Vortex configurations, matching, and domain structure in large arrays of artificial pinning centers

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High-resolution scanning Hall probe microscopy has been used to image vortex configurations in very large periodic arrays of artificial pinning sites. Strong matching effects are seen at fields where either one or two vortices can sit at a site; with three vortices per site, however, no clear matching is observed. Matching effects have been also been observed at several fractional multiples of the matching field, including 1/5, 1/4, 1/3, 1/2, and 3/4. These fractional values are characterized by striking domain structure and grain boundaries.

74.60.Ge, 74.25.Ha, 74.60.Db

The behavior of superconducting vortices in the presence of a periodic array of holes reveals rich and unexpected static and dynamic phenomena. Transport and magnetization studies show distinctive features at matching fields where the vortex structure is commensurate with the hole array. Commensurability can arise from vortex configurations in which each hole contains an integer number of flux quanta, or from interstitial structures where vortices occupy the regions between flux-saturated holes. Interesting configurations also arise at fractional matching fields, where the occupation number of each hole or the number of interstitial vortices forms a superstructure locked to the basic hole array.

Although magnetization and transport studies have elucidated much of the basic phenomenology of the array/vortex system, they can measure only its global properties and cannot deduce details of the local configurational vortex state. More recently Lorentz microscopy has been used to image vortex configurations, but only in relatively small arrays consisting of 13 × 13 = 169 pinning sites. In this paper we present large-area scanning Hall probe microscope (SHM) images of vortex configurations in arrays containing ≈ 10⁶ holes. Our images span some 5000 holes, and so yield important information on the large-scale structure of the vortex configurations. These studies reveal striking multi-quantum and interstitial vortex patterns in a square-periodic hole array. At fractional matching fields we resolve distinctive domains of phase-slip related vortex superstructures that are separated by domain walls with characteristic internal structure.

The SHM uses a large-range scanner yielding ≈ 130 × 130 µm images. The sample investigated was a 100-nm-thick niobium film with 0.3-µm-diameter holes on a square lattice. The lattice constant a of the film was 1.870 µm, yielding an expected first matching field $H_m = \Phi_0/a^2 = 5.913$ G. The array was produced using a lithographic technique based on the interference of light, which yields very large and uniform arrays (here ≈ 2 mm × 3 mm). Near $T_c = 8.37$ K, the array exhibits clear cusps in its magnetization at $H_m$ and 2$H_m$, but not at any higher integral multiples of $H_m$.

SHM images near several matching fields are shown in Fig. 1. For each image, the samples were field-cooled from above $T_c$ to a base temperature below 3 K where the images were taken. The top row of Fig. 1 shows the progression in the vortex configurations as the applied field $H$ is varied around $H = 5.913$ G. The array exhibits clear isolated vortices (dark spots). The actual vortex diameter is much smaller than these spots, whose size is determined by the Hall probe resolution. A somewhat darker spot, just to the right and below center, appears in all scans and is presumably associated with a physical defect in the hole lattice, which allows extra flux to sit at that point. As the field is increased from zero, vortices begin to enter the sample in larger numbers, as seen in the $H = 0.075$ and 0.15 images. A similar progression is observed for negative field increments away from zero, as shown at $H = -0.075$ and −0.15. Here the vortices appear as light spots, indicating that they are oppositely directed to those seen in positive fields.

As we continue to increase the field towards what we will be able to identify as the first matching field $H_m$ ($H = 1$), we begin to see a very remarkable progression (Fig. 1, second row). For instance, at an applied field of $H = 0.85 = 1 - 0.15$, the image looks statistically identical to the image at $H = -0.15$! And, remarkably, the image at $H = 1$ is essentially indistinguishable from that at $H = 0$. It is important to note here that in each image the average value of the field has been subtracted out. This is why the $H = 1$ image at about 6 G and the $H = 0$ image appear to have about the same overall gray
level. We can then understand the appearance of the $\mathbf{H} = 1$ scan as follows. The field increment from an exactly $H = 0$ image (no spots) to the next no-spot image is 5.929 G, very close to the first matching field of 5.913 G deduced from the lattice geometry. Thus we identify this later spot-free image at 5.929 G with the first matching field or $\mathbf{H} = 1$. The smooth gray background near $\mathbf{H} \approx 1$ can then be explained in the following way. Exactly at $\mathbf{H} = 1$, each hole contains exactly one vortex, leading to a dense and uniform configuration of vortices. Evidently the spatial resolution of our Hall probe is not good enough to image individual vortices when they are this close together and perfectly ordered [10], so this regular array of vortices appears as a smooth gray background. The few black spots in the $\mathbf{H} \approx 1$ image are thus (easily visible) extra vortices.

By the same token the white spots in the images at $\mathbf{H} = 0.85$ and 0.925 are not antivortices, as they were in the $-0.15$ and $-0.075$ images. Instead, they are vacancies in a smooth background of filled holes. Since vacancies—holes with no vortex—have a lower (whiter) field than the broad gray areas which are filled with vortices, they appear as dots.

The third row of Fig. 1 shows the vortex configurations as the field is further increased through the second matching field ($\mathbf{H} = 2$). A very similar progression is observed. At $\mathbf{H} \approx 2$, there is again a smooth background populated by a few black spots. Again, we interpret this background as the highly ordered state with now two vortices sitting in each hole: black spots for $\mathbf{H} > 2$ are again extra vortices, and white spots for $\mathbf{H} < 2$ now represent a hole with only one vortex. At the third matching field ($\mathbf{H} = 3$), however, the appearance is radically different (Fig. 1, bottom right). Instead of the smooth gray background we would expect if three vortices sat in each hole, we see a rather muddled image with no discernible structure. We believe this different appearance results from the sudden presence of interstitial vortices above $\mathbf{H} = 2$.

To probe this issue more directly, we have taken closeup scans just below and above $\mathbf{H} = 2$. Figure 2(a) shows a 25 $\mu$m $\times$ 28 $\mu$m scan at a field $\mathbf{H} = 2 - 0.084$, and Fig. 2(b) shows $\mathbf{H} = 2 + 0.084$. Also shown is the least-squares-fit positions of the holes as determined from an image taken at $\mathbf{H} = 1/2$ where the hole positions are unambiguous [see, e.g., Fig. 3(b)]. We also have used an absolute position sensor [1] mounted on the scanner head to compensate for any possible drifts between images. In Fig. 2(a) each white spot (i.e., a “missing” vortex) clearly sits directly on a hole, indicating as well that all vortices also sit on the holes. However, in Fig. 2(b) the black spots, which are now extra vortices, sit variously on holes or on interstitial sites. As is well known, each hole in a film can hold up to a saturation number $n_s$ of vortices [12]; with our material parameters we estimate that $n_s$ is near the boundary between 2 and 3. With the sputtering/lift-off lithography used here [8] there will be inevitable fluctuations in the hole diameter, perhaps yielding $n_s = 2$ for some holes and $n_s = 3$ for others. Vortices nucleating near $n_s = 2$ holes would end up as interstitials, while those near $n_s = 3$ sites could sit in a hole. This random-appearing admixture of vortices on holes and in interstitial sites would, by $\mathbf{H} = 3$, lead to the very disordered configuration observed at that field (Fig. 1).

It is also possible to have matching effects at non-integer multiples of $H_m$. Indeed, distinct features at $\mathbf{H} = 1/4, 1/2$, and possibly 1/5 (or 3/16), 1/8, and 1/16 have been observed in magnetization studies [13,14], and Harada et al. [3] have imaged non-integer matching at 1/4, 1/2, 3/2, and 5/2. In our imaging experiments, we also observe matching effects at several of these fractional fields, as well as some not previously observed. We find that vortex configurations at fractional matching fields are characterized by striking domain structure and associated grain boundaries.

By far the strongest submatching effects occur at $\mathbf{H} = 1/2$. Figure 3(a) shows that the configuration consists of large areas of well-matched vortices separated by curious stripe-like boundaries. The closeup in Fig. 3(b) reveals that the smooth regions consist of vortices occupying every other hole in a checkerboard-like fashion. Regions of different “polarity”—with the vortices occupying either the “red” or “black” squares of the checkerboard—are separated by striped grain boundaries [14]. Fig. 3(c) schematically shows how a polarity shift results in rows or columns of alternating pairs of vortices and vacancies, which appear in the images as the striking boundary features. At the junctions between north-south and east-west boundaries there is always a bright or dark spot, whose origin is again clear from Fig. 3(c). From considerations of the boundaries, we have mapped out the domains of differing polarity [inset, Fig. 3(a)]. One curious feature of these grain boundaries is that they run predominately north-south, indicating a breaking of the square symmetry of the lattice in these two directions. Weaker but still striking matching effects occur at $\mathbf{H} = 1/4$ as well as its complimentary [15] field of $\mathbf{H} = 1 - 1/4 = 3/4$ (Fig. 4). We note immediately that the matching here is much less distinctive than at 1/2, 1, or 2. Nonetheless, there do exist some relatively large ordered domains. Zooming in on the boundary of such a patch [outlined in Figs. 4(a) and 4(b)] allows us to explore the vortex configuration in detail [Figs. 4(c) and 4(d)]. Here we can clearly see areas with well-ordered vortices interspersed with phase slips (diagonal light and dark segments) and other, more complex features. The vortex configuration in the ordered regions is shown to scale schematically in Fig. 4. Notice that the configuration may be viewed in terms of alternating empty and half-filled rows [14]; this again indicates the presence of a symmetry-breaking field which selects this particular grain orientation. One possible source of this asymme-
try could be a small difference in the interhole spacing $a$ in the horizontal and vertical directions. However, no such asymmetry is visible at the $\approx 0.1\%$ accuracy of our optical diffraction measurements of $a$.

Besides the $1/2$, $1/4$, and $3/4$ states already discussed, we have found several other relatively well-ordered states at fractional fillings $0 \leq \overline{H} \leq 1$. Figure 5(a) shows the configuration at $\overline{H} = 1/5$. Although there are no large domains, in much of the image we can observe a general tendency towards forming a structure which consists of a square lattice of vortices tilted by an angle arctan(1/2) $\approx 26.6^\circ$. This structure is shown in detail in the inset. There is also striking structure at $\overline{H} = 1/3$ [Fig. 5(b)]. Here, the configurations consist of slope-one diagonal stripes of (unresolved) vortices separated by two empty diagonal stripes. Such a configuration has been predicted by Watson [10] for the general case of repulsive particles on a square lattice, and by Teitel and Jayaprakash [11] for the related case of vortices in a superconducting wire network [12]. Again, domains with this precise structure are small, and there are a large number of defects present. There is very weak ordering present at $\overline{H} = 2/5$ [Fig. 5(c)], where Teitel and Jayaprakash [11] predict states consisting of two empty diagonals and then a full-empty-full diagonal sequence. This later sequence has the appearance of a checkerboard state, and is barely visible between the bright (empty) diagonal stripes of the inset to Fig. 5(c). Finally, we show an image taken “at” the irrational field $\overline{H} = (\sqrt{5} - 1)/2 \approx 0.618$. No apparent order is present in this case.

Vortex configurations in square-periodic hole arrays thus reveal remarkably complex patterns reflecting the interplay between the pinning energy of the hole array and the interaction energy of the multi-quantum and interstitial flux structures. Our images show clear multi-quantum occupation of the holes up to saturation, followed by the appearance of interstitial Abrikosov vortices at higher fields. At fractional filling factors, domains of well-ordered vortices are separated by a network of domain boundaries displaying remarkably simple order for half filling and increasing complexity at other fillings. There appears to be a nontrivial set of ordered fractional states, a complete inventory of which awaits a general theory correctly incorporating the several competing interactions present. Our Hall probe images thus provide direct visual evidence for a rich diversity of collective ground states arising from competing commensurability, order, and randomness in the vortex phase diagram of periodic hole arrays.

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FIG. 1. SHM images obtained at applied magnetic fields $H$ near the matching fields $\overline{H} \equiv H/H_m = 1, 2$, and 3. The scans are $124 \mu m \times 138 \mu m$, contain some 5000 holes, and have a full scale of 0.73 G. Note the striking similarity between the vortex configurations near $\overline{H} = 1$ and 2 and those near $\overline{H} = 0$. The smooth backgrounds at $\overline{H} = 1$ (2) consist of holes uniformly filled with 1 (2) vortices. At $\overline{H} = 3$, however, the vortex configuration is highly disordered because of weakly-pinned interstitials competing with vortices in holes. The dark black spot is a local defect in the sample.

FIG. 2. Vortex configurations (a) just below $\overline{H} = 1.916$ and (b) just above $\overline{H} = 2.084$ the second matching field. The small dark circles are the positions of the holes. Below $\overline{H} = 2$ the vacancies (white spots) all sit directly on holes; thus all vortices must as well. Above $\overline{H} = 2$, the extra vortices (dark spots) sit on both hole and interstitial sites.

FIG. 3. (a) Vortex configuration at $\overline{H} = 1/2$. There are large areas of vortices arranged in a checkerboard pattern; domains [outlined in inset to (a)] of opposite checkerboard polarity are separated by stripe-like grain boundaries. A closeup of this configuration is shown in (b) and schematically in (c).
FIG. 4. Vortex configurations at $H = 1/4$ (a) and $3/4$ (b). Selected regions are expanded in (c) and (d). The configurations consist of relatively small well-ordered regions surrounded by complex disordered boundaries. Also shown are the inferred vortex arrangements in the ordered regions. Light circles represent empty holes, and dark circles occupied holes.

FIG. 5. Vortex configurations at several fractional values of $H$. Also shown is the “irrational” field $\phi = (\sqrt{5} - 1)/2$. 
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