Variation of local fields of pinned vortices with temperature

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(Dated: February 14, 2020)

Introducing artificial antidots into superconductors is an effective approach to manipulate vortex matter. It is of importance to study the effect of antidots on the magnetic field of a vortex and its temperature dependence. In our experiment, single vortices pinned at artificial antidots of different sizes as well as vortex pinned by random defects are investigated by using the scanning Hall probe microscope (SHPM). At certain height above the superconductor surface, the morphology of the vortices at various temperatures has been directly imaged. We have shown that the magnetic field distribution and its temperature dependences for all pinned vortices are similar. For both types of antidots, the penetration depth, rather than the antidot size, plays a dominant role in determining their vortex size at various temperatures. The Ginzburg-Landau (GL) simulations well support our experiments. The results set the stage for further theoretical analysis of the local field variations of the pinned vortices with temperature as well as for the design and fine tuning of pinned vortex lattices that can be used as magnetic templates for other systems.

In superconductors, single quantum vortices are the basic functional units, which determine the electronic and magnetic properties. Therefore, manipulation of vortex matter is of great importance when designing superconducting quantum devices such as SQUIDs [1, 2], vortex-memory devices [3–5] and magnetic field traps for ultra-cold atoms [6–9]. Among many ways to manipulate vortex matter, artificial antidots have been widely used due to the easy controllability of various geometries and arrangements [10]. Vortices in superconductors were predicted by Abrikosov in 1957 [11] and first observed in Bitter decoration experiments [12]. A randomly pinned vortex (RPV) is composed of a normal state core with the size about 2ξ (where ξ is the coherence length) and circulating supercurrents around it [13]. The distribution of circular supercurrents, and the induced magnetic field, are determined by the penetration depth (λ) and the coherence length (ξ) of a superconductor [14]. The magnetic field of RPVs in bulk samples can be well simulated by the monopole model [15–17]. However, when a vortex is pinned by a natural defect or artificial antidot, the monopole model, in general, becomes invalid. This is simply because the distribution of the Cooper pair density in the central part of this vortex is determined by the properties of the pinning center rather than by the superconductor coherence length. As a result, the distribution of supercurrent as well as the magnetic field distribution are rearranged accordingly. As shown by Fig. 1, there is no supercurrent inside the antidot area ($n_s = 0$, n_s is the Cooper pair density), and the magnetic field in this area is a nearly constant value [18].

This regime is realized when the antidot size is significantly larger than the coherence length. At high temperatures close to T_c , the dramatic increase of coherence

length might lead to a crossover between the field distribution typical for an artificially pinned vortex and that for a randomly pinned Abrikosov vortex. The study of magnetic field distributions and its temperature dependences are crucial for the development of new research lines in optics, electronics, spintronics and developing practical devices for field modulation. For example, the magnetic field landscape of a pinned vortex lattice can be designed to trap ultra-cold atoms for quantum simulations [7, 19], or as a potential well when coupling to artificial spin ice systems in hybrid structures [20, 21]. As the

Figure 1. (Color online) Schematic distributions of the Cooper pair density $n_{sc}(r)$ and magnetic field $B(x)$ for a randomly pinned vortex (on the left-hand side) and a vortex pinned by an antidot (on the right-hand side) on the surface of superconductor.

Figure 2. (Color online) SHPM images measured at 4.2 K, showing the magnetic field distribution of (a) a RPV and (b)-(e) four vortices pinned by circular antidots. The black circles in Figures (b)-(e) indicate the position of antidots with the diameter indicated on top of each image. The position coordinate is along the radial direction r (μm) (shown by the white arrow). The magnetic field is perpendicular to the surface of the films. Figures (f)-(j) present the corresponding magnetic field profiles along the dashed lines in Figures (a)-(e), respectively. The inset shows the magnetic field in the vortex center as a function of the antidot size at 4.2 K.

magnetic field distribution is important for these applications and can be measured only at a certain nonvanishing height above the superconductor surface, the relative study about it is necessary. Experimentally, the detailed distribution of magnetic fields, induced by vortices, and its evolution with temperature still remains elusive. The study of such magnetic field evolution for vortices pinned by artificial antidots is beneficial to both the understanding of vortex matter fundamentals in nanostructured superconductors and their practical applications.

In this paper, we have used superconducting samples with circular antidots of different sizes. The magnetic field distributions at different temperatures have been directly imaged by a low-temperature scanning Hall probe microscope (SHPM). We have found that, for RPVs, the magnetic field profiles can be well simulated by the monopole model, and the evolution of the field distribution with changing temperature is mainly determined by the temperature dependence of the penetration depth. For vortices pinned at antidots, the vortex field values are reduced. The larger the antidots, the smaller the field values. However, it is quite unexpected that rather similar temperature dependences are found for all the vortices pinned at antidots with different sizes. Our results suggest that the pinning does not modify the type of the temperature dependence of the vortex field distribution. This dependence is mainly determined by the penetration depth.

The Pb films of 90 nm thickness were prepared by electron beam evaporation on a SiO_2/Si substrate cooled by liquid nitrogen. All the films were covered by 10 nm thick Ge for insulating from oxygen and then by 35 nm thick

Au as a conducting layer to establish a tunneling junction as a feedback for SHPM measurements. Circular antidots with different diameters (0.8, 1.0, 1.5 and 2.0 μm) were introduced into the film by standard electron-beam lithography using a Raith electron-beam system. A plain film without antidots was used as a reference sample. The antidots were arranged at large distances from each other to make sure that the interaction between them can be neglected and therefore antidots can be considered as isolated ones. The critical temperature (T_c) of all the films used in the experiment is 7.3 K and the corresponding coherence length $\xi(T)$ at 4.2 K is 63 nm. The effective size of the Hall probe used in the direct imaging measurement is $0.4 \times 0.4 \mu\text{m}^2$. The Hall probe worked in a “lift-off” mode, namely, the probe was lifted to a safe work distance of about 700 nm away from the film surface (the work distance was obtained from the monopole model fitting of the RPV magnetic distribution, which will be elaborated later on).

To explore the influence of the antidot size on the magnetic field distribution, films with antidots of different sizes were prepared for research and a plain film was used as a reference. Figure 2 shows the magnetic field distributions of a RPV (Fig. 2(a)) and four vortices pinned by circular antidots of different sizes (Figures 2(b)-(e)). All the SHPM images were measured at 4.2 K with each antidot being occupied by one single-quantum vortex. The vortex field profiles (Figures 2(f)-(j)) show symmetric distributions with respect to the center of the vortex. The magnetic field at the vortex center, $B_z(0)$, measured at $T = 4.2$ K as a function of antidot diameter, is shown in the inset of Fig. 2(j). It is clear that $B_z(0)$ decreases monotonically with the antidot diameter. Since our SHPM measurements were performed in a “lift-off” mode with the Hall probe flying at around 700 nm height above the superconductor surface, the expected magnetic field plateau on top of the antidot is not clearly manifested. The behavior of the magnetic field at a certain height above the superconductor is of particular interest since just such a field is used to characterize vortices as well as to create magnetic templates, for example, for traps of ultra-cold atoms [19, 22, 23].

Fig. 3(a) shows the magnetic field evolution for a RPV at a few selected temperatures. It can be seen that, as the temperature increases, the field becomes weaker, which is directly related to the expansion of the penetration depth (Fig. 3(e)). The magnetic field profiles along the radial direction of the vortex at temperatures with further detailed subdivision are plotted in Fig. 3(b). Similarly, a global variation with temperature can be observed that the field intensity decreases gradually with increasing temperature. And it also can be seen that the FWHM (full width at half maxima) of the field distribution increases with temperature (for clarity, the inset in Fig. 3(c) shows the FWHM values versus reduced temperature), in line with previous re-

Figure 3. (Color online) (a) Variation of the magnetic induction distribution with temperature for a RPV. (b) Variation of the magnetic induction profile along the dashed line in Fig. 3(a) with temperature. (c) Magnetic induction in the center of a RPV as a function of temperature. The inset is the FWHM (full width at half maxima) of the magnetic induction profile for RPV-1. (d) Magnetic induction profile along the dashed line for RPV-1 at 4.2 K. The black solid line is fitting with the monopole model, which agrees well with the experimental result. (e) $\lambda + z_0$ as a function of reduced temperature, showing similar linear dependence.

Figure 4. (Color online) (a) Magnetic induction distribution of pinned vortex ($D = 0.8\text{ }\mu\text{m}$) with temperature. Variation of the magnetic induction distribution with temperature along the radial direction of the vortex core in films with antidot sizes of $D = 0.8\text{ }\mu\text{m}$ (b), $1.0\text{ }\mu\text{m}$ (c), $1.5\text{ }\mu\text{m}$ (d) and $2.0\text{ }\mu\text{m}$ (e), respectively. (f) Normalized magnetic induction of antidots with different diameter with temperature at position of $r = 0$ (f), $0.4\text{ }\mu\text{m}$ (g), $0.8\text{ }\mu\text{m}$ (h) and $1.5\text{ }\mu\text{m}$ (i), respectively.

ports [24–26]. The temperature dependence of the magnetic field in the vortex center ($B_z(0)$) extracted from Fig. 3(b) is shown in Fig. 3(c). A similar set of data was obtained on a different RPV (Fig. 3, blue circles), which shows identical temperature dependence. It can

also be seen that $B_z(0)$ varies only slightly at low temperatures, and then dramatically decreases towards zero close to T_c . Such a dependence is reminiscent of the temperature dependence of the penetration depth described

by the formula[27–29]: $\lambda(T) = \lambda_0 \left[1 - \left(\frac{T}{T_c} \right)^4 \right]^{-\frac{1}{2}}$,

where λ_0 is the penetration depth at zero temperature. Fig. 3(d) demonstrates the magnetic field profile for a RPV. As shown in Fig. 3(d), this profile can be well fitted by the monopole model[15, 24], $B(x, y, z_0) = \frac{\phi}{2\pi s^2} \int_{y-\frac{s}{2}}^{y+\frac{s}{2}} dy \int_{x-\frac{s}{2}}^{x+\frac{s}{2}} dx \frac{z_0 + \lambda}{[x^2 + y^2 + (z_0 + \lambda)^2]^{3/2}}$, where ϕ

is the magnetic flux carried by the vortex, z_0 is the distance between the Hall sensor and the superconductor surface and s is the effective size of the Hall sensor. By fitting the field profiles measured at different temperatures, we can further extract the temperature dependence of the quantity $\lambda + z_0$, where z_0 was kept constant in all the measurements. The results from fitting for two RPVs are plotted in Fig. 3(e), where $z_0 + \lambda(T)$ is seen to follow a linear dependence on $[1 - (T/7.3)^4]^{-1/2}$, in a good agreement with the two-fluid model [30] (We would like to mention that the GL dependence of penetration depth has also been used to fit the data, which yields a similar linear dependence.). The linear fitting yields the values $\lambda_0 = 0.138\text{ }\mu\text{m}$ and $z_0 = 0.708\text{ }\mu\text{m}$. The linear dependence

Figure 5. (Color online) The simulation results from the Ginzburg-Landau (GL) theory for the variation of the normalized magnetic induction with temperature at (a) $r = 0$ (b) $r = 0.8 \mu\text{m}$ (c) $r = 2.0 \mu\text{m}$. The “lift-off” distance used in the simulations is $z_0 = 700 \text{ nm}$. The legend label RPV means the randomly pinned vortex.

of $\lambda + z_0$ on temperature function of $[1 - (T/7.3)^4]^{-1/2}$ suggests that the field intensity at vortex core is mainly determined by the penetration depth.

Fig. 4(a) presents the magnetic field distributions of one pinned vortex at a few selected temperatures for the antidot size of $D = 0.8 \mu\text{m}$. The extracted magnetic field profiles, along the radial direction of the vortex core at various temperatures, are plotted in Fig. 4(b). The similar plots for antidot sizes of $D = 1.0, 1.5$ and $2.0 \mu\text{m}$ are shown in Figures 4(c)-(e), respectively. Besides the weakened field intensity, it is also clear that, at certain temperature, the FWHM of the profiles expands with the antidot size (see Figures S1(a)-(d) in supplementary material). The global increasing tendencies of FWHM with temperature for pinned vortex resemble the RPV case (see Fig. S1 in supplementary material). It is remarkable that, as seen in Figures 4(f)-(i), the temperature dependences of $B(T)$ for pinned vortices exhibit similar tendencies to those for RPVs. Only at large distances from the vortex center, the temperature dependence of $B(T)$ for pinned vortices seems to deviate from that for RPVs. At those distances, however, the effect of Hall

sensor noise on the relatively weak magnetic field signal cannot be neglected [31]. This might lead to a large uncertainty in the corresponding temperature dependence. Closer to the vortex center, the magnetic fields are relatively strong and hence the results of measurements are more accurate. Just the magnetic field landscape in this region is of main significance when using vortex lattices as magnetic templates for other systems. Importantly, our results suggest that the effect of the antidot size (or, more generally, the influence of the pinning center properties) on the temperature dependence of this field landscape is rather negligible.

To theoretically explore the temperature dependence of pinned and randomly pinned vortex morphology, the Ginzburg-Landau (GL) simulations have been carried out. Figures 5(a)-(c) show the variation of normalized magnetic induction with temperature at $r = 0, 0.8$ and $2.0 \mu\text{m}$ respectively for a “lift-off” distance of 700 nm . It can be seen that, at low temperatures, the temperature dependence of the magnetic field overlaps well for RPVs and vortices trapped by antidots of different sizes and only at the high temperatures near the T_c , the discrepancies among different vortices become obvious. The effect of the antidot size on the dependence becomes more pronounced when approaching T_c . The discrepancies are still very small, yet different between RPV and vortices pinned by antidots at different positions along the radial direction. However, the experimental results shown in Fig. 4 included the noise of Hall probe. So, within our field resolution, no clear difference could be told from the experimental results. All the results suggest that the effect of antidot size on the temperature dependence of vortex field distribution is rather small. Even in those cases the effect seems to be relatively weak, especially when taking into account that the antidot size varies in a rather wide range (from 0 to $2 \mu\text{m}$). Similar results (see Figures S2-S4 in supplementary material) have been obtained in the simulations for different “lift-off” distances (from 400 to 600 nm). The simulations are fully consistent with our experimental results. Both the experimental and simulation results suggest that the temperature dependence of the vortex field, measured at “lift-off” distances, is mainly determined by the behavior of the penetration depth, while the effect of vortex pinning on this field is rather minor. This means, in particular, that an analysis of the vortex field, measured at different temperatures, can provide reliable information on the behavior of the penetration depth even in the absence of data related to (possible) vortex pinning. In addition to the weak effect of antidot size, it can also be observed that, at larger r , the normalized $B_z(T)$ decreases much slowly than that at smaller r . From Fig. 3(b) and Figures 4(b)-(e), it is obvious that when the temperature approaches T_c , B_z will progressively decrease to zero. The maximum B_z at the beginning of T are obviously different and the variation tendencies of the field value extracted from the

cross section at different r are different. So the variation of normalized B_z with T is different. Moreover, in the field profiles mentioned above and also those of RPV in previous literatures[24–26], FWHM expands with temperature with similar tendency, which is consistent with our result.

By using scanning Hall probe microscopy and GL simulations, we have studied the magnetic field distribution and the temperature dependence of vortices pinned by both circular antidots and random pinning centers. Our results show that the existence of pinning (antidot) does not affect the temperature dependence of the vortex field distribution above the sample surface (except for a constant prefactor for the magnetic field strength). This field distribution is mainly determined by the penetration depth. Our study is beneficial to explore the interaction between vortex matter and other systems when they are coupled to artificial vortex lattices as magnetic templates.

SUPPLEMENTARY MATERIAL

See supplementary material for FWHM of the magnetic induction profile for vortices pinned by antidots with different sizes ($D = 2.0, 1.5, 1.0$ and $0.8 \mu\text{m}$) and the RPV and the results of GL theory simulation for different “lift-off” distances ($z_0 = 400, 500$ and 600 nm).

We would like to thank V. S. Zharinov for the help in making the sample. The study was supported by the National Key Research and Development Program of China (No. 2018YFA0704300), National Natural Science Foundation of China (Grant No. 11804217), the Methusalem funding by the Flemish government, and the Flemish Science Foundation (FWO). J.-Y. G. also thanks the support by the Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning. V. N. G. acknowledges support from the UA-BOF/FFB 150168 project.

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