Vortex Structures in the Ferromagnet-Superconductor Bilayer

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Abstract

Vortex structures in the ferromagnet/type-II superconductor bilayer are investigated when the ferromagnet has domain structure and perpendicular magnetic anisotropy. It is found that two equilibrium vortex structures can be realized: straight vortices with alternating directions corresponding to the direction of the magnetization in the ferromagnetic domains and vortex semi-loops connecting the ferromagnetic domains with opposite direction of the magnetization. The values of the critical magnetization for the formation of these vortex structures are determined.

Key words: superconductivity; ferromagnetism; vortices; domains

Much attention has been recently paid to the vortex properties in superconductor-ferromagnet bilayers (SFB). It was found that the domain wall can pin vortices, and the interaction between the magnetic domain wall and a single vortex have been determined in Ref. [1]. A two-dimensional vortex state has been considered in a SFB formed by a thin ferromagnetic film ($d_m \ll L$) having perpendicular magnetic anisotropy and a thin superconducting film ($d_s \leq \lambda_L$) [2]. Here L is the period of the domain structure in the ferromagnet, λ_L is the London penetration depth and d_m and d_s are the thicknesses of the ferromagnet and the superconductor, respectively.

In the present paper we consider a SFB consisting of a thick magnetic layer ($d_m \gg L$) with the magnetization perpendicular to the layer on top of a thick superconducting layer ($d_s \gg \lambda_L$). The magnetic field generated by the ferromagnet is strongly inhomogeneous in this case and the dependence of the vortex energy on its position is important for the vortex penetration process. In contrast to Ref. [2] dealing with the structures with many vortices per a domain, our goal was to find conditions for penetration of a *first vortex* into the domain. As usual, this transition is determined by the condition that the energy of a single vortex inside the superconductor becomes negative and the *first* vortex appears in the superconductor. This means that the vortex density is negligible near the transition, and one may neglect the vortex-vortex interaction U_{vv}. The energy of the first vortex is $U_{sv} = \phi_0 H_{c1} l/4\pi$, where l is the vortex length, ϕ_0 is the flux quantum and H_{c1} is the lower critical field of the superconductor. This energy takes into account only fields and supercurrents *inside* the superconductor. Meanwhile the vortex line generates also the magnetic field $\mathbf{H}_v = -\nabla\varphi_v$ outside the superconductor. The potential φ_v is similar to an electrostatic potential from a point charge located at the point ($r = 0$, $z = 0$), where the vortex line exits from the superconductor:

$$\varphi_v = \frac{\phi_0}{2\pi\sqrt{r^2+z^2}} \, . \tag{1}$$

Here $\mathbf{r}$ is the 2D position vector in the interface plane and the ferromagnet fills the space with $z > 0$. The integral $\int(\nabla\varphi_v)^2 d^3r$, which determines the energy of this field, is divergent at small distance. The divergence is cut-off by the London penetration depth λ_L and eventually this yields the energy $\sim \phi_0^2/\lambda_L$, which is less by a factor λ_L/l than the vortex energy inside the superconductor proportional to its length l.

Another relevant energy is the interaction energy between the vortices and the magnetic field generated by

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the domain structure:

$$U_{vm} = \frac{1}{4\pi}\int (\mathbf{H}_v \cdot \mathbf{H}_f + \lambda_L^2 \nabla \times \mathbf{H}_v \cdot \nabla \times \mathbf{H}_f) d^3r, \quad (2)$$

where $\mathbf{H}_v$ is the field induced by the vortices and $\mathbf{H}_f$ is the field induced by the ferromagnet. The energy U_{vm} can be divided into the integrals over the volume of the ferromagnet and the superconductor. The latter integral is small in the limit $\lambda_L \ll L$. Inside the ferromagnet the vortex field $\mathbf{H}_v = -\nabla\varphi_v$ is determined by Eq. (1). Transforming the integral over the ferromagnet by parts we arrive to the energy expression, which contains the magnetic charges $\epsilon_i\phi_0/2\pi$ of the vortex located at the vortex tips:

$$U_{vm} = -\sum_i \frac{\epsilon_i \phi_0 \varphi(\mathbf{r}_i)}{4\pi}, \quad (3)$$

where $\epsilon_i = \pm 1$ depends on the direction of the vortex flux and $\mathbf{r}_i$ is the position vector of the ith vortex tip in the interface plane. The magnetic potential $\varphi(\mathbf{r}_i)$ can be obtained by integration of H_{fx} field component [3]:

$$\varphi(\mathbf{r_i}) = \int_0^{x_i} H_{fx}\, dx = \pm 8M_0 \int_0^{x_i} \ln\tan(\pi x/2L) dx, \quad (4)$$

where x_i is the distance from the nearest left domain wall, the signs + and − are for the domains with the negative and the positive magnetization respectively. With a proper choice of the sign ϵ_i of the vortex circulation every term in the energy U_{vm} is negative.

Further we shall consider two possibilities for the vortex penetration comparing the energy of the following two vortex configurations: a vortex-antivortex pair placed in neighbouring domains (i) and a vortex semi-loop placed around a domain wall (ii).

(i) In this case straight vortices with alternating directions corresponding to the direction of the magnetization in the ferromagnetic domains are expected. In the considered vortex structure the vortex length is $l = d_s$, and the self energy of the vortices does not depend on their position, $U_{sv} = \phi_0 H_{c1} d_s/4\pi$, giving a constant contribution to the total energy. We consider the vortex-antivortex pair with the vortices placed symmetrically around the domain wall with separation $2x$. The energy of the vortex-antivortex pair $U_v(x) = [U_{vm}(x) + 2U_{sv}]$ has the minimum energy at the center of the domain. Increasing of M_0 results in lowering of the energy without shifting the minimum position. The minimum vortex energy U_v becomes negative if $M_0 > M_{c1}$, where

$$M_{c1} = \frac{H_{c1} d_s}{8\alpha L}, \quad (5)$$

with $\alpha = -\int_0^{0.5} \ln\tan(\pi x/2) dx$=0.583. Thus the critical magnetization M_{c1} determines the transition to the equilibrium mixed state. For $d_s \ll L$, M_{c1} can be considerably less than H_{c1}.

(ii) As in the previous case, most important are the energy of the interaction between the vortex semi-loop and the magnetic field of the ferromagnet, U_{vm}, and the self energy of the vortex, U_{sv}. The energy U_{sv} depends on the shape of the vortices. We shall consider the "macroscopic" vortex loops with size exceeding λ_L. The shape of the loop can be approximated by a line with length $2x$ connected with the surface by two tips at opposite ends with length larger than λ_L, but much smaller than x. Then $U_{sv} \approx 2\phi_0 H_{c1} x/4\pi$. The energy U_{vm} is given by Eq. (3) as before. The energy $U_v = U_{sv} + U_{vm}$ has a minimum at $x_0 = (2L/\pi)\arctan[\exp(-H_{c1}/8M_0)]$. The energy in the minimum is negative if H_{fx} is a decreasing function of x. This means that the semi-loop configuration is stable if the field $H_{fx}(x) > H_{c1}$ at $x \to 0$. However, one should remember that our calculation was based on the assumption that $x \gg \lambda_L$. We can use the equality $x_0 \approx \lambda_L$ as a condition that a vortex semi-loop becomes a stable configuration. This yields the critical magnetization for formation of the semi-loop:

$$M_{cl} = \frac{H_{c1}}{8\ln(2L/\pi\lambda_L)}\ . \quad (6)$$

Thus, at $M_0 > M_{c1}$ or M_{cl} there are two possible vortex configurations: vortex semi-loop, located at the walls, and straight vortices at the centers of the domains. If $M_{c1} < M_{cl}$ the configuration with vortices in domain centers is energetically more preferable.

To conclude, we have investigated two vortex structures (straight vortices and vortex semi-loops) in the ferromagnet/type-II superconductor bilayer. The values of the critical magnetization for its formation are determined.

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