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Triangular arrangement of defects in a mesoscopic superconductor

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ABSTRACT

By solving the time dependent Ginzburg–Landau equations, we investigated the influence of an internal triangular arrangement of point-like defects on the vortex configurations in a thin mesoscopic sample. The effect of the number of internal defects and their nature on the entrance position of the vortex is studied for a very thin circular sample. We found that the interplay between the vortex–vortex repulsion, the vortex–defect interaction and the interaction with the sample border leads to non-commensurate vortex configurations.

1. Introduction

A mesoscopic sample size is closed to the coherence length $\lambda(T)$ and/or penetration length $\xi(T)$, thereby involving some significant modifications to the physical properties of the superconducting state due to confinement effects. Therefore, for such mesoscopic samples, nucleation of the superconducting state depends strongly on the topology of the system [1]. Many different topologies have been studied experimentally and theoretically, i.e., simple single loops [2–4], disks [5–9], circular wedges [10–16], surface roughness and surface defects [17–20]. All these superconducting structures have attracted attention as potential new components for low-temperature electronics. In the present paper, by solving the non-linear time dependent Ginzburg–Landau (TDGL) equations, we calculate the magnetization, Gibbs free energy, vorticity and the superconductor electron density for a thin disk for two values of the number of point-like defects (small dots or anti-dots), namely, $n_d = 3{,}6$ forming a triangular arrangement inside the sample. The paper is outlined as follows. In Section 2 we present the theoretical formalism which was used in order to find the vortex configuration, vorticity, free energy and magnetization. Next, in Section 3 we present the results and discussions. Finally, in Section 4 we present the conclusions.

2. Theoretical formalism

We consider a thin superconducting disk immersed in an insulating medium in the presence of a perpendicular uniform magnetic field H_0. Using dimensionless variables, we write the system of the time dependent Ginzburg–Landau equations for the order parameter ψ and the vector potential $\boldsymbol{A}$ in the following form:

$$\frac{\partial\psi}{\partial t} = -(i\nabla + \boldsymbol{A})^2\psi + \psi(|\psi|^2 - 1) \tag{1}$$

$$\frac{\partial \boldsymbol{A}}{\partial t} = \mathrm{Re}[\bar{\psi}(-i\nabla - \boldsymbol{A})\psi] - \kappa^2\nabla\times\nabla\times\boldsymbol{A} \tag{2}$$

where T is the temperature in units of the critical temperature; lengths are in units of $\xi(T)$, and fields in units of $H_{c2}(T)$, the upper critical field; κ is the Ginzburg–Landau parameter which is material dependent; Re indicates the real part of a complex variable and the overbar means the complex conjugation; (for more details, see Refs. [21,22]). Here, we will neglect the z-dependence on the order parameter. This is reasonable for thickness of the disk d much smaller than the coherence length. Notice that Eqs. (1) and (2) are gauge invariant. Let $\mathbf{n}$ be an unit vector normal to the interface and directed outward the superconducting domain. We will assume that the normal current density vanishes at the interface, that is, $(-i\nabla - \boldsymbol{A})\psi\cdot\mathbf{n} = 0$, simulating a superconductor/vacuum interface. In order to solve Eqs. (1) and (2) we used the link variables approach as it was adapted for circular geometries as described in Ref. [5]. The grid used for the discretization of the TDGL equations on a circular sector and the other physical quantities, such as magnetization, free energy, vortex number, can be found in more detail in Ref. [5]. Let a thin superconducting disk domain be given by $\{(x,y,z)\in R^3: (x,y)\in R^2, |z| < d\ g(x,y)\}$, for all (x,y). Here, $g(x,y)$ is some function which describes the topology of the top surface of the disk. According to Refs. [23–25] the TDGL equations can be reduced to:

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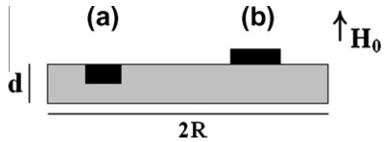

Fig. 1. Schematic side view of the sample: a superconducting disk of radius R and thickness d, with n_d point defects. $g = 1.0$ everywhere, except for (a) $g = 0.5$ simulating an anti-dot, (b) $g = 1.2$ simulating a dot.

$$\frac{\partial\psi}{\partial t} = -\frac{1}{g}(i\nabla + \mathbf{A}_0)\cdot g(i\nabla + \mathbf{A}_0)\psi + \psi(1 - |\psi|^2) \tag{3}$$

where the magnetic field is nearly uniform inside the superconductor, that is, $H_0\hat{z} = \nabla\times\mathbf{A}_0$. For the case of a thin disk, we take the function $g = 1$ everywhere, except in some points inside the disk where we use $g \neq 1$, simulating the presence of a small anti-dot ($g = 0.5$) and dot ($g = 1.2$) inside the sample (see Fig. 1).

3. Results and discussion

We solve the time dependent Ginzburg–Landau equations in order to obtain the vortex configuration in a mesoscopic superconducting disk of radius $R = 6.5\xi(T)$, thickness $d \ll \xi,\lambda$ with n_d defects distributed forming a triangular array. We consider the three following scenarios:

Case 1: $n_d = 3$ such that one defect is dot and two defects are anti-dots;

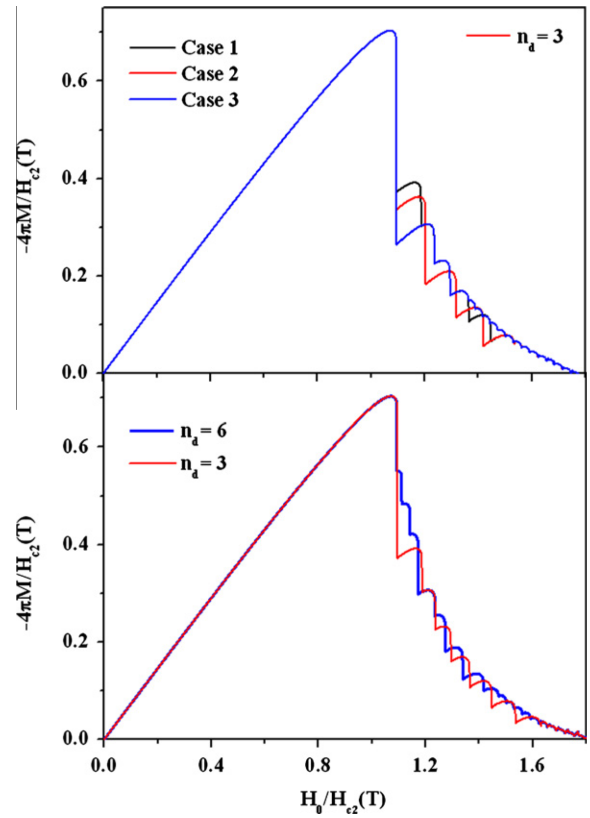

Fig. 3. Magnetization curves as a function of external magnetic field for the same situations as in Fig. 2.

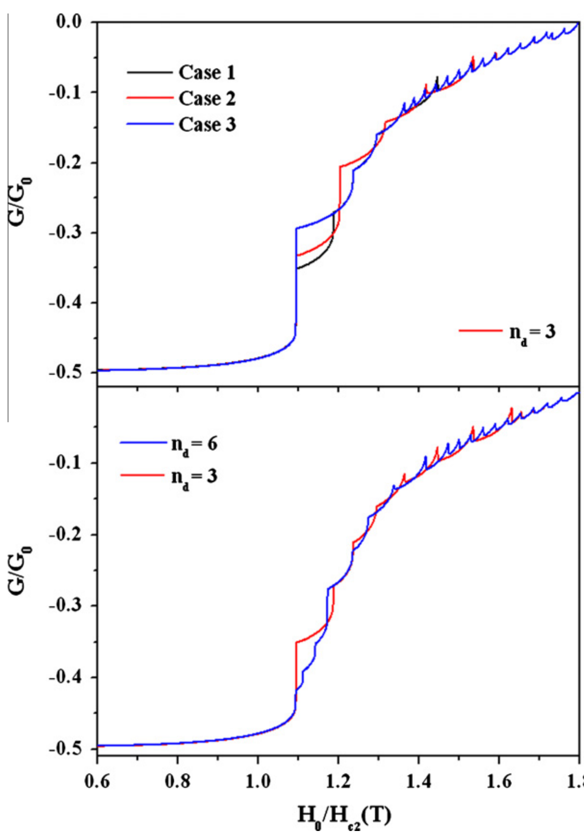

Fig. 2. Energy as a function of the applied field for a disk with radius $R = 6.5\xi(T)$: (Up) for $n_d = 3$ for all cases specified in the text, however, for case 3 we considered the defects as dots; (Down) for $n_d = 3,6$ as anti-dots (Case 3).

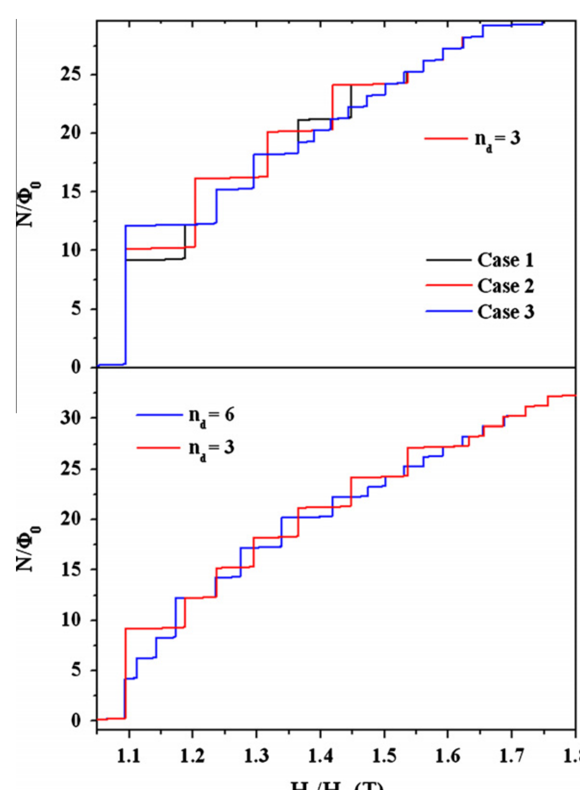

Fig. 4. Vorticity curves as a function of external magnetic field for the same situations as in Fig. 2.