Biologically-inspired Devices for Easily Controlling the Motion of Magnetic Flux Quanta

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Abstract

Motor proteins employ non-equilibrium fluctuations in anisotropic media to transport cargo at the cellular level. Here we consider anisotropic pinning to transport magnetic flux quanta inside superconductor. In particular, we consider: (1) composite pins by superimposing two interpenetrating arrays of weak and strong pinning centers; (2) triangular blind antidots; (3) V-shaped pinning sites. Specifically, we study stochastic transport of fluxons by alternating current (AC) rectification. Our simulated systems provide fluxon pumps, or fluxon "rectifiers", because the applied electrical AC force is transformed into a net DC motion of fluxons. The asymmetry of the ratchet-shaped pinning landscape induce this "diode" effect, which can have important applications in devices, like SQUID magnetometers, and for fluxon optics, including convex and concave fluxon lenses.

Key words: Superconducting vortex dynamics, Flux pinning, Devices for the control of vortex motion.

Motor proteins (e.g., kinesins, dynesins, myosins) play a key role in the transport of materials at the cellular level [1]. These biological motors are examples of Brownian motors that, driven by non-equilibrium fluctuations, bias the Brownian motion of particles in an anisotropic medium. Here we consider superconducting devices that are inspired by these biological motor proteins. These take advantage of anisotropic pinning, in order to *control* the transport of flux quanta [2–4].

Here, we present numerical simulations of the stochastic rectification of AC-driven superconducting vortices interacting with three different types of pinning potentials (shown in Fig. 1): (a) composite pins of two interpenetrating triangular arrays of weak and strong pinning centers; (b) triangular arrays of triangular blind antidots and (c) triangular arrays of V-shaped pinning sites.

All pinning centers in Fig. 1(a) and the boundaries of the triangular pinning antidots in Fig. 1(b) and the boomerang pinning centers in Fig. 1(c) are modelled by Gaussian potentials [4,5] with a decay length R_p.

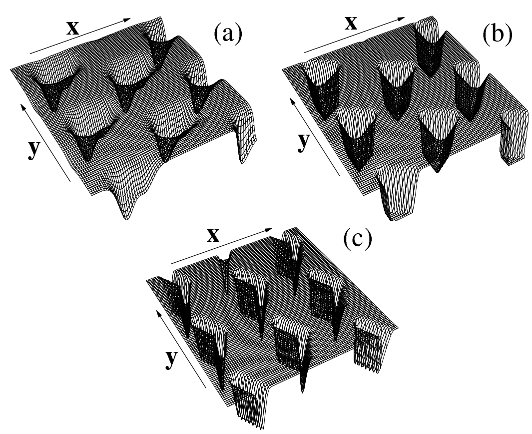

Fig. 1. Pinning potentials $U_p(x, y)$ of (a) composite pins, (b) triangular blind antidots and (c) V-shape for a small subset of the triangular pinning lattices.

The spacing parameter of the triangular pinning arrays is a_0. The applied square-wave AC driving Lorentz force acting on the vortices is parallel to the x-axis, i.e.,

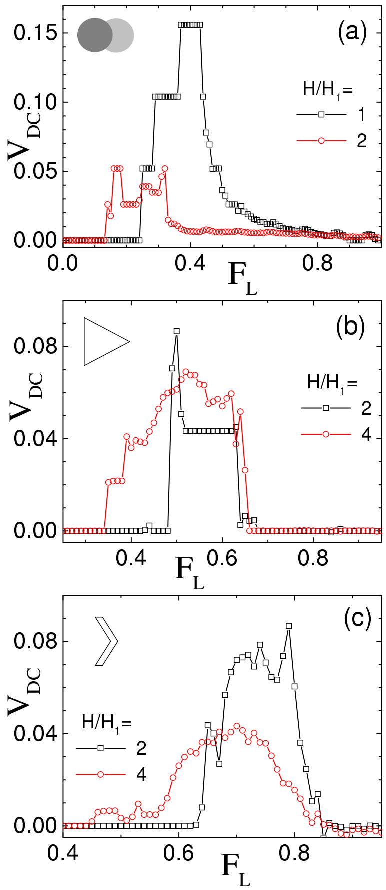

Fig. 2. Net average vortex velocity V_{DC} versus the amplitude F_L of the AC driving force: (a) composite pins, with $P = 2500\tau_0$ for $H/H_1 = 1$ and 2. Here, $a_0 = 1$ and the intrapin separation is $d = 0.2a_0$ ($\tau_0 = 0.0067$, $R_p = 0.13a_0$, $F_{vv0} = 0.1$, $F^s_{p0} = 0.5$, $F^s_{p0}/F^w_{p0} = 2$). (b) triangular blind antidots, with $P = 2000\tau_0$, for $H/H_1 = 2$ and 4. Here, $a_0 = 12$ and the side length of the equilateral triangle is $s_0 = 3$ ($\tau_0 = 0.03$, $R_p = 0.4$, $F_{vv0} = 0.1$, $F_{p0} = 1$). (c) Boomerang pins, with $P = 2000\tau_0$ for $H/H_1 = 2$ and 4. Here, $a_0 = 12$ and the length of each boomerang wing is $s_0 = 3$ ($\tau_0 = 0.03$, $R_p = 0.4$, $F_{vv0} = 0.1$, $F_{p0} = 1$, and the angle between the two wings in each boomerang is $\alpha = 2\pi/3$).

$\mathbf{F}_L = F_L(t)\hat{\mathbf{x}}$. The repulsive vortex-vortex interaction is modelled by a logarithmic potential. The equation of motion for each vortex is given by $\eta\mathbf{v} = \mathbf{F}_L + \mathbf{F}_{vv} + \mathbf{F}_p$. A detailed description of these asymmetric models, simulations and analytical results is in [4,5].

Here, we focus on the study of the net average DC velocities $V_{DC}(F_L)$ of the AC driven vortices. We have observed non-trivial voltage responses in these structures. These can be used for devices controlling the motion of magnetic flux quanta.

In the case of composite asymmetric pinning arrays, seen in Fig. 2 (a), with the increase of the amplitude F_L of the square-wave AC driving force, we find optimal F_L values for the DC response for $H/H_1 = 1$ and 2, with half-period $P = 2500\tau_0$. When F_L is smaller than a critical value F_m, all trapped vortices cannot be depinned and no DC response can be measured. The amplitudes of the AC driving force that maximize the DC response are dependent on the ratio of the densities of vortices and pins. When $H/H_1 = 1$, the critical depinning force for the vortex motion is maximum and the rectifying or ratchet effect is most efficient for all the vortices, which reach the highest net DC velocities, as seen in Fig. 2 (a). The flat plateaus and the very small oscillations in V_{DC} are both due to the fixed period of the AC driving force used here: each successive plateau corresponds to an additional pinning site explored by an increasing F_L. A larger amplitude F_L will force the vortices to cross many pinning sites, producing plateaus for each crossed pinning site. These turn into mild oscillations when the driving force F_L is strong enough. Additional related results can be found in Ref. [4].

In the case of triangular blind antidots (Fig. 1 (b)) and the boomerang pinning system (Fig. 1 (c)), Fig. 2(b)$-$(c) show the net average DC velocities of the driven vortices for $H/H_1 = 2$ and 4, respectively.

We want to emphasize that the pinning potential in each unit of the composite-pin model (Fig. 1(a)) has an intrinsic asymmetry, i.e., the critical depinning force for a trapped vortex depends on the orientation of the driving force. However, in the case of the triangular blind antidots and the boomerang pinning centers, for a single vortex trapped in one pinning unit, the critical depinning force is non-angular dependent, which results in a trivial *zero* average DC velocity at the *first* matching field. For magnetic fields larger than $H/H_1 = 1$, due to the asymmetric structure of the triangular blind antidots and the boomerang pinning structures, the vortex-vortex interaction between the multi-trapped vortices inside the same pinning centers produces an angular-dependent depinning force for the vortices. This results in a non-trivial DC voltage when $H/H_1 > 1$, as shown in Fig. 2 (b) and (c).

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