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Vortex lattice in effective type-I superconducting films with periodic arrays of submicron holes

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Abstract

The vortex matter and related phenomena in superconducting films with periodic arrays of microholes (antidots) are studied within the nonlinear Ginzburg–Landau (GL) theory. By varying the GL parameter κ, the vortex–vortex interaction is fine tuned, from repulsive to attractive behavior. This interaction is of crucial importance for equilibrium vortex structures, the saturation number of the antidots, and the related quantities, such as critical current. Due to vortex attraction in effectively type-I samples, the giant-vortex state becomes energetically favorable (contrary to the type-II behavior). For the same reason, the number of vortices which can be captured by antidots, increases with decreasing κ. As a result, for given magnetic field, the critical current is larger for effectively type-I superconductors than in conventional type-II cases.

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Keywords: Superconducting film; Antidot; Vortex pinning

1. Introduction

The increase and, more generally, control of the critical current in superconductors by including artificial pinning centers are of great importance for practical applications of superconducting (SC) materials. During the past decade much attention was given to the study of superconducting films with arrays of antidots which have a profound influence on both the critical current and the critical magnetic field [1–3]. Direct imaging experiments [4] of vortex structures in regularly patterned superconducting films have shown that the vortices form highly ordered configurations at integer and at some fractional matching fields. These commensurability effects between the pinning array and the vortex lattice are responsible for a very strong vortex pinning, resulting in a significantly increased critical current. Recently, an effort has been made to strengthen vortex pinning using the quasiperiodic pinning arrays [5], as well as composite antidot lattices [6], with the same governing idea of hindering vortex motion.

All previous studies have confirmed that vortices at interstitial sites have a higher mobility and are responsible for the sharp drop in the critical current [1]. In this respect, the maximal occupation number of the antidots plays a very important role, together with the vortex–vortex interactions. Most of the experiments on perforated superconducting films are carried out in effective type-II limit ($\kappa_{\text{eff}} = \kappa^2/d \gg 1/\sqrt{2}$, d being the thickness of the SC film in units of coherence length ξ). In this regime, the vortices act like charged point particles, and their interaction with periodic pinning potential can be described using a molecular dynamic simulations [7]. However, the overlap of vortex, and the exact shape of the inter-vortex interaction (depending on the properties of the SC material reflected through the Ginzburg–Landau (GL) parameter κ), may significantly change the vortex structures and the critical current.

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Therefore, in this paper we investigate effective type-I superconducting films ($\kappa_{\rm eff} < 1/\sqrt{2}$) patterned with a square array of circular holes. Our theoretical study is made within the nonlinear GL theory, where all parameters relevant to the superconducting state are taken into account.

2. Approach used

We consider a thin superconducting film immersed in an insulating media with a perpendicular uniform applied field H (see Fig. 1). For the given system we solved nonlinear GL equations in dimensionless units (see Ref. [8] for more details):

$$(-i\vec{\nabla} - \vec{A})^2\psi = \psi(1 - |\psi|^2), \tag{1}$$

$$-\kappa_{\rm eff}\Delta\vec{A} = \frac{1}{2i}(\psi^*\vec{\nabla}\psi - \psi\vec{\nabla}\psi^*) - |\psi|^2\vec{A} \tag{2}$$

for the order parameter ψ and the vector potential $\vec{A}$. The magnitude of the applied field H is determined by the number of quantum fluxes piercing through the simulation region. While the Neumann boundary condition is applied on the antidot edges, we use periodic boundary conditions at the edges of the square $W_{\rm s} \times W_{\rm s}$ simulation region. They have the form [9]:

$$\vec{A}(\vec{\rho} + \vec{b}_i) = \vec{A}(\vec{\rho}) + \vec{\nabla}\eta_i(\vec{\rho}), \tag{3}$$

$$\Psi(\vec{\rho} + \vec{b}_i) = \Psi\exp(2\pi i\eta_i(\vec{\rho})/\Phi_0), \tag{4}$$

where b_i, $i = x, y$ are lattice vectors, η_i is the gauge potential, and Φ_0 is the flux quantum. We use the Landau gauge $\vec{A}_0 = Hx\vec{e}_y$ for the external vector potential and $\eta_x = HW_{\rm s}y + C_x$, $\eta_y = C_y$, with C_x, C_y, being constants. Generally speaking, depending on the geometry of the antidot lattice, one must minimize the energy with respect to the latter coefficients. The size of the supercell in our calculation is typically 4×4 unit cells (containing 16 holes, i.e. $W_{\rm s} = 4W$). We solved the system of Eqs. (1) and (2) self-consistently using the numerical technique of Ref. [8]. In order to calculate the critical current, first we determine the ground vortex state for a given applied magnetic field starting several times from a randomly generated initial distribution of the Cooper-pairs. Then the applied current in the x-direction is simulated by adding a constant $A_{\rm cx}$ to the vector potential of the applied external field [10]. With increasing $A_{\rm cx}$, the critical current can be reached, where no stationary solution of Eqs. (1) and (2) can be found since a number of vortices is driven in motion by the Lorentz force. The current j_x in the sample resulting from applied $A_{\rm cx}$ is obtained after integration of the x-component of the induced supercurrents (calculated by Eq. (2)) in the $y = $ const. line across the sample. The maximal achievable value of j_x is the critical current $j_{\rm c}$.

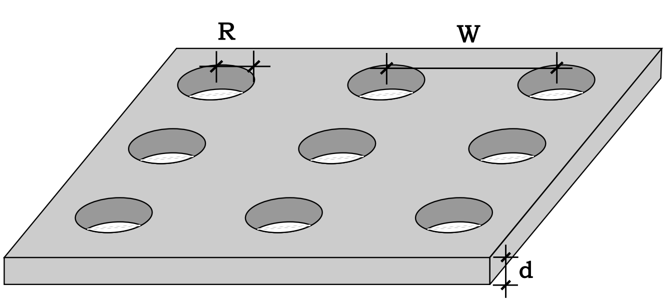

Fig. 1. Schematic view of a superconducting film (with thickness d) patterned with a regular array (periodicity W) of circular antidots (with radius R).

3. The vortex structure at matching fields

Here, we investigate the vortex structure of a sample of thickness $d = 0.1\xi$, radius of antidots $R = 1.2\xi$, and period of the antidot lattice $W = 6\xi$ (see Fig. 1). When speaking of type-II sample, GL parameter $\kappa = 1$ (i.e. $\kappa_{\rm eff} = 10$) will be used, whereas the type-I sample has $\kappa = 0.1$ (i.e. $\kappa_{\rm eff} = 0.1$). No external drives are applied, and the sample is exposed to a homogeneous magnetic field H. To find the different vortex configurations, which include the metastable states, we search for the lowest energy solutions of Eqs. (1) and (2) starting from different randomly generated initial configurations. We will restrict ourselves to the cases when the number of external flux lines piercing through the sample is the integer multiple of the number of antidots (the so-called "matching" fields).

3.1. Ground state configurations: type-I vs. type-II

Fig. 2 shows the contourplots of the Cooper-pair density for both samples, type-II (left column) and type-I (middle column, with the corresponding phase contourplots shown on the right), for first, second, third and fourth matching field. As can be seen from Fig. 2(a)–(d), each antidot pins exactly one vortex. For fields larger than the first matching field, the remaining vortices sit at interstitial sites. The final configuration of the flux lines piercing the interstitials is determined not only by their mutual repulsion, but also by the attraction by antidots and the repulsion by there pinned vortices. Therefore, at matching fields, instead of the Abrikosov lattice, we obtain square-shaped lattices of individual flux-lines (see Fig. 2(c) and (d)). Note that these configurations agree with the ones observed experimentally [4] using Lorentz microscopy.

When the GL parameter κ is decreased, the expulsion of the magnetic field from the superconductor is enhanced resulting in a higher occupation number of the antidots. Furthermore, the vortex–vortex interaction gradually changes *from repulsive to attractive* (depending on ln κ). This again favors capturing more than one vortex in the antidot. As can be seen from Fig. 2(e)–(h), the occupation number of each hole is increased to two in the type-I sample. Moreover, due to the inter-vortex attraction, *giant vortices* become energetically favorable (see Fig. 2(h) and (l)), contrary to conventional behavior.