Magnetization of layered superconductors with ferromagnetic nanorods

V A Kashurnikov, A N Maksimova and I A Rudnev

National Research Nuclear University, Moscow, Kashirskoe shosse, 31, 115409, Russia

e-mail: nastymaksimova@yandex.ru

Abstract. The magnetization of layered high-temperature superconductors (HTSC) with ferromagnetic nanorods as bulk pinning centers is studied in the 2D model of layered HTSC by using Monte Carlo method. Magnetic part of the interaction energy between a ferromagnetic cylinder of arbitrary radius and constant magnetization and an Abrikosov vortex was calculated in London approximation. The magnetization at different radius of magnetic defects was investigated. The results of calculations were compared with the results for extended nonmagnetic defects.

1. Introduction

The transport properties of type-II superconductors strongly depend on the dynamics of vortex system and the pinning properties of the defects structure. The experimental and theoretical study of the interplay between superconductivity and ferromagnetism has suggested that ferromagnetism can actually enhance superconductivity in artificial superconductor-ferromagnet hybrid structures under certain conditions. In general, artificial ferromagnet-superconductor hybrid structures are characterized by a superconducting film on the top or underneath a textured ferromagnetic layer. The ferromagnetic layer can be either solid (superconductor-ferromagnet bilayer, [1-4]) or made of magnetic dots or dipoles [5,6]. In [5,6] the dynamics of ac-driven vortices and antivortices in a superconducting film with an array of magnetic dipoles was investigated by hybrid molecular dynamic – Monte Carlo simulations. The spontaneous appearance and stabilization of vortex-antivortex (v-av) pairs was observed, the *E-J* curves were obtained. The periodic sequence of production and annihilation v-av pairs results in the peaks of the *E-J* curve. In [7] the superconductor with ferromagnetic nanoparticles as bulk pinning centers was studied experimentally, the magnetization curves were obtained. The interaction of a vortex with ferromagnetic particle of arbitrary radius was theoretically analyzed. In [8] the enhancement of a single vortex pinning by a magnetic cylinder was calculated, it was shown that a magnetic inclusion can reduce the Lorenz force on a vortex yielding an enhanced critical current density.

The Monte Carlo method has demonstrated the high efficiency in the calculation of the transport properties and magnetization of layered HTSC. The calculations in presence of nonmagnetic defects were performed in [9-11], the effect of ferromagnetic impurities in the case of bulk ferromagnetic defects were analyzed in [12]. But the model [12] suggests the size of ferromagnetic particles much smaller than superconducting magnetic penetration depth and does not work for magnetic inclusions of arbitrary radius and shape. The aim of our work is to investigate the pinning properties of the array of ferromagnetic rods in the bulk of the superconductor and to investigate the magnetization and the transport properties at different concentration and size of ferromagnetic defects.

2. Model and the calculation method

The calculations were performed within the two-dimensional model of a layered HTSC by using Monte Carlo algorithm [9-11]. The model is a limiting case of the realistic three-dimensional model involving various types of in-plane interactions and the inter-plane interaction. In this model, a vortex line in the bulk of the superconductor is represented in the form of a set of interacting planar vortices (pancakes). Early calculations in this approximation as well as comparison with the experimental data confirm that such an approach provides an adequate description of the situation. Thus, the Gibbs thermodynamic potential of a two-dimensional system with variable number of interacting pancakes (in the absence of inter-plane interaction) takes a form:

$$G = N\varepsilon + \sum_{i<j} U_{in-plane}\left(r_{ij}\right) + \sum_{i,j} U_p\left(r_{ij}\right) + \sum_{i,j} U_{surf}\left(r_{ij}^{(im)}\right),$$

where $\varepsilon = \varepsilon_0\left(\ln[\lambda(T)/\xi(T)] + 0.52\right)$ is a self-energy of a vortex, N is a number of pancakes in the layer under consideration, the second term describes the pair interaction of vortices, the third term is the interaction of vortices with pinning centers and the fourth term corresponds to the interaction of vortices with the surface and Meissner current. $\varepsilon_0 = \Phi_0^2 s/\left(4\pi\lambda\right)^2$, $\Phi_0 = \pi\hbar c/e$ is the quantum of magnetic flux (see [9-11] for details).

In this work, we introduce the ferromagnetic rods of arbitrary radius as bulk pinning centers. For calculations, the interaction energy between the vortex line and ferromagnetic rod must be obtained. Let us consider an infinite ferromagnetic cylinder of radius R and magnetization **M**, embedded into an infinite type-II superconductor containing straight vortex lines. Similarly to [7], we solve in cylindric coordinates the London equation for the vector-potential **A** in a superconductor and the Maxwell equation inside the ferromagnetic particle and obtain the supercurrent induced around the rod:

$$j_\varphi = -\frac{cM}{\lambda^2} \frac{K_1\left(\dfrac{r}{\lambda}\right)}{\dfrac{2}{R}K_1\left(\dfrac{R}{\lambda}\right) + \dfrac{1}{\lambda}K_0\left(\dfrac{R}{\lambda}\right)},$$

where K_0 and K_1 are the McDonald functions, λ is a superconductive penetration depth. The energy of interaction between ferromagnetic rod and vortex line is calculated as an inverse work of Lorenz force when the vortex moves from infinity to the position r at the distance r from the centre of the rod:

$$U = -\int_\infty^r F dx = -\delta \frac{\Phi_0 M}{\dfrac{2\lambda}{R}K_1\left(\dfrac{R}{\lambda}\right) + K_0\left(\dfrac{R}{\lambda}\right)} K_0\left(\dfrac{r}{\lambda}\right) \qquad (1)$$

The coefficient δ denotes a thickness of a superconductive layer. It is worth noting that at $R \ll \lambda$ this expression turns to the energy of point magnetic dipole in the field of the vortex. The calculations were performed for temperatures of 1-10 K and for typical parameters of $Bi_2Sr_2CaCu_2O_{8-\delta}$: $\lambda(0)$=80 nm, $\xi(0)$=2 nm, T_c=84 K. Ferromagnetic particles have a size about $0.1\lambda - \lambda$, the magnetization of the particles is about $10^2 - 10^3$ Gs, the size of superconducting region under consideration is 6×3 μm.

3. Results

Let us consider the superconductive slab with periodic lattice of ferromagnetic rods. The magnetic moment of the defects is perpendicular to the superconductive layers and does not change during the magnetization process. We analyze now the magnetization curves at different size of ferromagnetic defects. Fig.1 represents the two typical magnetization loops at different radius, magnetization and concentration of the rods (a) and the dependence of the square of the loop (which is proportional to the value of hysteretic losses) for the configurations from (a) on the amplitude of external magnetizing field (b). According to [11], the smaller the square of the loop, the greater the critical current (in the

regime of hysteretic losses). A zero residual magnetization at the second half of the magnetization cycle (when the external field drops from maximal negative value to zero; see the curves in fig. 1a) is a special feature of magnetic defects with constant magnetization and takes place because the ferromagnetic particles do not pin the vortices of opposite polarity. The calculations were done for both periodic and non-periodic lattices of defects and it was shown that the results in both cases qualitatively coincide.
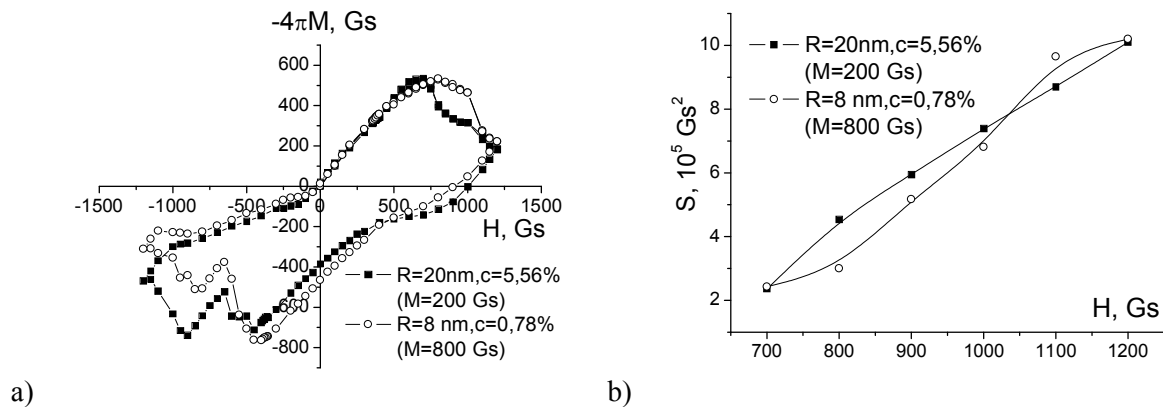

Fig. 1. The magnetization loops at different size of ferromagnetic rods (a) and the square of the magnetization loop as a function of the amplitude of the external field (b). R is a radius of the ferromagnetic defect, c is a volume concentration of a ferromagnetic in the superconductor.
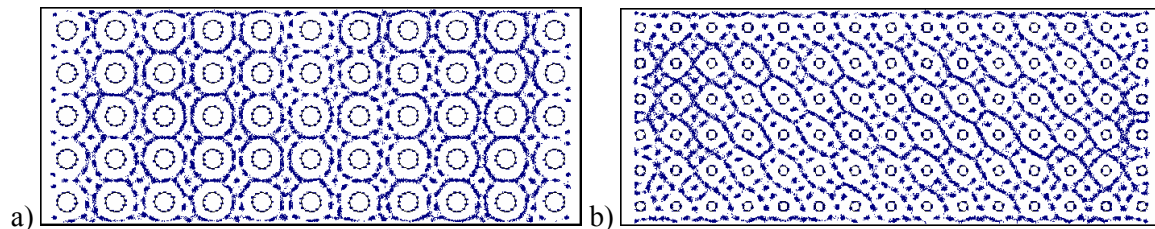

Fig. 2. Different configurations of vortices arising during magnetization process: a) c=31%, R=180 nm, b) c=13%, R=90 nm. The opened circles denote the magnetic defects.

Note that at some sizes and concentrations of magnetic defects the vortices form superlattices like shown in fig.2 during magnetization.

Let us analyze now the transport properties of the superconductor with extended magnetic defects. We fix the volume concentration of the ferromagnetic and then change the size of individual rod. The smaller the radius of the defect, the higher the number of defects per unit square and vice versa. We then obtain the current-voltage characteristics and estimate the critical current j_c as a current at which the electric field strength in the superconductor reaches $0.1\,\mu$ V/cm. The results are shown in fig. 3. It is readily seen that at each concentration there is some optimal combination of R, N at which j_c reaches a peak and the peak shifts left at smaller concentrations.

The computational model introduced above is applicable for cylindric ferromagnetic defects but does not include the case of defects of arbitrary shape. In order to describe this case we may consider the extended defect as an ensemble of point defects (of the radius ξ). The potential produced by extended defect is therefore the sum of point defects potential. The simulations show a satisfactory agreement between two potentials, especially far from the defect's surface.
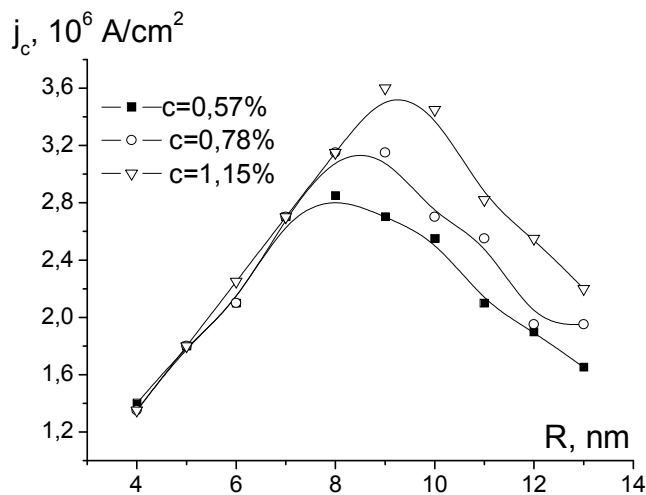
Fig. 3. The critical current as a function of the radius of the rod at different concentrations of the ferromagnetic. The magnetization of the ferromagnetic M=800 Gs and is the same for all curves

4. Conclusion

The description of the interaction between straight vortex line and ferromagnetic rod of arbitrary radius in the bulk of the superconductor was introduced in the 2D – model of layered high-temperature superconductor. The magnetization curves of the superconductor were obtained at the different size of magnetic defects. The transport properties at different configurations of ferromagnetic defects were investigated. The model can be used to investigate the magnetization and transport properties of the layered HTSC with bulk ferromagnetic defects of arbitrary size and configuration.

Acknowledgements

References
[1]   L.S. Uspenskaya, S.V.Egorov, Physica B (2013), http://dx.doi.org/10.1016/j.physb.2013.09.040
[2]   T. Tamegai, Y. Nakao, Y. Tsuchiya, Y. Nakajima, Physica C 468 (2008) 1308–1312
[3]   Dong Ho Kim, T.J. Hwang, Physica C 455 (2007) 58–62
[4]   Yoshio Nakao, Yasuyuki Nakajima, Tsuyoshi Tamegai, Physica C 470 (2010) S801–S803
[5]   Clessio L.S. Lima, Clecio C. de Souza Silva, J. Albino Aguiar, Physica C 479 (2012) 147–150
[6]   Cléssio L. S. Lima and Clécio C. de Souza Silva, Phys. Rev. B 80, 054514 (2009)
[7]   A. Snezhko, T. Prozorov, R. Prozorov, Phys. Rev. B 71 024527 (2005)
[8]   M G Blamire, R B Dinner, S C Wimbush and J L MacManus-Driscoll, Supercond. Sci. Technol. 22 (2009) 025017
[9]   D.S. Odintsov, I.A. Rudnev, V.A. Kashurnikov, JETP 103 (2006)**,** 66
[10]   I.A. Rudnev, D.S. Odintsov, V.A. Kashurnikov, Phys. Lett. A 372 (2008) 3934-3936
[11]   D.S. Odintsov, I.A. Rudnev, V.A. Kashurnikov, JETP 105 (2007)**,** 253
[12]   V.A. Kashurnikov, A.N. Maksimova, I.A. Rudnev, Physics of the Solid State 56 (5) (2014) 894-911