Physics Letters A 379 (2015) 3130–3135

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Superconducting properties of a mesoscopic parallelepiped with anisotropic surface conditions

J. Barba-Ortega [a,*], Edson Sardella [b,c]

[a] Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia
[b] UNESP-Universidade Estadual Paulista, Departamento de Física, Caixa Postal 473, Bauru-SP, Brazil
[c] UNESP-Universidade Estadual Paulista, IPMet-Instituto de Pesquisas Meteorológicas, CEP 17048-699 Bauru, SP, Brazil

ARTICLE INFO

Article history:
Received 19 May 2015
Received in revised form 9 October 2015
Accepted 10 October 2015
Available online 20 October 2015
Communicated by L. Ghivelder

Keywords:
Ginzburg–Landau
De Gennes parameter
Mesoscopic
Anisotropic surfaces

ABSTRACT

We consider a mesoscopic superconducting parallelepiped with different boundary conditions on different parts of the surface, xy, xz and yz surface planes. This is realized by considering different values of the de Gennes extrapolation length b on different surfaces of the sample. Our investigation was carried out by solving the three-dimensional (3D) time dependent Ginzburg–Landau (TDGL) equations. We studied the local magnetic field, order parameter, and both the magnetization and vorticity curves as functions of the external applied magnetic field for different values of b on the surfaces of the sample. We show that this surface anisotropy has very strong influence on the vortex configurations and the magnetization as a function of the external applied magnetic field, both experimentally accessible.

1. Introduction

A very important consequence to consider a 3D superconductor sample in a homogeneous external applied magnetic field is the demagnetization effect. The study of such systems by using the 3D TDGL equations requires an enormous computational effort. However, from the quantitative point of view it is much more advantageous than the two-dimensional (2D) TDGL model, since we obtain precisely the critical fields, the vortex configurations, energy and magnetization stability curves, etc. There are many experimental (see for instance [1–6]) and theoretical (see for instance [7–10]) studies for 3D systems. In all these theoretical studies, the Ginzburg–Landau model has been proven to give a good account of the superconducting properties in samples of several geometries, i.e., disks with finite thickness and spheres [11,12], shells [13], cone [14], thin circular sectors, thin disks and SQUID geometry [15–18].

As is well-known from the microscopic theory, the Ginzburg–Landau approach gives accurate results close to the critical temperature T_c. However, from the experience it is well known that it is also capable of gives reasonable results beyond this limit.

In a recent work, the authors of this paper made a comparative study between the 2D and 3D Ginzburg–Landau models. We determined an analytical dependence of the thermodynamic fields and the magnetization as functions of the lateral dimension of the superconductor [19]. There, we have considered only the more common situation of a superconductor–vacuum interface.

In this paper, we have gone further by investigating the effects of the boundary conditions of the superconducting order parameter at the surface of the specimen; they modify the structural and magnetic properties of the vortex state as the size of the sample is comparable to the coherence length ξ or the London penetration depth λ [20]. We consider a superconductor covered by a very thin layer of a different material. Three types of interfaces are taken into account: superconductor–vacuum, superconductor–normal metal, superconductor–superconductor at a higher critical temperature. Either we employ the same boundary conditions in all the six faces of a parallelepiped geometry (isotropic interface type), or we combine them in several different manners (anisotropic interface type).

The paper is outlined as follows. In Section 2 we briefly describe the theoretical formalism used to study a mesoscopic superconducting parallelepiped in the presence of an external applied magnetic field. We also present all the seven scenarios of boundary conditions which will be undertaken. Then, in Section 4 we present the results coming out from the numerical solution of the TDGL equations for the magnetization, vorticity, vortex configurations and local magnetic field profiles.

* Corresponding author.
E-mail address: josejbarba@gmail.com (J. Barba-Ortega).

http://dx.doi.org/10.1016/j.physleta.2015.10.013
0375-9601/

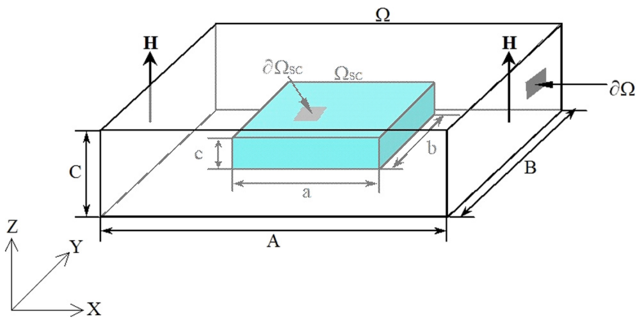

Fig. 1. (Color online.) Schematic view of the geometry of the system under investigation. The meaning of all symbols are described in the text.

2. Theoretical formalism

The geometry of the problem that we investigate is illustrated in Fig. 1. The domain Ω_{sc} is filled by the mesoscopic superconducting parallelepiped of thickness c and lateral sizes a and b. The interface between this region and the vacuum is denoted by $\partial\Omega_{sc}$. Because of the demagnetization effects, we need to consider a larger domain Ω of dimensions $A \times B \times C$, such that $\Omega_{sc} \subset \Omega$. The vacuum–vacuum interface is indicated by $\partial\Omega$. We consider a mesoscopic superconducting parallelepiped in the presence of an uniform applied magnetic field $\mathbf{H}$ along the z direction. The domain Ω is taken sufficiently large such that the local magnetic field equals the applied field $\mathbf{H}$ at the surface $\partial\Omega$ (see Ref. [19] for more details). The general form of the time dependent Ginzburg–Landau equations in dimensionless units are given by:

$$\frac{\partial\psi}{\partial t} = -(-i\nabla - \mathbf{A})^2\psi + \psi(1-|\psi|^2), \quad \text{in } \Omega_{sc}, \tag{1}$$

$$\frac{\partial\mathbf{A}}{\partial t} = \begin{cases} \mathbf{J}_s - \kappa^2\nabla\times\nabla\times\mathbf{A}, & \text{in } \Omega_{sc}, \\ -\kappa^2\nabla\times\nabla\times\mathbf{A}, & \text{in } \Omega\backslash\Omega_{sc}, \end{cases} \tag{2}$$

where

$$\mathbf{J}_s = \mathrm{Re}\left[\bar{\psi}(-i\nabla - \mathbf{A})\psi\right] \tag{3}$$

is the superconducting current density.

In Eqs. (1)–(3) dimensionless units were introduced as follows: the order parameter ψ is in units of $\psi_\infty = \sqrt{-\alpha/\beta}$, the order parameter at the Meissner state, where α and β are two phenomenological constants; length is in units of the coherence length ξ; time is in units of the Ginzburg–Landau characteristic time $t_{GL} = \pi\hbar/8K_BT_c$; magnetic field is in units of H_{c2}, the bulk upper critical field; the vector potential $\mathbf{A}$ is in units of ξH_{c2}; $\kappa = \lambda/\xi$ is the Ginzburg–Landau parameter.

The phase diagram of mesoscopic superconductor is strongly influenced by the boundary conditions for the order parameter. In general, they are given by the de Gennes boundary conditions:

$$\mathbf{n}\cdot(i\nabla + \mathbf{A})\psi = -\frac{i}{b}\psi, \quad \text{at } \partial\Omega_{sc}, \tag{4}$$

$$\nabla\times\mathbf{A} = \mathbf{H}, \quad \text{at } \partial\Omega, \tag{5}$$

where $\mathbf{n}$ is the unit vector outward normal to the superconductor-medium interface, b is the de Gennes surface extrapolation length which describes this medium; as we have stated previously, Ω is a domain sufficiently large such that the local magnetic field $\mathbf{h} = \nabla\times\mathbf{A}$ equals the external applied magnetic field $\mathbf{H}$.

It must be emphasized that the space between the interfaces $\partial\Omega_{sc}$ and $\partial\Omega$ is not filled by any material. The superconductor is covered by a very thin layer of another material which is contained in the domain Ω_{sc}. This layer is described by the de Gennes extrapolation length b.

In order to solve equations (1)–(3) numerically, we used the link-variable method as sketched in Refs. [21,22]. This is not the unique method available to solve these equations. A method valid for very thin films has been devised in Ref. [23], in which fast Fourier transform combined with the link-variables was employed. Although we used the TDGL equations, we are concerned only with the stationary state; they are used only as a relaxation method to obtain the equilibrium state.

By varying the values of b, we can change the nucleation field and the critical current. From the microscopic point of view, it is possible to show that b depends on the properties of the interface; it is maximum for an ideal surface with the mirror reflection of quasi-particles and minimum for the rough surface with the diffusive reflection [24–27]. The values of b can be estimated according to Refs. [28,29]. The superconductor–vacuum interface, $b \to \infty$, has been extensively studied by many authors (see for instance [30–35]). The case in which $b > 0$ is used, the order parameter is suppressed in the vicinity of the sample surface, a normal metal. For the superconductor–normal metal interface b is always small, $b \sim \xi$, because of diffusion of normal electrons from the metal to the superconductor. The enhancement of the order parameter is reached at the interface by using negative values of b. This can be realized by covering the superconductor sample with a very thin layer of another superconductor having a higher critical temperature [36]. This can also be achieved by covering it with a semiconductor, such that there is an overlap of the band gap of the semiconductor with the superconducting gap. In this paper, we will study a mesoscopic superconducting parallelepiped for several types of interfaces.

According to Fig. 2, we have considered the three following scenarios:

- Case 1: the upper and lower faces of the sample, xy planes, are in contact with a metallic material, $b = 5\xi$; or a superconductor material at higher critical temperature, $b = -5\xi$; the xz and yz planes are in contact with vacuum, $b \to \infty$; left panels of the figure.

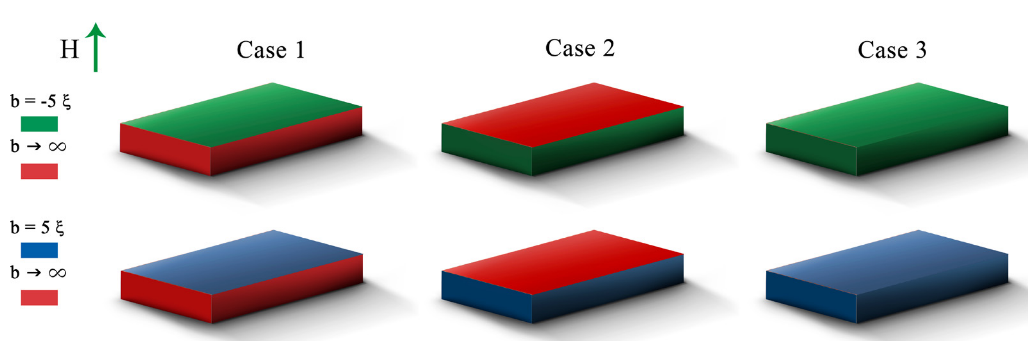

Fig. 2. Layout of the studied samples; the external applied magnetic field **H** is pointed perpendicular to the xy plane.