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Coupled domain structures in superconductor/ferromagnet Nb-Fe/garnet bilayers

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We investigate the magnetic structure in a superconducting Nb and ferromagnetic garnet hybrid film. Direct magneto-optical observations reveal a strong interaction between the superconducting vortices in Nb and the magnetic domains in the garnet, resulting in a unique coupled domain structure. The cooperative motion of vortices and domain walls results in an enhanced pinning and a modified electromagnetic response of the hybrid similar to that in type I superconductors. Application of ac field, routinely used for equilibration of domains, leads to their significant contraction. Our calculations explain this effect by a domain shrinkage instability induced by the vortex annihilation around oscillating domain walls.

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The enhanced mobility of vortices at elevated temperatures poses a major challenge to high-temperature superconductor (HTS) based technologies, leading to rapid decay of the critical currents and increased electromagnetic noise. A solution to the problem is to utilize magnetic pinning of vortices in superconductors (SC).[1] Magnetic pinning is practically temperature independent, provides high pinning energy and correlated pinning geometries [as in the case of domain walls (DWs) and magnetic grains] and thus can efficiently attenuate flux dynamics in HTS. It can be engineered by placing a superconductor in intimate contact with a ferromagnet (FM). Such close contact of materials with antagonistic order parameters can generate a wide variety of phenomena induced by short-range (proximity) and long-range (orbital) interactions. Effects such as the appearance of π- and intermediate-phase shifts of the superconducting order parameter, the variations in SC transition temperatures, the reentrant and domain-wall superconductivity, and magnetic pinning have lately been studied intensively and discussed in several recent reviews.[2–6] In this work we address the appearance of *coupled domain structures* (CDSs) which define the unique coherent dynamics of FM domains and SC vortices and lead to a modified complex electromagnetic response in the FM/SC hybrid system. The cooperative effect of vortex and domain-wall pinning effectively restrains magnetic-flux mobility and can provide a route to improve the high-temperature properties of superconductors.

Here we study coupled domain structures in superconducting/ferromagnetic bilayer and show their peculiar properties and effects on magnetization of the hybrid. In bare ferromagnets the equilibrium DS results from the balance between the magnetic stray field energy, which decreases when domains contract and the energy of domain walls, which increases when the domains become narrower. If a FM film is covered with a SC layer, the Meissner screening modifies the stray fields at the FM/SC interface and can noticeably reduce the FM domain width D, as was predicted in Refs. 7–9. This is valid for narrow domains $D < d_F$ (d_F is the thickness of the FM film). In this case the total screening increases the energy of stray fields and can reduce D by a factor of $\sqrt{1.5}$.[7,10,11] In contrast, for $D \gg d_F$ the magnetostatic energy is strongly suppressed by screening and a considerable expansion of the domains is expected.[11] However, the recent observation of the domain shrinkage beyond the factor of $\sqrt{1.5}$ in Pb coated magnetic garnet even for the case of $D > d_F$ (Ref. 12) indicates that another scenario may be at play.

The Meissner screening of FM domain stray fields by a superconductor is not the only possible effect that defines the domain structure in SC/FM hybrids. An alternative scenario[7,13] is the spontaneous nucleation of SC vortices on top of a FM film if the film has perpendicular magnetic anisotropy. Counterintuitively, this should occur even in the absence of magnetic stray fields. In wide domains ($D \gg d_F$), where the stray fields exist only in the vicinity of the domain walls, a vortex flux (Φ_0) in the SC layer interacts with the FM domain magnetization ($\mathbf{M}$) and reduces the energy of the system by $E_M = -\mathbf{M}\Phi_0 d_F$. Thus, for large enough M, when E_M exceeds the vortex energy $E_v = d_s\Phi_0 H_{c1}/4\pi$ (H_{c1} is the lower critical field and d_s is the SC film thickness) spontaneous vortices polarized along $\mathbf{M}$ should appear above the FM domains. The condition for vortex nucleation is $M > H_{c1}d_s/4\pi d_F$ for $D \gg d_F$.[14] A similar condition, $M > H_{c1}d_s/4.66d_F$, is found for $D \ll d_F$.[15] As a result, a specific CDS will be formed defined by both FM and SC properties which can be different from regular magnetic domains. The CDS should always be considered in thin SC films with $d_s/d_F \ll 1$ and in all films close to T_c (when $E_v \sim 0$). As was predicted in Ref. 14, the coupled domains should strongly *contract* below T_c. However, we find that correction of a coefficient in the vortex/magnetization coupling energy ($-M\Phi_0$ instead of $-1/2\ M\Phi_0$) yields an opposite forecast, a significant expansion of the *equilibrium* domains.

In this work we directly image the domain structure of a rare-earth iron garnet film with perpendicular magnetic anisotropy that is half covered with a Nb layer and observe a strong coupling between SC vortices and magnetic domains resulting in the coupled domain structure. Our experiment shows that the CDS is a key property of FM/SC hybrids. It modifies their electromagnetic response and yields efficient "magnetic" pinning for arresting vortex motion at high temperatures. In the ac field, we find a strong contraction of domains over the Nb area at $T < T_c$. The equilibrium state of the FM/SC coupled domain structure is described by the total-energy balance including strong interaction between vortices and magnetic domains, which reduces the effective magnetization M_{eff} at $T < T_c$. For $D \gg d_F$ the domain width increases exponentially with decreasing magnetization (see also Ref. 16). Therefore, in the FM/SC system the reduced $M_{\rm eff}$ should cause the *expansion* of coupled domains compared to domains in the normal state. Instead, we observe a remarkable contraction of the coupled domains after equilibration in an ac field. We show that such a behavior emerges from a specific shrinkage instability if the *vortex density* in the domains is *reduced* compared to the equilibrium value. The reduced vortex density results from the vortex-antivortex annihilation around oscillating domain walls. The final CDS is affected by the cooperative domain/vortex dynamics and depends on the pinning and ac field. Similar to the ordinary SC critical state it represents a metastable flux configuration supported by the cooperative flux pinning and can be stationary for a very long time. Below we present the main results of our experiment and theoretical model.

A 3.9-μm-thick rare-earth substituted yttrium iron garnet film epitaxially grown on a nonmagnetic (111) gadolinium gallium garnet was used as the FM substrate. At room temperature this film with perpendicular magnetic anisotropy had 6.6-μm-wide labyrinth domains, typical for materials with high quality factors $Q=K/2\pi M^2 \gg 1$ (K is the uniaxial anisotropy constant). These domains could be transformed into cylindrical domains which collapse at a field $H_c=53$ Oe along the easy axis. With decreasing T the easy axis remained along [111] but both domain width and H_c increased. We covered half of this 7×5 mm^2 film with a 100-nm-thick Nb layer, magnetron sputtered at 6.5×10^{-10} Torr base pressure in 4 mTorr Ar atmosphere. The film exhibited a SC transition at 8.5 K with transition width ~0.2 K.

The use of a dielectric FM garnet film substrate eliminates proximity interactions and enables exploring effects of purely magnetic coupling. Also, in garnet films the equilibrium domain width and collapse field are well described by experimentally proven formulas[17–19] allowing us to extract the magnetic parameters such as the dipolar length $l_c=\frac{\sqrt{AK}}{\pi M^2}$ (A is the exchange constant) and M. For $D=6.6$ μm and $d_F=3.9$ μm, these formulas yield $l_c=0.87$ μm and $M=11.8$ G. From superconducting quantum interference device magnetization measurements we obtained the in-plane saturation field $H_s=2K/M=3200$ Oe yielding the anisotropy constant $K=1.9\times 10^4$ erg/cm^3 and $Q=21.36$. Finally, from l_c we obtained $A=0.8\times 10^{-7}$ erg/cm and the domain-wall energy $\sigma_{DW}=4\sqrt{AK}=0.156$ erg/cm^2.

The domains tended to expand upon cooling but with a noticeable delay due to the increased pinning of DWs. To achieve an equilibrium DS at lower temperature, we used a traditional "magnetic shaking" technique by applying and slowly reducing a magnetic ac field perpendicular to the film. The optimum amplitudes ($h_\perp$) and frequencies (f) for this process were determined through direct observation of the DW motion and changes in the DS. Figure 1 shows temperature dependence of the equilibrated D obtained after reducing h from 50 Oe to 0 at 17 Hz. At low temperatures we observed an unusually large increase in the DS period. However, it turns out to be in accordance with the increase in magnetic constants extracted from magnetization measurements. At 8.5 K we have $D=26.9$ μm, $M=15.9$ G, and $K=6\times 10^4$ erg/cm^3. This yields $l_c=2.49$ μm and $A=6.6\times 10^{-7}$ erg/cm. The increase in the domain-wall energy $\sigma_{DW}(8.5\text{ K})/\sigma_{DW}(300\text{ K})=5$ is larger than that of the magnetostatic energy $M^2(8.5\text{ K})/M^2(300\text{ K})=1.8$ which explains the observed expansion of the domains.

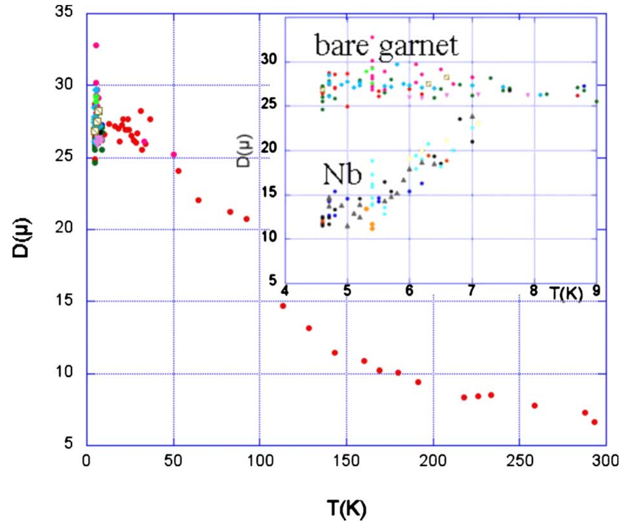

FIG. 1. (Color online) Temperature dependence of the domain width in bare garnet and Nb covered areas. Low-T data collected at several cooling/heating runs around T_c are shown in the insert.

Cooling slightly below $T_c \sim 8.5$ K does not show any obvious effect of the SC layer on the domain structure even after magnetic shaking. However, at ~2 K below T_c the ac equilibrated domains under the Nb film become narrower than in the bare garnet layer as shown in Fig. 2(a). To the right of the Nb edge marked by the white line in Fig. 2, there is a transition band (marked by dotted line), where the domain width evolves from that of the bare garnet film (D_M) to a smaller value in the SC area (D_S). This band shrinks at lower T [see broken lines in Fig. 2(a)]. Deeper in the SC region, where the ac field is screened by the Nb film, wider domains may stay frozen from higher temperatures. Intensities of the contrast in Fig. 2, obtained using a magneto-optical (MO) indicator, show that domains in the Nb area have nearly the same alternating induction as domains in the bare garnet and reveal their dense population with vortices and formation of the combined DS. The ac field amplitude required for shaking domains in the SC region at lower T is larger than that for the bare garnet film. Here vortex pinning significantly contributes to the coercivity of the domain walls over the SC area. In turn, domain walls restrain the vortex dynamics. So, the flux attenuation in the hybrid is defined by the cooperative action of both pinning components making the total flux pinning more efficient.

Figure 2(a) shows that after application of the ac field the domain size in the SC region varies but the average width D_S decreases with decreasing temperature and tends to saturate as shown in the inset of Fig. 1. The ratio D_M/D_S for the narrowest domains in the SC area is ~3 and the average ratio below 6 K is ~1.9. It is well above the maximum ratio of 1.2 achievable with total Meissner screening of the stray fields of narrow ($D<d_F$) FM domains[7,10] and it is in contrast to the expected expansion of domains for $D>d_F$.[11] Thus our results indicate that the effect of the SC screening is negli-

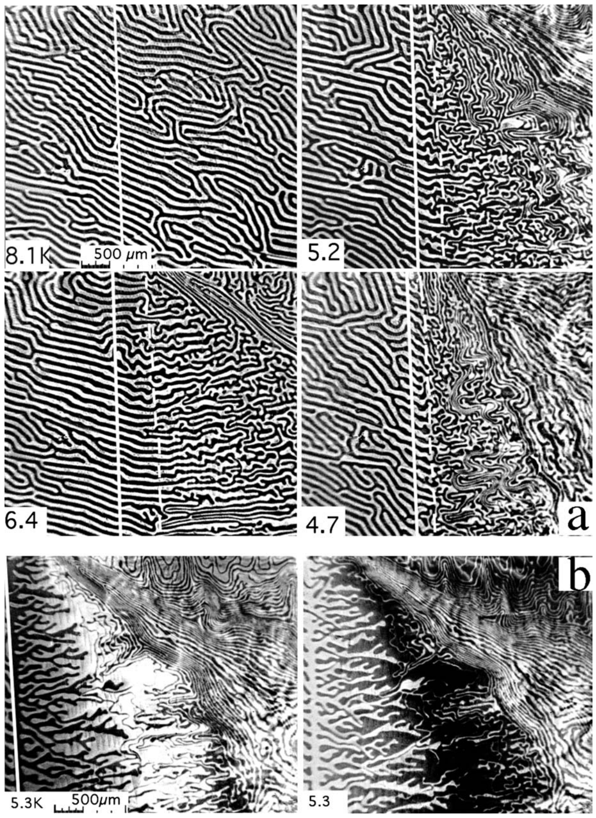

FIG. 2. (a) Pictures of the domain structure in a Fe-garnet film half covered with Nb layer (on the right from white line) after application and gradual decrease in a perpendicular ac field $h_\perp(17\ \text{Hz})=50$ Oe at shown temperatures. Bright and dark contrast corresponds to opposite local normal fields in domains visualized using magneto-optical indicator on top of the hybrid. Dashed lines marks the boundary of the transition zone near the Nb edge (see text). (b) MO images at +40 and −40 Oe. The sample is slightly shifted.

gible and the domain contraction has another origin. In the model below we explain the domain shrinkage by a specific magnetic instability of the coupled domain structure induced by the vortex/antivortex annihilation in ac fields.

At small $h_\perp$ coupled domains of both polarities are equal, slightly vibrate, and do not change their size. However, at larger amplitudes the field penetrates deep into the Nb film resulting in the collapse of domains polarized against the field. Images at application of +40 and −40 Oe and at $T\sim 5$ K [Fig. 2(b)] reveal an important feature of the remagnetization process in our sample. Unlike in a single SC layer, where vortices enter forming a smooth front advancing from the sample edge, in our hybrid structure the flux penetrates in the shape of fingering CDS extended from the SC edge. The picture is similar to the magnetization of a type-I SC where the field penetrates in the form of normal domains expanding at the expense of superconducting Meissner domains. In our system the magnetization also occurs through domain-wall motion advancing coupled domains polarized along the field. Such a cooperative domain/vortex behavior has a significant effect on the hybrid electromagnetic response due to the synergy of the vortex and domain-wall pinning which arrests the flux dynamics more efficiently and thus can lead to larger critical currents. A comparison with a similar Nb layer simultaneously sputtered on a glass substrate shows that the hybrid structure has essentially larger pinning, which in fact strongly suppresses thermomagnetic avalanches. Clearly, this cannot be referred to the Foucault current damping because the garnet film is dielectric.

To introduce our model we first consider a single FM film with perpendicular anisotropy and stripe domains with $D \gg d_F$, where the magnetostatic energy acquires a logarithmic form (see, e.g., Ref. 16) $E_{MS}(D)\approx 2\pi M^2 d_F -(4M^2 d_F^2/D)\ln(D/d_F)$. This renders a dramatic effect on the domain width yielding a strong exponential dependence $D = d_F \exp(1+\sigma_{DW}/4M^2 d_F)$. A SC overlay, which screens the stray fields will suppress the magnetostatic term and increase the equilibrium D.[11] To account for the spontaneous nucleation of vortices in domains one has to analyze the total energy including the energy of individual vortices, vortex-vortex and vortex-magnetization coupling, vortex interactions with domain stray fields, and the FM magnetostatic energy. Following Ref. 14 with a correct coefficient, $\varepsilon_0 d_s - M\Phi_0 d_F$, for the single vortex energy we calculate the total energy per unit area of the FM/SC bilayer with $d_F \gg \lambda$ and obtain the equilibrium coupled domain width which is larger than in the normal state,

$$D_{eq} = d_F \exp\{1 + \sigma_{DW}/4d_F[M - \varepsilon_0 d_s/(\Phi_0 d_F)]^2\}. \qquad (1)$$

Next, similar to Ref. 14, we find the equilibrium distribution of vortices in domains and by integrating over the domain area get the total number of vortices per unit domain length,

$$N_{eq} \approx \{8d_F[M - \varepsilon_0 d_s/(\Phi_0 d_F)]/\Phi_0\}\ln(D/d_F). \qquad (2)$$

The important conclusion from Eq. (2) is that the equilibrium number of vortices in domains is strictly related to their width D.

Obviously, our experimental situation is different from equilibrium. It involves a complicated coupled domain/vortex dynamics. However, assuming a partial annihilation of vortices due to DWs oscillations in the ac field we can consider a simplified static case, where the number of vortices N in the domains is less than N_{eq}. In equilibrium, the maximum gradient of the vortex density at the domain walls is supported by a strong (depairing) current along the DWs. If N is decreased, the current along the DW drops preventing any further change in the vortex density and vortices get locked in the domains. Therefore, we can consider a situation with N=const. It is described by the energy functional where instead of the standard factor $-M\Phi_0+\varepsilon_0 d_s/d_F$ in the single vortex energy we use a Lagrange coefficient that can be written as $-\tilde{M}\Phi_0$. Then similar to Eq. (2) we obtain $N=N_{ne} =(8d_F\tilde{M}/\Phi_0)\ln(D/d_F)=\text{const}$ and the energy per unit area,

$$E_{tot}^{ne} = d_F\sigma_{DW}/D - N_{ne}^2\Phi_0^2/16D\ \ln(D/d_F).$$

This energy is positive at large D. With decreasing D, it increases to a maximum at $D_{max}=d_F \exp(1 +N_{ne}^2\Phi_0^2/16 d_F\sigma_{DW})$ and then decreases and changes sign as shown in Fig. 3.

Therefore, at $D<D_{max}$ the system becomes unstable with respect to domain contraction. The contraction stops when D

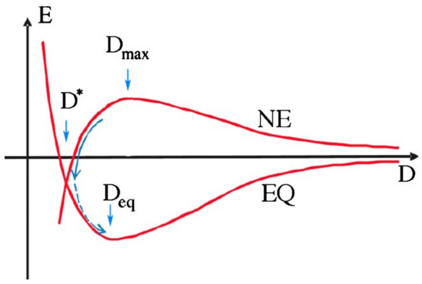

FIG. 3. (Color online) Dependence of the CDS energy on the domain width, $E(D)$, for the equilibrium (EQ) and nonequilibrium (NE) states. Arrows illustrate the evolution of the system from the NE to the EQ state.

reaches the equilibrium value corresponding to the given N_{ne} which occurs at the crossing of the nonequilibrium (NE) and equilibrium curves (see Fig. 3) at

$$D^* = d_F \exp\{N_{ne}\Phi_0/8d_F[M - \varepsilon_0 d_s/(\Phi_0 d_F)]\}.$$

At this D^* the contraction stops because the current along the DWs increases back to the depairing value, unlocking the vortices so that new vortices can populate the domains. Although the above calculations do not account for the pinning-dependent flux dynamics, they allow us to explain the observed domain shrinkage in the ac field. In the absence of h_{ac} on cooling through T_c, an equilibrium number of vortices and antivortices will be created in neighboring domains. Close to T_c the domain size is practically the same as in the normal state [small ε_0 and $d_s/d_F \ll 1$ in Eq. (1)]. In the presence of h_{ac}, the DWs oscillate, resulting in the vortex/antivortex annihilation and reduction in the total number of vortices in domains below N_{eq}. Consequently, the evolution of domains follow the nonequilibrium route with N_{ne} =const. The domains shrink until $D=D^*$. If there would be a sufficient supply of vortices allowing to increase their density, the system could return to the equilibrium state and the domains would expand from D^* to D_{eq} (Fig. 3). However, if the vortex supply is limited due to pinning, the observed domain width can remain at D^*. We estimate D^* by taking $D_{max} \sim D_{eq}$, which yields $N_{ne} = \sigma_{DW}/[M - \varepsilon_0 d_s/(\Phi_0 d_F)]\Phi_0$ so that

$$D^* = d_F \exp\{\sigma_{DW}/4d_F[M - \varepsilon_0 d_s/(\Phi_0 d_F)]^2\} = D_{eq}/e.$$

Thus the domain width can be ~3 times smaller than D_{eq} and for $M \gg \varepsilon_0 d_s/(\Phi_0 d_F)$ less than the normal state D in remarkable correspondence with our observations. Such an effect is not expected at larger temperatures, where the fast flux relaxation restores the equilibrium. This can explain the absence of the domain shrinkage near T_c. Also, it clarifies why the domains are wider near the edge of the SC film and narrower at the ac field penetration front. Close to the edge, h_{ac} provides a better supply of vortices and here the situation is closer to equilibrium. With decreasing T pinning increases and the transition zone of equilibrium domains shrinks (dotted line in Fig. 2 moves to the Nb edge). Further inside the SC the vortex supply is reduced due to pinning. Therefore, the nonequilibrium state forms easier and yields the smallest domains at the largest field penetration distance.

In conclusion, we have studied the magnetic structure in a hybrid composed of SC Nb layer on a FM garnet film with perpendicular anisotropy. A strong coupling between FM stripe domains and vortices of the same polarity in the SC layer results in a coupled domain structure which defines an electromagnetic response of the hybrid and efficiently arrests the magnetic-flux dynamics. In our samples the remagnetization occurs through the expansion and shrinkage of the coupled domains similar to the motion of normal and Meissner domains in type I superconductors. A critical state is defined by flux gradients formed by combined domains rather than by the usual vortex density gradients. Our preliminary experiments show that the cooperative domain/vortex pinning is essentially enhanced compared to that in a single superconducting layer and considerably suppresses thermomagnetic avalanches. This offers an effective route to improve the performance of superconducting components for power applications and electronics. In contrast to our predictions of the expansion of equilibrium coupled domains we observe the strong contraction of CDS after the ac field demagnetization. The effect is explained by the *nonequilibrium* evolution of CDS initiated by the partial annihilation of vortices in an ac field. Our model describes a consecutive scenario of this ac instability in the SC/FM hybrids.

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[1] L. N. Bulaevskii *et al.*, Appl. Phys. Lett. **76**, 2594 (2000).
[2] Y. A. Izyumov *et al.*, Phys. Usp. **45**, 109 (2002).
[3] A. I. Buzdin, Rev. Mod. Phys. **77**, 935 (2005).
[4] I. F. Lyuksyutov and V. L. Pokrovsky, Adv. Phys. **54**, 67 (2005).
[5] F. S. Bergeret *et al.*, Appl. Phys. A: Mater. Sci. Process. **89**, 599 (2007).
[6] A. Yu. Aladyshkin *et al.*, Supercond. Sci. Technol. **22**, 053001 (2009).
[7] G. M. Genkin *et al.*, J. Magn. Magn. Mater. **130**, 51 (1994).
[8] L. N. Bulaevskii and E. M. Chudnovsky, Phys. Rev. B **63**, 012502 (2000).
[9] L. N. Bulaevskii *et al.*, Phys. Rev. B **66**, 136502 (2002).
[10] E. B. Sonin, Phys. Rev. B **66**, 136501 (2002).
[11] A. Stankiewicz *et al.*, J. Phys.: Condens. Matter **9**, 1019 (1997).
[12] T. Tamegai *et al.*, J. Phys.: Conf. Ser. **150**, 052263 (2009).
[13] I. F. Lyuksyutov and V. L. Pokrovsky, Mod. Phys. Lett. B **14**, 409 (2000).
[14] S. Erdin *et al.*, Phys. Rev. Lett. **88**, 017001 (2001).
[15] R. Laiho *et al.*, Phys. Rev. B **67**, 144522 (2003).
[16] B. Kaplan and G. A. Gehring, J. Magn. Magn. Mater. **128**, 111 (1993).
[17] Z. Málek and V. Kamberský, Czech. J. Phys., Sect. A **8**, 416 (1958).
[18] C. Kooy and U. Enz, Philips Res. Rep. **15**, 7 (1960).
[19] T. G. W. Blake *et al.*, IEEE Trans. Magn. **18**, 985 (1982).