Physica C: Superconductivity and its applications 528 (2016) 17–22

Contents lists available at ScienceDirect

Physica C: Superconductivity and its applications

journal homepage: www.elsevier.com/locate/physc

The critical current density in the layered superconductors with ferromagnetic nanorods

V.A. Kashurnikov, A.N. Maksimova*, I.A. Rudnev, D.S. Odintsov

National Research Nuclear University MEPHI (Moscow Engineering Physics Institute), 115409, Kashirskoe shosse, 31, Moscow, Russia

ARTICLE INFO

Article history:
Received 5 April 2016
Revised 3 June 2016
Accepted 7 July 2016
Available online 9 July 2016

Keywords:
High-temperature superconductor
Ferromagnetic nanoparticle
Vortex pinning
Critical current
Monte Carlo simulation

ABSTRACT

In this paper, we have calculated the dependence of critical current density j_c on the radius R and concentration of extended ferromagnetic defects in the system simulating a high-temperature superconductor (HTSC) layer. It was shown that at fixed volume concentration of ferromagnetic fraction the j_c (R) dependence, as against nonmagnetic defects, has one maximum or two maxima at certain magnetization values of ferromagnetic fraction. We found that these maxima are due to the interplay of two parameters: concentration and effective depth of potential wells of defects.

1. Introduction

It is well known that the structure of pinning centers strongly influence the transport characteristics of type-II superconductors and define the dynamic of vortex lattice. One way of increasing the critical current is enhancement of pinning by means of using superconductor-ferromagnetic hybrid structures or embedding into the superconductor the ferromagnetic impurities as additional pinning centers [1–7]. Superconducting films with magnetic pinning centers have been widely studied both theoretically and experimentally [8–16]. Vortices in thin superconducting films in presence of the arrays of magnetic dots have been studied [8–10], the reciprocal influence of vortices and magnetic domain structure in superconductor-ferromagnet bilayers has been analyzed [11–13]. In particular, the “field-induced superconductivity” [9] produced by an array of out-of-plane magnetized magnetic dots have been examined, it has been demonstrated that the “field-induced superconductivity” strongly depends on radius of magnetic disks. Vortex configurations near magnetic disks have been obtained numerically within Ginzburg–Landau theory [14–16]. The authors of papers [1–3] have studied magnetic properties of superconductor/ferromagnet multilayers and analyzed the magnetic domain structure and vortex pinning by ferromagnetic layer. In Refs. [5,6] the voltage-current characteristics as well AC-losses have been studied by numerical simulation and experimentally. The dynamics of interaction in the vortex-antivortex system in superconducting layer containing the array of magnetic dipoles with square arrangement have been investigated numerically in [7]. The density of vortex-antivortex pairs n_s and the vortex-antivortex pairs creation rate r_{cr} as a functions of AC current density J_{ac} applied to the superconducting layer were calculated. The authors found that both n_s and r_{cr} had the sequence of peaks due to vortex movement from defects and annihilation of neighboring vortex-antivortex pairs. Effect of ellipsoidal and spherical magnetic nanoparticles on pinning properties in type-II superconductor has been studied theoretically in the frame of London approximation [19,20] and possibility of vortex pinning enhancement by magnetic particles was shown. The rise of a single vortex pinning due to magnetic interaction of vortex with ferromagnetic cylinder has been demonstrated in [21]. It was found that magnetic rod may cause the reduction of Lorenz force acting on a vortex, what, as a consequence, results to growth of critical current density for given pinning force.

Because of high complexity of vortex system, numerical simulations are essential for studying type-II superconductors. Direct solution of Ginzburg–Landau equations (see, e.g. [14–16]) is a very powerful tool but this method requires, in particular, an exact form of vector potential $\boldsymbol{A}$ which is a nontrivial task in case of arbitrary defects configuration. The situation becomes especially complicated in the case of magnetic defects. For bulk superconductive samples or layered superconductors, when magnetic field is perpendicular to the layers, molecular dynamic [17] or Monte Carlo [18] methods can be applied. However, in most numerical studies which used these methods only vortex-vortex interaction and interaction of vortices with pinning centers have been taken into

---

* Corresponding author.
E-mail address: nastymaksimova@yandex.ru (A.N. Maksimova).

http://dx.doi.org/10.1016/j.physc.2016.07.005
0921-4534/

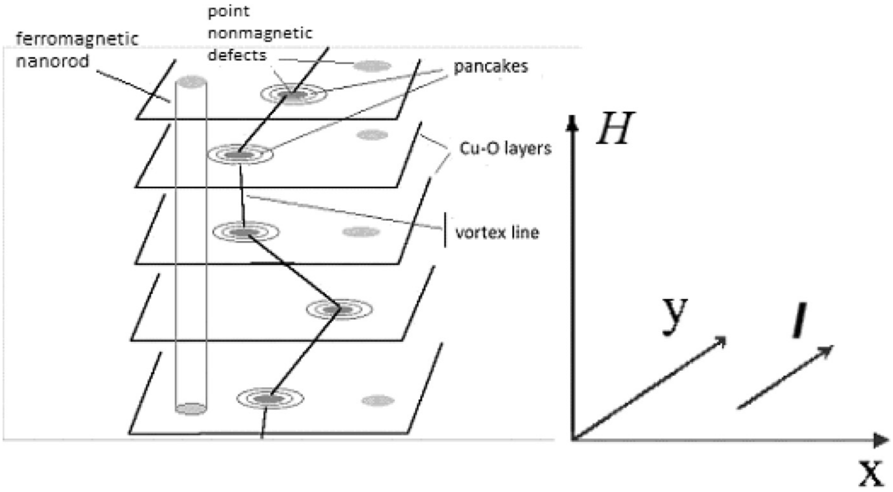

Fig. 1. The geometry of simulations. Ferromagnetic rods and defects have a few nanometers size.

account or simulations have been made for typical limiting cases such as the triangular vortex lattice, constant number of vortices, regular array of magnetic or nonmagnetic defects. So that, simulations do not provide fundamentally correct analysis of vortex production and penetration through Bean–Livingston barrier able to form the realistic equilibrium vortex configuration for given transport current, external magnetic field and arbitrary array of defects. In our previous work [22] we analyze the effect of ferromagnetic nanoparticles on pinning properties of superconductor. But the model [22] suggests that the radius of ferromagnetic particles is much smaller than superconductive penetration depth λ and is not applicable in case of magnetic inclusions of micrometer size.

In the present work we analyze the pinning properties of the array of ferromagnetic nanorods in the superconducting matrix by means of Monte Carlo simulations to obtain the value of critical current. Our method works with a variable number of vortices and can be used for estimation of the magnetic and transport properties in a wide range of the superconductive parameters and at arbitrary size and configuration of magnetic and nonmagnetic defects.

2. Simulation method

We discuss now the basic principles of our simulations. To obtain equilibrium vortex configuration, we use Monte Carlo simulations in the framework of Lawrence–Doniach model [23]. In this model, the vortex line is represented as a stack of pancake vortices with Josephson interaction between pancakes in adjacent layers. Let us consider the stack of superconducting layers with finite width L_x in x direction and periodic boundary conditions in y and z directions (z direction is perpendicular to the layers, Fig. 1). External magnetic field is directed along z axis, the transport current is applied along y-axis. In this case, the Gibbs thermodynamic potential of vortex system has a form:

$$G=\sum_{z}\left\{N_z\varepsilon+\sum_{i<j}U_{in-plane}\left(r_{ij}\right)+\sum_{i,j}U_p\left(r_{ij}\right)+\sum_{i,j}U_{surf}\left(r_{ij}^{(im)}\right)\right.$$
$$\left.+\sum_{i}U_{\text{inter}-plane}\left(r_i^{z,z+1}\right),\right\},$$

where $\varepsilon=\varepsilon_0(\ln[\lambda(T)/\xi(T)]+0.52)$ is a self-energy of a flux line per unit length, N_z is a number of pancakes in the zth layer, the second term corresponds to the pair interaction of vortices, the third term describes the interaction between vortices and pinning centers (both magnetic and nonmagnetic) and the fourth term is the interaction of pancake vortices with the surface and Meissner current (see [24–30] for further details). Our previous simulations demonstrated that in this approximation the Monte Carlo method is effective for description of vortex system and the simulation results are in satisfactory agreement with experiment [25,31].

In the general Lawrence–Doniach model, the superconductor acts as anisotropic but three-dimensional system but in the limiting case of infinitely strong (or infinitely weak) coupling the only one plane gives an adequate description of a realistic three-dimensional superconductor and the two-dimensional model [27–29] can be applied. Taking into account the configuration of defects (infinite ferromagnetic cylinders directed along z-axis in this work) we consider the limiting case of strong inter-layer coupling and utilize two-dimensional model to examine the magnetization by the self-field of transport current and obtain the critical current estimation.

To derive the interaction potential for the vortex line close to the ferromagnetic rod, we solve London equation in a superconductor and Maxwell equation in a ferromagnetic particle (see Ref. [8]). Thus, the energy of interaction between a ferromagnetic rod of radius R and magnetization M and vortex line reads [30]:

$$U_{pm}=-\delta\frac{\Phi_0 M}{\frac{2\lambda}{R}K_1\left(\frac{R}{\lambda}\right)+K_0\left(\frac{R}{\lambda}\right)}K_0\left(\frac{r}{\lambda}\right),\qquad(1)$$

where r is a distance from the center of the rod, K_0 and K_1 are the McDonald functions, δ is a thickness of a CuO_2 superconductive layer. At $R<<\lambda$ (1) reduces to the interaction energy of point magnetic dipole with the field of the vortex. In our model, we suppose that the ferromagnetic rod is covered by a thin insulating layer to eliminate proximity effect. The interaction U_{pn} with nonmagnetic pinning centers has a form [24–26]

$$U_{pn}=-\alpha\frac{1}{1+r/\xi}\exp\left(-\frac{r}{2\xi}\right),\qquad(2)$$

where α is an effective depth of the potential well of the defect and has a magnitude 0.01–0.1 eV [24–26]. For individual magnetic defect the potential has a form (1) but we can also estimate effective depth α as a magnitude of U_{pn} at $r=R$.

To obtain the critical current estimation we compute the current-voltage characteristics using method developed by the authors of Ref. [24]. When the transport current density exceeds j_c, the vortices start to flow towards the center of the wire inducing electric field E in the superconductor. Whereas one vortex-antivortex pair annihilates in the center, the new vortex and an-