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Magnetic skyrmions in ferromagnet-superconductor (F/S) heterostructures

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The problem of the skyrmion stability in the magnetic film with perpendicular anisotropy covered with a superconducting layer is considered. The expression of the magnetic skyrmion energy is derived analytically within the London model for the superconductor. It is shown that skyrmion can be stabilized by the superconducting dot or antidot even in the absence of Dzyaloshinskii–Moriya interaction. The corresponding stability conditions are obtained numerically. The wide range of the material and geometrical parameters of the system is analyzed. *Published by AIP Publishing.*
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Topological invariant spin configurations, i.e., magnetic skyrmions, have been predicted for 2D Heisenberg spin lattice in 1970s.[1–3] The skyrmions can be viewed as magnetic bubble domains (MBD) with a nonzero topological charge[4] which depends on the behavior of the magnetization within the domain wall. Assuming the domain wall width to be zero, one cannot distinguish between the MBDs with different topological charges considering the stray magnetic field only. However, if the finite width of the domain wall is taken into account, the configurations with different charges produce different stray fields. In this paper, we study the stability of the MBDs with the unit topological charge which have the simplest structure of the stray field.[5]

The magnetostatic energy of the stray field and the exchange energy of the magnetization configuration are known to cause the instability of the skyrmion in the absence of an external applied magnetic field. Depending on the material parameters and film thickness, the skyrmion can experience collapse or expansion.[5] It is known that the external magnetic field can stabilize MBD. Another possibility to stabilize the magnetic skyrmion is to introduce Dzyaloshinskii–Moriya interaction (DMI) in the system.[6] Magnetic skyrmions stabilized by DMI were observed experimentally in chiral magnetic materials.[7–10] Their size in such materials ($\sim$50 nm) is much less than the typical size of the MBD in yttrium iron garnet ($\sim$1–10 μm). The increase in the average density of the topological charge should make its contribution to different observable quantities more pronounced. The hope to realize unique topological effects such as the topological Hall effect,[11,12] current-driven motion in ultralow currents,[13] or flexomagnetoelectric effects[14] causes rising interest to skyrmionic materials.

Is it possible to stabilize small enough skyrmions in ordinary ferromagnetic materials without DMI at the zero external field? One should remember that the skyrmion is a ring-like domain wall. Therefore, it is possible to form a local potential well for the skyrmion by changing the local energy of the domain wall. Such a potential well can be formed by the exchange interaction with a ferromagnetic vortex,[15,16] spatial modulation of the film thickness,[17,18] or local change of the material parameters (anisotropy constant).[19,20] The domain wall divides areas with the opposite directions of the magnetization. Therefore, it is a source of stray magnetic fields which contribute to the energy of the domain wall. The distribution of these fields and their energy should change in the presence of the superconducting layer.[21] Today, the problem of the topological states in the F/S structures is at the very beginning of its investigation. The very limiting number of the works are devoted to the interaction between vortices and skyrmions in F/S systems with DMI[22–24] or to the influence of the skyrmion on the electronic states in superconductor.[25–29] In our work, we investigate on how the Meissner screening changes the energy of magnetic skyrmion and influences its stability.

As noted earlier, in the absence of DMI, soft magnetic bubbles (and so the skyrmion) are unstable in the ferromagnetic film at a zero magnetic field. Depending on the initial radius, the skyrmion collapses (if $R < R_c$) or expands in the labyrinth structure (if $R > R_c$). The radius critical value R_c corresponds to the unstable equilibrium and depends on the material parameters and on the thickness of the film. This critical radius R_c goes to infinity if the thickness of the ferromagnetic film h_f is less than the critical thickness h_c. The typical value of h_c is 5–10 nm for ferromagnetic metal films. So, according to this classification, we will consider magnetic films as "thin" ($h_f < h_c$) if the magnetic bubble collapses and as "thick" in the opposite case ($h_f > h_c$).

The magnetostatic energy of the domain wall in the ferromagnetic layer should increase under the superconducting coating due to the Meissner screening. The edge of the superconductor may act as a barrier for the domain wall. So, the superconducting dot in the center of the magnetic bubble can prevent its collapse in the "thin" magnetic film. In the same way, a superconducting antidot can confine magnetic skyrmion preventing its expansion in the case of the "thick" film. In this letter, we analyze how the Meissner screening changes the energy of magnetic skyrmion and influences its stability in both these limits.

We consider a F/S system shown in Fig. 1. The superconducting dot/antidot is placed onto the ferromagnetic film of the thickness h_f. The thickness of the superconducting layer is h_s, and the radius of the dot/antidot is R_0. The free energy of such F/S comes as a sum of the exchange energy

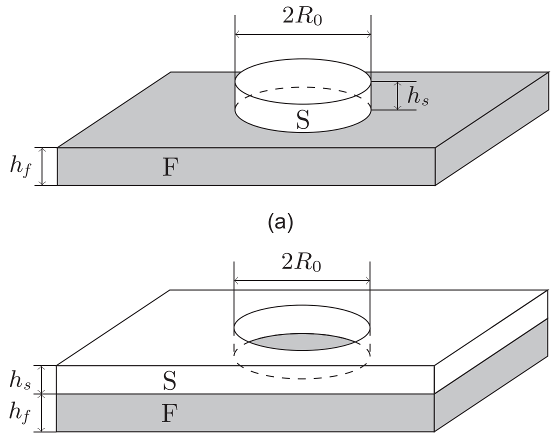

FIG. 1. F/S system with (a) the superconducting dot and (b) the superconducting antidot.

in the ferromagnet film and magnetostatic energy of the stray fields

$$E = E_{ex} + \frac{1}{8\pi}\int\left[(\mathrm{curl}\,\mathbf{A})^2 + \Lambda^{-2}(\mathbf{r})\mathbf{A}^2 - 8\pi\mathbf{M}\,\mathrm{curl}\,\mathbf{A}\right]d\mathbf{r}, \quad (1)$$

where E_{ex} is the exchange energy, $\mathbf{A}$ is the vector potential of the magnetic field, Λ equals to the London penetration length λ within the superconductor, and $\mathbf{M}$ is the magnetization of the ferromagnetic film. We focus on the magnetostatic problem assuming an explicit form of $\mathbf{M}$ without optimization of the exchange energy self consistently and neglect the suppression of the superconductivity caused by the magnetic field. For the MBD of the radius R, we take $\mathbf{M}(r) = M_s\mathrm{sgn}(r-R)\mathbf{z}_0$ inside of the ferromagnet film and $E_{ex} = 2\pi R h_f \sigma$, where $\sigma = 4\sqrt{AK}$ is the energy of the ferromagnetic domain wall per the unit area, M_s, A, and K are the saturated magnetization, the exchange coefficient, and the uniaxial anisotropy, respectively, and sgn is the sign function. Hereafter, we focus on the case of the skyrmion with the unit topological charge which allows us to neglect additional contributions to the stray fields arising from the magnetization texture inside the domain wall.[5]

In the framework of our model, we consider the domain wall thickness to be equal to zero so only the magnetic fields generated by currents connected with curl $\mathbf{M}$ are taken into account. Soft MBD (which are skyrmions) have closed lines of the in-plane component of magnetization, which do not produce stray fields (the corresponding distribution of the currents have the form of toroid). So, the considered model is appropriate in this case. Other nonskyrmionic types of the MBD have Bloch lines in the domain wall. In this case, the in-plane component of the magnetization also produces stray field, additionally increasing the energy of the system, which can be taken into account within a more complicated model.

First, we consider the homogeneous superconducting film and show that it cannot stabilize the skyrmion. We neglect the thicknesses of the both films and assume $M_z(\mathbf{r}) = M_s h_f \delta(z)\mathrm{sgn}(r-R)$ and $\Lambda = \lambda_{eff}^{-1}\delta(z)$, where $\lambda_{eff}^{-1} = h_s\lambda^{-2}$. Performing the Fourier transform in the xy plane, one can find the following expression for the magnetostatic energy of the skyrmion:

$$E_m = -2\pi^2 M_s^2 R^2 h_f^2 \lambda_{eff}\int_0^{+\infty}\frac{J_1^2(kR)k\,dk}{1+2k\lambda_{eff}} \approx -\pi M_s^2 h_f^2 R \ln\left(\frac{2k_{max}R\lambda_{eff}}{2\lambda_{eff}+R}\right). \quad (2)$$

The logarithmic divergence of the above integral is a result of our assumption of the infinitely thin films and the sharp domain wall in the ferromagnetic. One has to introduce the cut-off wavenumber $k_{max} \sim \min\left(h_f^{-1}, \sqrt{K/A}\right)$, where $\sqrt{A/K}$ is the width of the domain wall in the ferromagnetic film. In the limit of the large MBD radii $R \gg \lambda_{eff}$, the energy of the skyrmion has a linear dependence on its radius

$$E_{fs} \approx R\left[2\pi\sigma h_f - \pi M_s^2 h_f^2 \ln(2k_{max}\lambda_{eff})\right]. \quad (3)$$

The energy of the skyrmion in a ferromagnetic film can be obtained from the expression (2) in the limit $\lambda_{eff} \to +\infty$. Then, we have the following expression for the energy of the MBD in the ferromagnetic film:

$$E_f \approx R\left[2\pi\sigma h_f - \pi M_s^2 h_f^2 \ln(k_{max}R)\right]. \quad (4)$$

The absolute value of the magnetostatic energy grows as $R\ln R$ so the large enough skyrmions are likely to expand until the azimuthal instability comes into play.

The energy of the domain wall in the F/S bilayer is higher than in the single ferromagnetic film due to the Meissner screening effect. This may allow to stabilize the skyrmion with artificial nanostructuring of the superconducting layer. If the radius of the skyrmion differs much from the radius of the dot/antidot, then the stray field is not affected by the boundary of the superconductor. This means that the energy of the skyrmion in F/S dot (antidot) system coincides with the energy of the skyrmion in the single ferromagnetic film while $R \gg R_0$ ($R \ll R_0$ in the case of the antidot) and coincides with the energy of the skyrmion in the F/S system with the nonstructured superconducting layer if $R \ll R_0$ ($R \gg R_0$ in the case of the antidot). Thus, the edge of the superconductor is a potential barrier for the domain wall. Evidently, the superconducting dot or the antidot forms the ring shaped barrier. The potential well for the skyrmion can exist in this case. In order to verify this statement, the magnetostatic problem was solved numerically. The depth of the potential well for the skyrmion depends on the screening properties of the superconductor which are stronger in terms of the shorter penetration depth for the thick superconductors. Due to this reason, the thickness of the superconducting layer was taken comparable to the London penetration depth λ in the numerical calculation. Indeed, a further increase in the thickness of the superconductor above λ cannot affect the trapping potential for the skyrmion because of the Meissner screening. The choice of the ferromagnetic material parameters for calculation is usual for the ordinary magnetic materials with the perpendicular magnetic anisotropy $M_s = 9.5\cdot 10^5$ A/m, $K = 8\cdot 10^5$ J/m^3, and

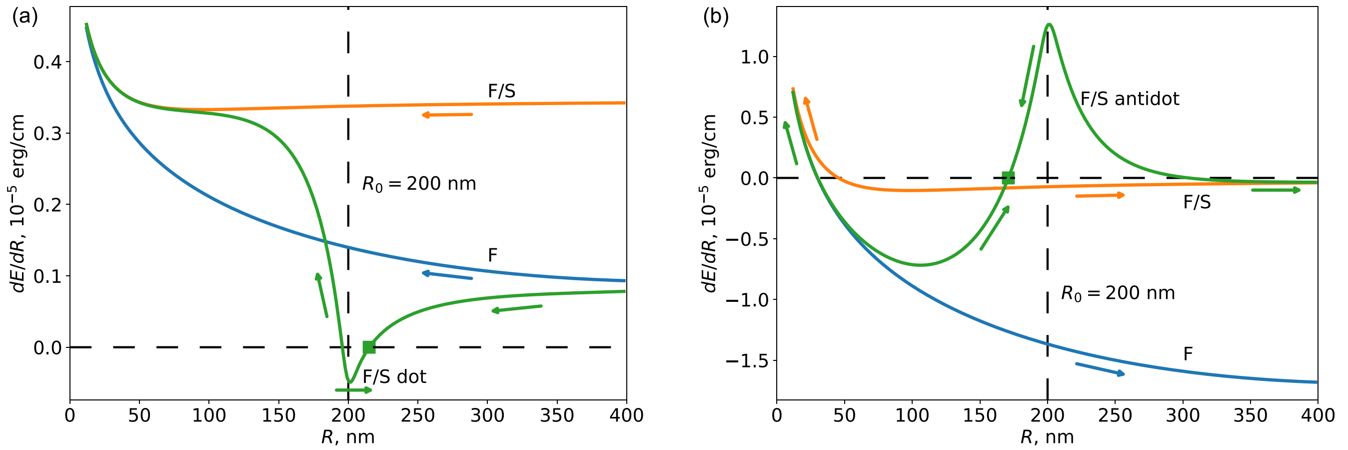

FIG. 2. The dependence of dE/dR vs. the skyrmion radius R in the F/S systems. The parameters of the calculation are $\lambda = 45\,\mathrm{nm}$, $R_0 = 200\,\mathrm{nm}$, $h_s = 100\,\mathrm{nm}$, (a) $h_f = 1.5\,\mathrm{nm}$, and (b) $h_f = 5\,\mathrm{nm}$. The derivatives dE/dR for the ferromagnetic film, F/S bilayer, and F/S (a) dot (b) anti-dot are shown by the blue, orange green lines, respectively. The squares show the local minima of the free energy of the skyrmion which are the metastable states. The arrows denote the direction of the change of the MBD radius while it relaxes to the stable value corresponding to the free energy minimum.

$A = 5 \cdot 10^{-12}$ J/m. For the best screening properties, it is necessary to use the superconductors with the small values of the London penetration depth such as clean Nb ($\lambda \approx 41\,\mathrm{nm}$) or Pb ($\lambda \approx 39\,\mathrm{nm}$).[30] Of course in realistic experimental situation, the disorder in film samples can strongly shorten the mean free path and increase, thus, the penetration depth (see e.g., Refs. 31–33). The minimal radius of the stable MBD grows with the increase in the penetration depth and, thus, only rather large skyrmions can be stabilized by a nanostructured dirty superconducting film.

The result of the numerical calculation is shown in Fig. 2. This figure shows the derivative of the skyrmion energy E by its radius R for the case of the (a) thin and (b) thick ferromagnetic films. The stable radius of the skyrmion which corresponds to $dE/dR = 0$ and $d^2E/dR^2 > 0$ is denoted by the square. Thus, the nanostructuring of the superconducting layer may stabilize the skyrmion at the radius close to the radius of the dot/antidot.

The dependence of the trapping potential on the London penetration length is shown in Fig. 3. There is a critical penetration length λ_c at which the equilibrium of the skyrmion is neutral ($dE/dR = 0$, $d^2E/dR^2 = 0$). For the $\lambda < \lambda_c$ (stronger screening), the skyrmion can be stabilized, while for $\lambda > \lambda_c$ (weaker screening), the stabilization is impossible. This critical length λ_c depends on the geometry of the sample and the properties of the ferromagnet. The dependence of the λ_c on the thickness of the superconducting film is shown in Fig. 4.

In the above model, we have completely neglected the action of the stray field on the superconducting order parameter absolute value (density of the Cooper pairs). As long as the stray field is less than the field of the vortex entry into the superconductor, the effect of the magnetic field results in the effective change of the dot/anti-dot radius due to the local suppression of the superconductivity near the MBD. This may lead to the decrease in the critical penetration depth λ_c, i.e., the superconductor with the stronger screening properties may be needed in order to stabilize the skyrmion. In the case of the stronger stray field, the vortices penetrate the superconducting film and the proposed mechanism of the skyrmion stabilization is suppressed.

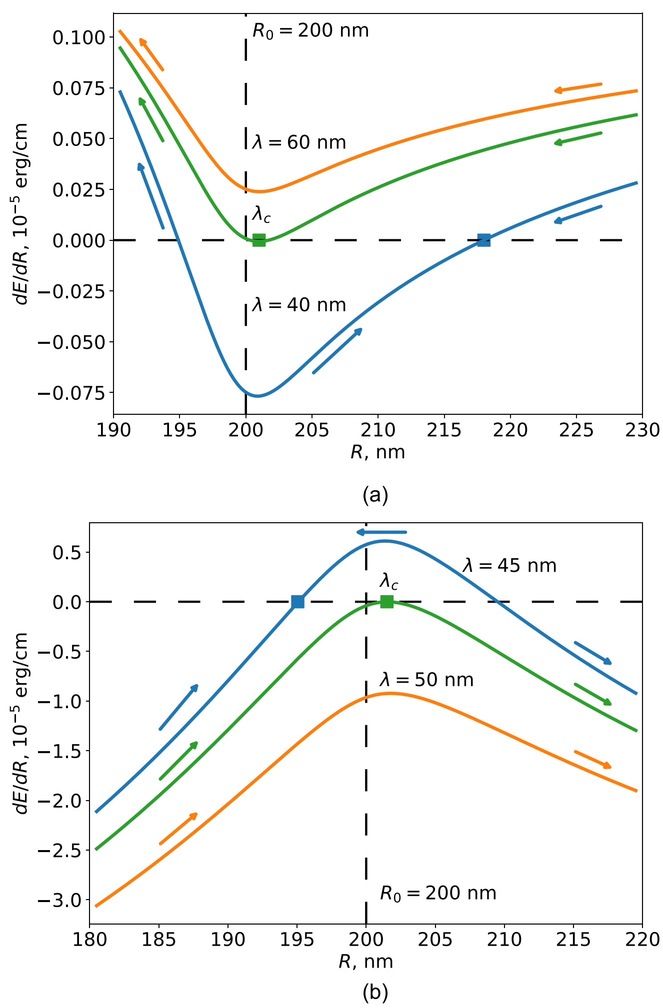

FIG. 3. The dependence of dE/dR vs. the skyrmion radius R in the F/S (a) dot (b) antidot systems for different penetration lengths λ. The parameters of the calculation are $h_s = 100\,\mathrm{nm}$, (a) $h_f = 1.5\,\mathrm{nm}$, and (b) $h_f = 10\,\mathrm{nm}$. The squares show the local minima of the free energy of the skyrmion which are the metastable states. The critical λ_c for which the skyrmion can be stabilized is (a) $\lambda_c \approx 53.4\,\mathrm{nm}$ and (b) $\lambda_c \approx 48.6\,\mathrm{nm}$. The arrows denote the direction of the change of the MBD radius while it relaxes to the stable value corresponding to the free energy minimum.

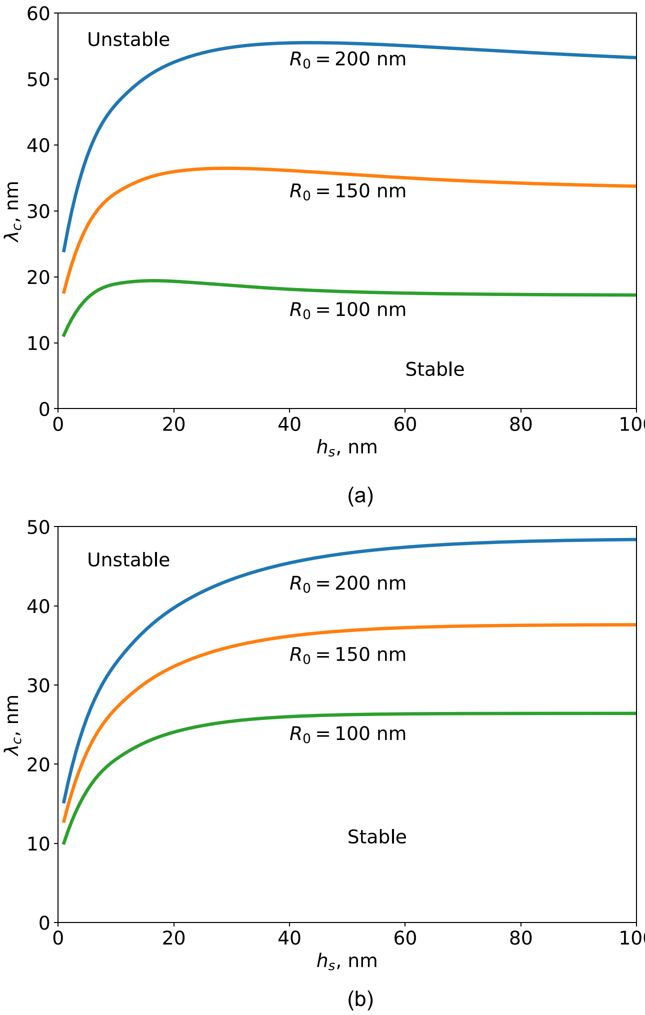

FIG. 4. The skyrmion stability diagram for the various (a) dot and (b) anti-dot radii. The thickness of the ferromagnetic film is (a) $h_f = 1.5$ nm and (b) $h_f = 10$ nm.

To sum up, we demonstrate that the MBD in the S/F bilayer can be stabilized by nanostructuring of the superconducting layer. Meissner screening of the stray fields of the MBD leads to the stabilization of the skyrmion at radius close to the radius of the dot/anti-dot. The stabilization takes place if the penetration depth in the superconductor λ does not exceed the critical value λ_c. The radius of the stable MBD can be small enough (up to 150 nm) which allows to obtain rather large density of the skyrmions in realistic experimental systems.

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