Shrinkage of magnetic domains in superconductor/ferromagnet bilayer

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Abstract. Shrinkage of magnetic domains in a ferromagnetic garnet film in contact with a superconducting Pb film is experimentally investigated by magneto-optical imaging. Nonequilibrium effects due to pinning of magnetic domains are suppressed by demagnetizing the sample by AC magnetic field. Although qualitative behavior follows the theoretical prediction, much larger shrinkage of the width of magnetic domains is observed. Possible origins for this discrepancy are discussed. We also confirm the magnetic shielding of the stray field from the garnet film by Pb by observing magnetic domain structures from the Pb side.

1. Introduction

Superconductors (SCs) and ferromagnets (FMs) have two antagonistic magnetic characteristics. SCs repel magnetic fields by the Meissner effect, while FMs concentrates magnetic flux on magnetic domains (MDs). In FMs, MD structures are formed to reduce magnetic energy due to stray field. The distribution of stray field from FMs depends on local magnetic environments. Recent theoretical studies have predicted that the presence of SC on top of FM greatly modifies the distribution of stray field, and eventually leads to a shrinkage of the width of MDs by a factor of \( (2/3)^{1/2} \approx 0.82 \) [1-4]. We have prepared Pb film on a garnet film with perpendicular anisotropy and attempted to observe the above-mentioned effect [5]. However, strong non-equilibrium effect due to the pinning of MDs prevents us from observing shrinkage of MDs in the equilibrium state. Time-dependent magnetic field is known to be effective to reduce the non-equilibrium pinning of MDs. We apply AC demagnetizing field to the Pb/garnet bilayer system below the superconducting transition temperature of Pb and succeeded in observing the shrinkage of the width of MDs in the garnet film.

2. Experiments

SC/FM bilayer is fabricated by depositing Pb film onto a magnetic garnet film by thermal evaporation. We use a Bi-substituted iron-garnet film with perpendicular anisotropy grown by the liquid phase epitaxy as a FM. The garnet film has a saturation field of about 80 Oe at room temperature and its magnetic characteristics have already been reported [5]. The 2x2 mm² garnet film is divided into four sections and Pb films of different thicknesses are deposited as shown in Fig. 1(a) after covering a half of the garnet by an aluminum mask. We first deposit 100 nm of Pb, and it is followed by a 200 nm Pb deposition after rotating the mask by 90 degrees. A typical pressure during the Pb deposition is \( \sim 3x10^{-7} \) Torr with a base pressure of \( \sim 5x10^{-9} \) Torr. We cover Pb film with 20 nm Ge film for protection. MDs in the garnet film are visualized by using the Faraday effect of the garnet...
itself. A cooled-CCD camera (Hamamatsu, ORCA II-ER) is used for the image acquisition. In the previous experiments, non-equilibrium effects due to the pinning of MDs prevented observation of the shrinkage of MDs in a similar system [5]. In the present study, effect of pinning is strongly reduced by demagnetizing the sample with AC magnetic field. For this purpose, AC field of 1 Hz with maximum amplitude of 150 Oe, which is larger than the saturation field, is applied and its amplitude is reduced to zero in 75 sec. After this demagnetization process, MD structures of the garnet film are imaged. The image acquisition after demagnetization is repeated hundred times to see the reproducibility of the phenomena. It turns out that although details of MD patterns are different for each demagnetized state, resulting average width of MDs are rather reproducible.

3. Results and Discussion

Figures 1(b)-(e) show MO images of the Pb/garnet bilayer from the garnet side at several temperatures. The optical contrast of the region without Pb film (right upper) is enhanced because the intensity of the reflected light is much less than regions with Pb film due to the absence of reflecting Pb layer. At 6.6 K, close to the superconducting transition temperature of Pb, there are no obvious differences in the width of MDs for four regions with different Pb thicknesses as shown in Fig. 1(b). As temperature is lowered to 6.2 K, the width of MDs in the region with 300 nm Pb starts to shrink after demagnetization (Fig. 1(c)). At this temperature, we also identify a slight shrinkage of MDs in the region with 100 nm of Pb as well as 200 nm of Pb. At 5.6 K, shrinkage of MDs even in the region with 100 nm Pb is clear (Fig. 1(d)). Finally, at the lowest temperature of 5.0 K, MDs in all regions with Pb film shrink appreciably as shown in Fig. 1(e). It is obvious that the shrinkage of the width of MDs is due to the presence of superconducting Pb in close contact with the garnet, since the effect is lost above the superconducting transition temperature of Pb. The shrinkage of the width of MD is not uniform possibly due to the presence of the defects in the garnet film. We evaluate the shrinkage factor by comparing the average width of MDs in regions without and with the thickest Pb. Since the width of MDs is not uniform even in the region with constant Pb thickness, we calculate the width of MDs, \( l \).
by averaging more than 100 points in the same region. The temperature dependence of the shrinkage factor $l(300 \text{ nm Pb})/l(\text{without Pb})$ is plotted in Fig. 2. The strongest shrinkage of 0.47 is observed at $T = 5.2 \text{ K}$, and it increases as the temperature is increased. The fact that the shielding of the stray field

![Fig. 2 Temperature dependence of shrinkage ratio of the width of magnetic domains in garnet in contact with 300 nm Pb film.](image)

from the garnet by Pb is responsible for the shrinkage of the width of MDs is further confirmed by observing the magnetic field profile from the Pb side. For this purpose, Bi-substituted garnet indicator film is placed on top of Pb side of Pb/garnet bilayer. Figures 3(b) shows MO images at 6.8 K, close to $T_c$ of Pb. At this temperature the effect of shielding by Pb is negligible and MDs of garnet are visible and their widths in all four regions are almost the same. At lower temperature of 6.4 K, shielding by Pb becomes effective in the region with 300 nm of Pb and stray field from the shrunk domains penetrate Pb film (Fig. 3(c)). At 5.4 K, stray field from MDs in region with 300 nm Pb becomes invisible by the shielding effect of Pb (Fig. 3(d)). At the lowest temperature of 4.4 K, stray fields from MDs in region with 300 nm and 200 nm become invisible by the shielding effect of Pb (Fig. 3(e)).

Theoretically, the minimum shrinkage factor of the width of MDs in contact with a thick enough SC is calculated to be $(2/3)^{1/2} \sim 0.82$ [1-4]. This value in the case of small London penetration depth is explained as follows. The width of MDs is determined to minimize the total energy of FM, $E_{\text{total}}$, which is the sum of magnetic energy $E_m$ and the energy of MD walls $E_{\text{DW}}$. Since $E_m$ is proportional to the width of MD $l$, and $E_{\text{DW}}$ is inversely proportional to $l$, the total energy is expressed as $E_{\text{total}} = E_m + E_{\text{DW}} = A l + B/l$. Hence, the minimum total energy is realized for $l = (B/A)^{1/2}$. For a FM in contact with a SC, magnetic field close to the face in contact with SC cannot penetrate the SC and it is concentrated inside the FM, making magnetic induction in the FM double. Total magnetic energy close to this face is diminished into half in the expense of four times larger energy inside the FM. Hence the total magnetic energy on this face becomes twice compared with an isolated FM. If the width of the MD is small compared with the thickness of the film, as is assumed in the theoretical work, magnetic energy on the other face of the FM is unaffected by the presence of SC. As a result, total magnetic energy of FM becomes 1.5 times larger than that in the isolated case. This increase of magnetic energy leads to the shrinkage of the width of MDs by a factor of $(2/3)^{1/2}$.

The observed shrinkage factor of 0.47 is much smaller than the minimum theoretical estimate. One possible reason for this strong effect could be due to the fact that we are still not observing equilibrium properties of the SC/FM bilayer system even after the extensive demagnetization. The presence of SC could make the effect of AC field limited due to shielding. In addition, the dynamics of MD walls becomes sluggish at lower temperatures where the influence of SC is significant. However, the fact that we always obtain similar amount of shrinkage makes this explanation unlikely. Another possible reason is the different aspect ratio of the MDs. In all theoretical estimates for SC/FM bilayer, the thickness of the FM, $t$, is assumed to be much larger than its width $l$. However, in the present garnet...
Fig. 3  (a) Thickness variations of Pb film on four sections of the garnet film. MO image of Pb/garnet bilayer from the Pb side at (b) 6.4 K (c) 6.0 K (d) 5.4 K (e) 4.4 K.

film, \( l \) is about 25 \( \mu \)m and \( t \) is 6 \( \mu \)m. When \( t/l \) is small, the presence of SC affects the magnetic energy on the other face of FM and makes magnetic energy of FM even larger. As a result, we may expect a stronger reduction of the width of MDs. It should also be noted that local fields near the MD boundaries increase divergently for small \( t/l \). Quantitative estimate of magnetic energy for FM in such a limit is highly requested.

4. Summary
We have studied the effect of superconductor on the magnetic domain structure of ferromagnet in Pb/garnet bilayer system. We confirm the theoretically predicted shrinkage of the width of magnetic domains due to the shielding of stray field by superconductor. The obtained shrinkage is much stronger than the theoretical estimate. We ascribe this discrepancy to the different aspect ration of magnetic domains of our garnet film from that assumed in the theory.

Acknowledgements
We thank Mitsubishi Gas Chemical for supplying the Bi-substituted iron-garnet film. We also thank E. Sonin and A. I. Buzdin for valuable comments. This work is partly supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology

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