Interaction between a magnetic domain wall and a superconductor

L. E. Helseth, P. E. Goa, H. Hauglin, M. Baziljevich, and T. H. Johansen
Department of Physics, University of Oslo, P.O. Box 1048 Blindern, N-0316 Oslo, Norway
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The interaction between a magnetic thin film and a superconductor is studied. In particular, the equilibrium width of a Bloch wall is estimated with and without the superconductor. It is shown that the Bloch wall experiences a small shrinkage on cooling through the critical temperature of the superconductor. Furthermore, the interaction between the Bloch wall and a single vortex is estimated.

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I. INTRODUCTION

The interaction between superconductivity and magnetism has been studied for several decades. Systems composed of alternating magnetic and superconductive layers are of interest not only because they are model systems for the interplay of competing superconducting and magnetic order parameters, but also because of numerous possible applications. Recently, the development of magnetic thin film technology has triggered new interest in this field. Of particular importance is the possibility of examining the interaction between superconductivity and magnetism in high-temperature superconductors.[1–5]

Bulaevskii *et al.* showed that magnetic domain structures in a magnetic film in close contact with a superconducting film may enhance the pinning of vortices, since this gives an opportunity to pin the magnetic flux of the vortex rather than its core.[1] It was suggested that the pinning of vortices in superconductor/ferromagnetic multilayers can be 100 times greater than the pinning by columnar defects. Later, this proposal was partially verified, but only in the case of a bilayer structure.[3]

Another interesting proposal is that of Sonin, who suggested that the magnetostatic field from a domain wall may create a weak link at which single vortices could be localized.[4] Then, by moving the domain wall, one should also be able to move the weak link as well.

Evidently, many interesting applications could be developed if such interactions are better understood. In the present work we examine the interaction between a magnetic domain wall and a superconductor. First we investigate the interaction between a thin magnetic film and a superconducting substrate, and estimate the equilibrium width of a Bloch wall in the film. It will be shown that due to flux repulsion, the domain wall experiences a small shrinkage on cooling through the critical temperature of the superconductor. This could be exploited in magnetooptic waveguide systems. In such systems it is possible to match the interacting mode's phases using the spatial periodicity of a sequence of Bloch walls.[6] Altering the width of these domain walls simply by tuning the temperature could be an effective way to change the light propagation in the waveguide.

We also study the interaction between the domain wall and a single vortex in a type-II superconductor. This is of interest both in fundamental and applied physics. If we build further on the idea of Sonin, it should be possible to create a memory device based on active control of generation and annihilation of vortices by means of one or more domain walls. In recent years superconducting circuits based on single-flux-quantum pulses have been shown to provide a family of digital electronics with ultrahigh speed and very low-power dissipation. At clock rates exceeding 10 GHz and an operation speed of many hundred GHz, these devices can in the future outrun any semiconductor device.[7] Using domain walls as active "vortex gates," we may add an additional degree of freedom in these devices. It is known that bismuth-substituted ferrite garnet films with in-plane magnetization have domain walls with very low coercivity that can be moved without ambiguity at frequencies up to several GHz.[6] Furthermore, in such materials Bloch walls are easily formed by external magnetic fields or stress patterns, and these could be manipulated in numerous ways suitable for a memory device.

II. EQUILIBRIUM WALL WIDTH

Consider a magnetic film of thickness d with two domains of opposite in-plane magnetization. The domains are separated by a 180° Bloch wall of width w and length L. The magnetic film is placed in contact with a type-I superconductor. We assume that the superconductor has a zero penetration depth, so that an image of the Bloch wall is formed inside the superconductor as shown in Fig. 1. Here we want to estimate the equilibrium wall width with and without the superconductor. To this end, we use a linear wall model

$$\theta=\frac{\pi x}{w}, \quad -w/2<x<w/2, \tag{1}$$

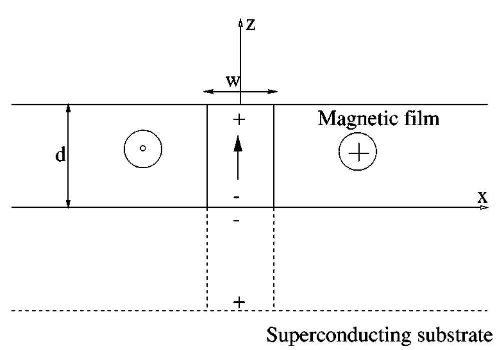

FIG. 1. A magnetic thin film with two in-plane magnetized domains placed on top of a superconducting substrate.

where θ is the angle between the magnetization vector and the z axis. Contributions to the total wall energy comes from the exchange interaction, the crystalline anisotropy, the magnetostatic energy, and magnetoelastic effects. Here we neglect the magnetoelastic energy, which is justifiable when the wall width is small. Also, if the substrate on which the magnetic film is deposited is thick, a large portion of the stress is dissipated in the substrate as well (note that this substrate is not necessarily the superconductor, but could be some other material on which the magnetic film is deposited).

For a Bloch wall the anisotropy energy per unit length of wall is given by

$$E_u = wd\frac{1}{\pi}\int_{-\pi/2}^{\pi/2} K_u \sin^2\theta d\theta = \frac{1}{2}wdK_u, \tag{2}$$

where K_u is the uniaxial anisotropy constant.

The exchange energy per unit length of wall is expressed by

$$E_{ex} = wdA\left(\frac{\partial\theta}{\partial x}\right)^2 = \pi^2 A\frac{d}{w}, \tag{3}$$

where A is the effective exchange constant.

The magnetostatic energy of a Bloch wall can be found by approximating the wall with a homogenously magnetized elliptic cylinder,[8]

$$E_m = \frac{1}{2}\mu_0\frac{w^2 d}{w+d}M_s^2, \tag{4}$$

where μ_0 is the permeability of vacuum, and M_s is the saturation magnetization in the magnetic material. Equation (4) is a reasonable approximation for materials with low permeability, and has been used to model the domain wall behavior in ferrite garnet films (see, e.g., Ref. 9, and references therein).

In the presence of the superconducting substrate the magnetic surface charge at $z=0$ is at most doubled, which means that the energy density cannot increase by more than four times. In the limit $d \gg w$ the energy density at $z=d$ is not altered. If we now assume that the area occupied by the magnetic field is not decreased, then the average energy in the presence of the superconductor is $(4+1)/2=2.5$ times that without the superconductor. This is an upper estimate of the increase in energy, since the area will change upon introduction of the superconductor, and the energy density is lower than that assumed here. To date, to our knowledge nobody has performed an accurate analysis of the magnetostatic energy resulting from the influence of a superconducting substrate. However, it is reasonable to expect that the magnetostatic energy has a similar functional dependence of film thickness and wall width as in Eq. (4), if we assume that only the width of the domain wall changes upon introduction of the superconductor. Therefore, we will characterize the increase in energy by a factor γ,

$$E_m = \frac{\gamma}{2}\mu_0\frac{w^2 d}{w+d}M_s^2, \tag{5}$$

where $\gamma=2$ with and $\gamma=1$ without the superconductor. We strongly emphasize that $\gamma=2$ is only a reasonable guess made in order to estimate an upper bound for the superconductor's influence on the wall width, and that a complete micromagnetic analysis is required to obtain a more accurate answer. Such an analysis should take into account the finite penetration depth and the fact that the magnetization in the Bloch wall changes in a continuos manner.

To find the equilibrium wall width, we must minimize the total energy according to

$$\frac{\partial E}{\partial w} = 0. \tag{6}$$

Here we will only consider the limit $d \gg w$,

$$\gamma\mu_0 M_s^2 w^3 + \frac{1}{2}dK_u w^2 - \pi^2 Ad = 0, \tag{7}$$

which can easily be solved numerically.

Increasing the magnetization increases the effect of the superconducting substrate as well. It is seen that when the anisotropy constant can be neglected, the equilibrium wall width becomes

$$w = \left(\frac{\pi^2 Ad}{\gamma\mu_0 M_s^2}\right)^{1/3}, \tag{8}$$

and the wall width decreases at most by $2^{1/3} \approx 1.3$ by crossing the critical temperature of the superconductor.

Sonin analyzed a periodic array of domains with magnetizations perpendicular to the film, and found that in the limit $K_u \gg 1/2\mu_0 M_s^2$ the domain width decreases at most by $\sqrt{1.5}$.[5] In our case the change is probably smaller, since the contribution due to the uniaxial anisotropy is often comparable to that from the magnetization. However, when the magnetostatic energy can be neglected, the wall width is given by

$$w = \pi\sqrt{\frac{2A}{K_u}}, \tag{9}$$

and the superconductor has no influence.

As an example we calculate the equilibrium wall width in the case of a ferrite garnet film of composition $Lu_{3-x}Bi_xFe_{5-z}Ga_zO_{12}$. In these films it is easy to obtain single Bloch walls of the kind discussed here. Reasonable material parameters are $A \sim 2\times10^{-11}$ J/m and $K_u \sim 10^3$ J/m^3. Figure 2 shows the wall width as a function of the magnetization M_s with $(\gamma=2)$ and without $(\gamma=1)$ the superconducting substrate. It is seen that the wall width decreases with increasing magnetization. Also note that the difference between $\gamma=1$ and $\gamma=2$ is around 20%. In a magnetooptic waveguide a 20% change in the wall width is probably enough to alter the light propagation substantially. A larger difference can be obtained by reducing the anisotropy constant K_u. In $Lu_{3-x}Bi_xFe_{5-z}Ga_zO_{12}$ this is often done by reducing the Bi content.

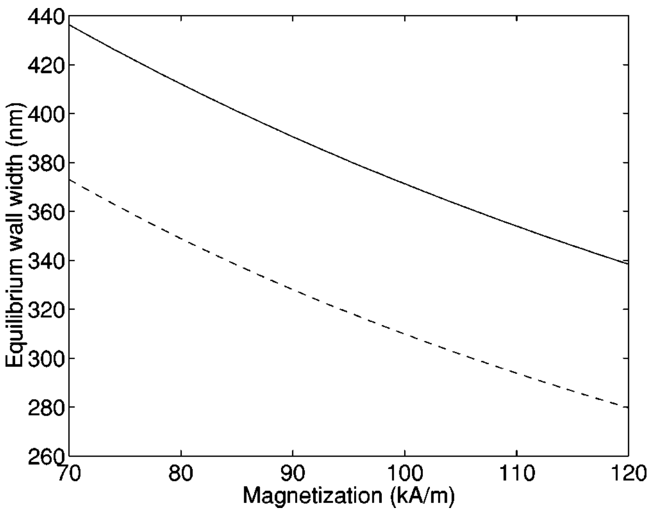

FIG. 2. The equilibrium wall width as a function of magnetization with (dashed line) and without (solid line) the superconducting substrate. We have assumed that $A\sim 2\times 10^{-11}$ J/m, $K_u \sim 10^3$ J/m^3, and $d=5$ μm.

III. INTERACTION BETWEEN A DOMAIN WALL AND A SINGLE VORTEX

Consider a straight vortex located a distance a from the Bloch wall, see Fig. 3. Due to the magnetic field from the Bloch wall, there will be an interaction between the two. We assume that the magnetic film is so thick that the magnetic poles at $z=d$ and $-d$ do not "feel" the field from the vortex, and the pole strength at $z=0$ is now two times that of the domain wall alone (if the distance a is large and the penetration depth is small). To find the interaction between the vortex and the domain wall, one should in general solve the London-Maxwell equations, including the contributions from supercurrents. However, here we estimate only the purely magnetostatic interaction, which means that the interaction energy can be calculated considering only the magnetostatic forces between a magnetic monopole and a magnetic surface charge, using the following integral:

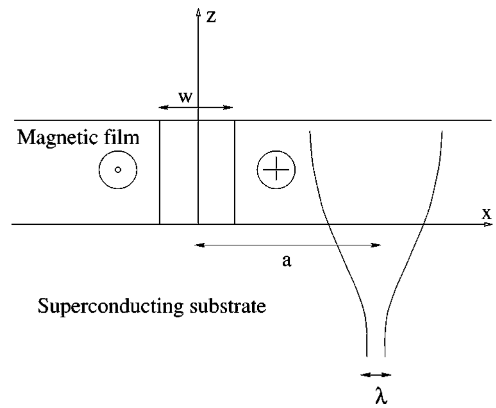

FIG. 3. The basic geometry for a Bloch wall located a distance a from a single vortex.

$$E_{int}=\mu_0\int_S \phi \boldsymbol{M}\cdot d\boldsymbol{S}. \tag{10}$$

It has been found that the field from a vortex is similar to that from a magnetic monopole located a distance $z_0=-1.27\lambda$ (λ is the penetration depth) below the superconductor surface.[10] In this approximation the scalar potential can be written as

$$\phi=\frac{\Phi_0}{2\pi\mu_0}\frac{1}{\sqrt{(x-a)^2+y^2+(z-z_0)^2}}, \tag{11}$$

where Φ_0 is the flux quantum. Note that Eq. (11) assumes that the medium above the superconductor is isotropic with permeability μ_0. An accurate calculation should take into account the anisotropy of the magnetic film. However, here we will neglect the fact that the magnetic film alters the field from the vortex, in order to obtain a simple estimate of the interaction energy. Then the x component of the force acting on the vortex is given by

$$F_x=-\frac{\Phi_0 M_s}{\pi}\ln\left|\frac{\left[\frac{L}{2}+\sqrt{\left(\frac{L}{2}\right)^2+\left(\frac{w}{2}-a\right)^2+(z-z_0)^2}\right]\left[-\frac{L}{2}+\sqrt{\left(\frac{L}{2}\right)^2+\left(\frac{w}{2}+a\right)^2+(z-z_0)^2}\right]}{\left[\frac{L}{2}+\sqrt{\left(\frac{L}{2}\right)^2+\left(\frac{w}{2}+a\right)^2+(z-z_0)^2}\right]\left[-\frac{L}{2}+\sqrt{\left(\frac{L}{2}\right)^2+\left(\frac{w}{2}-a\right)^2+(z-z_0)^2}\right]}\right|. \tag{12}$$

We have assumed that the magnetic charge is $\sigma=-2M_s$, which is strictly valid for a zero penetration depth and $z=0$. If the magnetic wall is moved away from the superconductor ($z\neq 0$), the magnetic charge changes, and Eq. (12) must be regarded as a rough approximation. It must also be pointed out that the vortex is a normal-state region, and is therefore expected to change the magnetic charge when it is near the Bloch wall. Thus the expression for F_x should be regarded as an upper limit of the force between the vortex and the Bloch wall, but should have the correct order of magnitude.

When L is much larger than λ, w, and a, then F_x is almost independent of L. Note that the interaction strength can be tuned by changing the magnetization, which could be useful in a potential memory device. To visualize the strength of the interaction for different magnetizations, Fig. 4 shows the

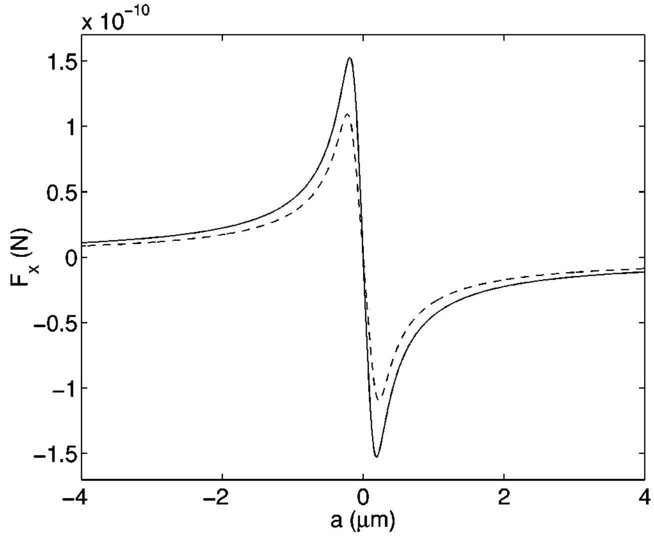

FIG. 4. The force F_x as a function of distance *a* from the vortex when $M_s = 120$ kA/m (solid line) and $M_s = 70$ kA/m (dashed line).

force as a function of distance when $A = 2\times10^{-11}$ J/m, $K_u = 10^3$ J/m^3, $d = 5$ μm, $\lambda = 100$ nm, $L = 100$ μm, and $z = 0$ nm, and Eq. (7) was used to calculate the wall thickness *w*. The solid line correspond to $M_s = 120$ kA/m, and the dashed line to $M_s = 70$ kA/m. The figure shows that by decreasing the magnetization, the force decreases as well. As expected from Fig. 3, the vortex is attracted toward the domain wall from both sides of the domain wall, and can be captured if it comes close enough. Also note that the vortex is repelled if the polarity of the Bloch wall is reversed. We see that the force F_x is rather small. Thus only if the pinning strength is small enough, can the Bloch wall be used to move the vortex. To develop a memory device as discussed in Sec. I, one needs carefully designed high-temperature superconductors with low pinning strengths.

IV. CONCLUSION

We have studied the interaction between a magnetic thin film and a superconductor. In particular, the equilibrium width of a Bloch wall is estimated with and without a superconducting substrate. It is shown that the Bloch wall experiences a 20% shrinkage on cooling through the critical temperature of the superconductor. Furthermore, the interaction between the Bloch wall and a single vortex is estimated, and it is found that the domain wall is able to trap the vortex if the vortex comes close enough.

ACKNOWLEDGMENT

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