $1.8 \times 10^{-8}$ N m$^{-1}$. If the temperature is increased further, tip-induced distortions can be observed. Finally, thermal fluctuations and lateral shear forces exerted by the MFM tip result in a decoupling of near-surface PVs. In this state, the image contrast exhibits a liquid-like behavior. However, not all of the specimen is in a liquid state. Only the area close to the tip and at a depth of the order of $\lambda$ (the MFM information depth) is affected by a tip-induced local melting.

It is a considerable achievement that the arrangement of PVs in all three dimensions can be analyzed and that even the weak signal from decoupled PVs are detectable by MFM. Hence, this real space imaging technique seems to be a well-suited tool for investigation of the various different phases found in vortex matter, and in particular to evaluate the role of pinning. A very interesting experiment would be to depin PVs by applying an ac field [13, 25]. In this way, depinning could be studied at a constant temperature by measuring $R_{FL}$ utilizing the high spatial resolution of MFM.

Acknowledgments

We thank Y S Kim and Z G Khim from the Seoul National University for providing the magnetization data of our BSSCO sample, and J Wiebe from the University of Hamburg for helpful discussions.

6 This topic will be presented in a separate publication.

New Journal of Physics 12 (2010) 033022 (http://www.njp.org/)
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