Magnetic dipole induced guided vortex motion

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We present evidence of magnetically controlled guided vortex motion in a hybrid superconductor/ferromagnet nanosystem consisting of an Al film on top of a square array of permalloy square rings. When the rings are magnetized with an in-plane external field $H$, an array of point-like dipoles with moments antiparallel to $H$, is formed. The resulting magnetic template generates a strongly anisotropic pinning potential landscape for vortices in the superconducting layer. Transport measurements show that this anisotropy is able to confine the flux motion along the high symmetry axes of the square lattice of dipoles. This guided vortex motion can be either re-routed by 90 degrees by simply changing the dipole orientation or even strongly suppressed by inducing a flux-closure magnetic state with very low stray fields in the rings.

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During the last years there has been a considerable effort to conceive and realize new superconducting devices that allow to modulate locally the magnetic fields practically at will [1]. These systems rely essentially on either static arrays, such as pinning centers [2] [3] [4] [5] and vortex-antivortex generators [6] [7], or components influencing the vortex dynamics like channels [8] [9] [10] [11] and ratchets [12] [13]. The ultimate motivation behind the manipulation of the local vortex density is to enhance the performance of superconductor-based devices by reducing the noise in squid-based systems [14] [15], gaining control on superconducting THz emitters [16] or even providing a way to predefine the optical transmission through the system [17].

Unfortunately, for the majority of the components used in fluxonics devices, once they are created there is no margin for further modifications. In some cases this lack of flexibility becomes a limiting factor in the performance of the devices. For instance, a predefined ratchet system designed to effectively remove vortices from a specific location can work properly at low fields but ignores the inevitable reversed ratchet at higher fields thus making its functionality rather impractical [12] [13] [18] [19]. A way to circumvent this shortcoming can be worked out by introducing magnetic pinning centers which have additional internal degrees of freedom not available in conventional nanostructured pinning sites or defects created via irradiation.

In this work we demonstrate that reversible and switchable guidance of the vortex motion can be achieved using a square array of magnetic square rings lying underneath a superconducting film. Transport measurements unambiguously show that the vortex dynamics is fully dominated by the magnetic landscape generated by the ring structures. When the magnetic unit cell is rotated 45 degrees off the Lorentz force $F_L$ the average vortex velocity $v$ follows the direction of the principal axis of the magnetic lattice rather than the driving force. This channeling effect can be easily suppressed when inducing a nearly isotropic pinning landscape by setting the square rings in a flux-closure state with very low stray fields.

The two samples used for this investigation consist of a 50 nm thick Al film evaporated on top of a checker-board (CB) patterned array and a close-packed (CP) square array of permalloy square rings with lateral size 1 $\mu$m, line width 150 nm and thickness 25 nm [Fig. 1(a) and (b)]. The magnetic template is electrically separated from the superconducting film by a 5 nm Si buffer layer added to reduce proximity effects. The ring-shaped patterns and the transport bridge were fabricated with electron-beam lithography and lift-off technique on a silicon substrate. A superconducting coherence length $\xi(0) \approx 130$ nm for the $CB$ sample and $\xi(0) \approx 138$ nm for the $CP$ sample was estimated from the superconducting/normal phase boundary as determined by 10% normal state resistance criterion of a coevaporated reference film. The superconducting critical temperature at zero field for the CB and CP sample in the onion state (i.e. maximum stray field) is $T_c = 1.356$ K and $T_c = 1.274$ K, respectively.

It has been shown recently that multiply connected magnetic structures make it possible to readily switch between different magnetic states [20] [21]. For the particular square geometry chosen in this work, an in-plane external field along the diagonal of the squares can induce six different domain distributions [22], namely four dipolar states (onion states) obtained at remanence after saturation and two flux-closure states with opposite chirality when the field is reduced from saturation to $\pm 36$ mT and then set to zero. Interestingly, when these rings are placed in close proximity to a superconducting layer, either a strong vortex pinning or weak pinning can be obtained by simply switching from onion to flux-closure
state, respectively. Although the influence of these magnetic templates on the vortex pinning is relatively well understood [23], little is known about their influence on the vortex dynamics.

In order to address this issue we carried out transport measurements recording simultaneously the electric field parallel ($E_{xz}$) and perpendicular ($E_{xy}$) to the external current. This allows us to estimate the direction $\alpha$ (see Fig.1) of the average vortex motion $\mathbf{v}$ with respect to the Lorentz force $\mathbf{F}_L$. Notice that in contrast to previous works studying the in-plane angular dependence of the vortex motion [9,10,11] where the orientation of the driving force was changed by combining two independent current sources, our ability to change the potential landscape \textit{in-situ} allows us to use a simpler setup where the current orientation is kept constant. In all cases unwanted contributions to the measured signal like thermoelectric coupling, Hall resistance and misalignment of the transverse voltage contacts are small and have been properly taken into account.

A representative set of experimental data for the CB sample [Fig.1(a)] and different magnetic states of the square rings is shown in Fig.2 at $T/T_c = 0.89$. Fig.2(a) shows the electric field-current density ($E-J$) characteristic for the case when the squares have been set in the onion state magnetized 45° away from the current direction [see inset in panel (a)] and setting an out-of-plane field $H/H_1 = 1.2$ where $H_1 = \Phi_o/d^2$, with $\Phi_o$ the flux quantum and $d$ the period of the lattice. From Fig.2(a) it can be seen that for low enough currents ($J < 8$ MA/cm$^2$) the vortex lattice remains pinned as no dissipation is detected in either direction ($E_{xz} = E_{xy} \approx 0$). Surprisingly, for currents higher than the critical current the direction of vortex motion does not coincide with the Lorentz force. More specifically since $E_{xx} \approx E_{xy}$ vortices move at an angle $\alpha = 45^\circ$ as indicated in the inset of Fig.2(a). This is a clear evidence that the net displacement of the vortices is along the high symmetry axis of the magnetic pinning landscape indicated with a dashed line in Fig.1(a) and (b). Essentially this effect is the result of an anisotropic depinning force $F_{dp}$ which reaches its maximum $F_{dp}^\perp$ (minimum $F_{dp}^\parallel$) value perpendicular (parallel) to the channel direction defined by the principal axes of the magnetic landscape. In Fig.2(a), since the applied force is in this case 45° away from the channel direction, the critical current $J_{c2}$ at which vortices start moving is determined by the condition $J_{c2} = F_{dp}^\parallel \sin(45^\circ)/\Phi_o$. This situation persists up to $J_{c2} \approx 25$ MA/cm$^2$ where $E_{xy}$ and $E_{xx}$ gradually separate from each other which means that now the component of the Lorentz force perpendicular to the channels is large enough to overcome $F_{dp}^\perp$, i.e. $J_{c2} = F_{dp}^\perp \cos(45^\circ)/\Phi_o$, and vortices flow along the direction of the Lorentz force. This allows us to estimate the ratio of depinning forces as $F_{dp}^\perp/F_{dp}^\parallel = J_{c2}/J_{c1} \approx 3$.

By keeping a constant current density and progressively increasing the applied field it is possible to realize the same dynamic behaviors, as shown in Fig.2(b). For the low current density $J = 0.005$ MA/cm$^2$ vortices remain pinned up to a field $H/H_1 \approx 1.5$ where the vortex-vortex interaction becomes stronger than the vortex-pinning interaction. At higher fields clear commensurability effects can be seen for $H/H_1 = 2$ and $H/H_1 = 3$. In this field region ($H/H_1 < 4$) the fact that $E_{xx} \approx E_{xy}$ indicates that vortices are guided by the pinning potential as described above.

These findings clearly demonstrate that under certain conditions the vortex motion can be effectively guided along the principal axes of the underlying pinning potential, but tell us little about the origin of this pinning potential. In other words, it is necessary to find out whether the guided vortex motion (GVM) is resulting from the magnetic landscape or from the corrugation of the superconducting film deposited on top of the squares. In order to answer this question we magnetized the square rings with an in-plane field 135° away from the current direction (0°) as shown in the inset of Fig.2(c). In this way the topographic pinning remains the same whereas...
FIG. 2: (color on-line) Parallel ($E_{xx}$) and transverse ($E_{xy}$) electric field as a function of current density $J$ (upper row) and field (lower row) at $T/T_c = 0.89$. The first column [panels (a) and (b)] corresponds to the square rings magnetized at 45° as indicated in the inset of panel (a). The second column [panels (c) and (d)] presents the data for the square rings magnetized at 135°, as indicated in the inset of panel (c). The third column [panels (e) and (f)] corresponds to the squares in the vortex state, as indicated in the inset of panel (e).

If the magnetic landscape is responsible for the GVM then a channeling along the -45° direction with respect to $\mathbf{F}_L$ should be detected. This is in agreement with the results shown in Fig. 2(c) and (d), where $E_{xx}$ remains unchanged while $E_{xy}$ reverses sign. The most convincing evidence however comes from panels (e) and (f) corresponding to the square rings in the flux-closure state. In this case the stray field generated by the domain walls in each square ring is reduced to a minimum level and as a consequence it is expected a minor influence from the magnetic landscape on the vortex dynamics. This is indeed corroborated by the lack of guided motion as is evidenced by the condition $E_{xx} >> E_{xy}$.

It is worth to note that the fact that for the same geometry of the pinning lattice the GVM reverses sign when switching the dipole orientation from 45° to 135°, clearly points out the relevance of the local symmetry of the pinning centra. However, the question arises whether the geometry of the pinning lattice plays any role in the vortex guidance. In order to tackle this issue we have changed the lattice geometry from the checker-board pattern to a close-packed array [see Fig. 1(b)]. In this way we maintain a square lattice of nearly point-like dipoles oriented at 45° away from the current direction but change the lattice period from 1.5 $\mu$m to 1.07 $\mu$m. In addition, the unit cell of the dipolar lattice is rotated by 45° as illustrated in Fig. 1(a) and (b) with dashed lines.

The $E - J$ characteristics and the field dependence of the electric field for this sample with the square rings in the onion state are shown in Fig. 3 for similar experimental conditions shown in Fig. 2. Strikingly, the resulting measurements indicate the lack of vortex guidance (i.e. $E_{xx} >> E_{xy}$) at all temperatures and fields explored ex-
FIG. 3: (color on-line) Parallel ($E_{xx}$) and transverse ($E_{xy}$) electric field as a function of current density $J$ (upper panel) and field (lower panel) at $T/T_c = 0.94$ for square rings in a close-packed array and magnetized at $45^\circ$ as indicated in the inset.

Experimentally, this clearly demonstrate the relevance of the particular orientation of the magnetic unit cell for the GVM.

In order to understand the origin of the guided vortex motion lets first hypothetically separate the different contributions arising from the lattice symmetry and from the local symmetry of the dipoles. This is schematically illustrated in panel (c) and (d) of Fig. 1 for the checker-board and close-packed arrays, respectively. In order to unveil the lattice symmetry contribution we can assume that each dipole behaves as an effective isotropic pinning center, very much like a lattice of circular antidots or magnetic dots. In this case it has been previously shown [10] that the minimum pinning force is along the principal axes of the pinning lattice [broken line in Fig. 1(c) and (d)]. On the other hand, ignoring the presence of the lattice and just considering the pinning force produced by one single dipole gives rise to a strongly anisotropic pinning force [schematically displayed as an off-centered circle in Fig. 1(c) and (d)]. It is precisely the lack of inversion symmetry of the dipolar stray field which makes these structures efficient ratchet systems as well [25, 26]. The solid line in Fig. 1(c) and (d) shows the resulting pinning force combining both effects: the four-fold symmetric lattice contribution and the non-symmetric local magnetic field. It is clear from this analysis that the presence of the non symmetric magnetic landscape lifts the degeneracy expected in the channeling of the CB sample [see Fig. 1(c)] as experimentally observed. Moreover, the lack of guided motion in the CP sample for the used current direction is also expected since the minimum of the pinning force is along the direction of the Lorentz force [see Fig. 1(d)], irrespective of the asymmetries introduced by the magnetic dipoles. It should be emphasized that although the above description helps to identify the basic mechanisms behind the guided motion of vortices, it is derived from the unphysical assumption that magnetic and non-magnetic contributions are separable.

In summary, we have reported experimental evidence indicating that the anisotropic potential landscape of a square array of magnetic dipoles is capable of directing the vortex motion $45^\circ$ degrees away from the driving force direction. The multiple states of the used magnetic rings allow us to switch this direction ($\pm 45^\circ$ for two different dipolar states and $0^\circ$ for the flux-closure state) resulting in a control of the transverse voltage signal. The contrasting behavior of the two different lattices explored (checker-board and close-packed arrays) demonstrate that the guidance of vortices is not only a consequence of the dipole orientation relative to the driving force direction but that also the orientation of the square lattice unit cell is important.

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