Magnetization of layered high-temperature superconductors with extended ferromagnetic defects

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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 a 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 periodic and non-periodic lattices of magnetic defects were considered. The magnetization was investigated at different radii of magnetic defects. The results of calculations were compared with the results for extended nonmagnetic defects.

Keywords: layered high-temperature superconductors; ferromagnetic nanoparticles; vortex pinning; hysteretic losses; Monte Carlo simulations

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 have revealed 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, Uspenskaya and Egorov (2014), Tamegai et al. (2008), Kim and Hwang (2007), Nakao et al. (2010)) or made up of magnetic dots or dipoles Lima et al. (2012), Lima and de Sousa Silva (2009). In Refs. Lima et al. (2012), Lima and de Sousa Silva (2009) the dynamics of ac-driven vortices and antivortices in a superconducting film with an array of magnetic dipoles was investigated by hybrid molecular dynamics – Monte Carlo simulations. The spontaneous appearance and stabilization of vortex-antivortex (v-av) pairs were observed, the $E$-$J$ curves were obtained. The periodic sequence of production and annihilation of v-av pairs have resulted in the peaks of the $E$-$J$ curve. In Ref. Snezhko et al. (2005) the superconductor with ferromagnetic nanoparticles as bulk pinning centers were studied experimentally, the magnetization curves were obtained. The interaction of a vortex with ferromagnetic particle of arbitrary radius was theoretically analyzed. In Ref. Blamire et al. (2009) 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 high efficiency in the calculation of transport properties and magnetization of layered HTSC. The calculations were performed in Refs. Odintsov et al. (2006), (2007), Rudnev et al. (2008), in presence of nonmagnetic defects, the effect of ferromagnetic impurities were analyzed by Kashurnikov et al. (2014) in the case of bulk ferromagnetic defects. But the model by Kashurnikov et al. (2014) suggests that the size of ferromagnetic particles be much smaller than superconductive penetration depth $\lambda$ 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 obtain the magnetization curves to estimate the value of the critical current.

2. Model and the calculation method

The calculations were performed within the two-dimensional model of a layered HTSC by using a Monte Carlo algorithm, Odintsov et al. (2006), (2007), Rudnev et al. (2008). The model is a limiting case of the realistic three-dimensional model involving various types of in-plane interactions and 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 a variable number of interacting pancakes (in the absence of inter-plane interaction) takes the following form:

$$G = N\varepsilon + \sum_{i<j} U_{\text{in-plane}}(r_{ij}) + \sum_{i,j} U_{\text{in-plane}}(r_{ij}) + \sum_{i,j} U_{\text{surf}}(r_{ij})$$

where $\varepsilon = \varepsilon_0 (\ln[\lambda(T)/\xi(T)]) + 0.52$ is the self-energy of a vortex, $N$ is the 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. $\varepsilon_0 = \Phi_0^2 s/(4\pi \lambda)^2$, $\Phi_0 = \pi \hbar c/e$ is the quantum of magnetic flux (see Refs. Odintsov et al. (2006), (2007), Rudnev et al. (2008) 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. Similar to Snezhko et al. (2005), we solve the London equation for the vector-potential $A$ in a superconductor and the Maxwell equation inside the ferromagnetic particle:
\[
\begin{aligned}
\Delta \mathbf{A} &= 0, r < R \\
\mathbf{A} - \lambda^2 \Delta \mathbf{A} &= 0, r \geq R
\end{aligned}
\]
In cylindric coordinates we have
\[
\begin{aligned}
\frac{\partial^2 A_\varphi}{\partial r^2} + \frac{1}{r} \frac{\partial A_\varphi}{\partial r} - A_\varphi \left( \frac{1}{r^2} + \frac{1}{\lambda^2} \right) &= 0, r \geq R \\
\frac{\partial^2 A_\varphi}{\partial r^2} + \frac{1}{r} \frac{\partial A_\varphi}{\partial r} - A_\varphi \frac{1}{r^2} &= 0, r < R.
\end{aligned}
\]
Taking into account the boundary conditions
\[
A_\varphi^{sc} \bigg|_R = A_\varphi^{m} \bigg|_R, \quad \text{rot} \mathbf{A}^{sc} \bigg|_R = \left( \text{rot} \mathbf{A}^{m} - 4\pi \mathbf{M} \right) \bigg|_R,
\]
we obtain the following solutions:
\[
\begin{aligned}
A_\varphi &= 4\pi M - \frac{1}{R} K_1 \left( \frac{R}{\lambda} \right), r, r < R \\
A_\varphi &= \frac{2}{R} K_1 \left( \frac{R}{\lambda} \right) + \frac{1}{\lambda} K_0 \left( \frac{R}{\lambda} \right), r \geq R
\end{aligned}
\]
\(K_0\) and \(K_1\) are the McDonald functions. Corresponding screening current induced by the magnetic rod has the only component \((0, j_\varphi(r), 0)\) and is calculated from the vector-potential via
\[
\frac{4\pi}{c} j_\varphi = -\left( \Delta \mathbf{A} \right)_\varphi = -\frac{1}{\lambda^2} A_\varphi.
\]
Supercurrent induced around the rod is given by
\[
j_\varphi = -\frac{cM}{\lambda^2} \frac{K_1 \left( \frac{r}{\lambda} \right)}{2 \left( \frac{R}{\lambda} \right) K_1 \left( \frac{R}{\lambda} \right) + \frac{1}{\lambda} K_0 \left( \frac{R}{\lambda} \right)}.
\]
The energy of interaction between a ferromagnetic rod and vortex line is calculated as the inverse work of Lorenz force when the vortex moves from infinity to the position \(r\) at a distance \(r\) from the centre of the rod:
\[
U = -\int_\infty^r F dx = -\frac{\Phi_0 M}{2\lambda} \frac{K_0 \left( \frac{r}{\lambda} \right)}{2 \lambda K_1 \left( \frac{R}{\lambda} \right) + K_0 \left( \frac{R}{\lambda} \right)}.
\]
The coefficient \(\delta\) denotes 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 Bi2Sr2CaCu2O8-\(\delta\): \(\lambda(0)=80\) 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 the superconducting region under consideration is \(6 \times 3\) \(\mu m\).

3. Results

Let us consider a superconductive slab with the 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 radii of ferromagnetic defects. The number of defects per unit square is the same for all curves. Fig.1 represents the magnetization loops at different radii of the rods (a) and the dependence of the square of the loop (which is a function of the value of the critical current) on the radius of the...
It is readily seen that the square of the loop increases with increasing the size of the defects as long as the distance among defects is greater than their radius (and superconductive penetration depth). According to Odintsov et al. (2007), the value of the critical current hence decreases with the radius of the defects. A zero residual magnetization in negative external fields (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 coincide qualitatively.

We obtain now the magnetization curves for the superconductor with extended nonmagnetic defects. Fig. 2 represents the loops for the case of nonmagnetic defects and the loop for the case of magnetic defects of the same concentration for comparison. The effective depth of the potential well is approximately equal for both kinds of defects. The concentration of nanoparticles is the same as in fig. 1. One can see that the residual magnetization (and therefore the pinning force) is smaller for magnetic defects at this amplitude of the external field. To explain this, we take into account that the effective distance at which the potential of defect drops to zero is about the coherence length $\xi$ for nonmagnetic defect and about $\lambda$ for the magnetic one. Hence, the magnetic potential wells overlap considerably. This situation is similar to the collective depinning described in Ref. Rudnev et al. (2008).
The computational model introduced above is applicable for cylindric ferromagnetic defects but it 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 $\xi$). The potential produced by the 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.

4. Conclusion

The description of interaction between a straight vortex line and ferromagnetic rod of arbitrary radius in the bulk of the superconductor has been introduced in the 2D – model of the layered high-temperature superconductor. The magnetization curves of the superconductor were obtained at the different size of magnetic defects. The results were compared with the results for nonmagnetic defects. 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.

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References