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Magnetic Properties of Ferromagnetic-Superconducting Hybrid Films

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Magnetic properties of ferromagnetic and superconducting hybrid films were investigated. The magnetization process of the hybrid films exhibits peculiar behavior which suggests the existence of the magnetostatic interaction between the ferromagnetic and the superconducting layers.

Key words: ferromagnet, superconductor, hybrid film, magnetization curve

1. Introduction

Most studies concerning the ferromagnetic-superconducting hybrid films have focused on the proximity effect, i.e., the competition between the ferromagnetism and the superconductivity [1),2)]. In addition, the magnetostatic interaction between a ferromagnet and a superconductor also exists in the hybrid films. Recently, theoretical studies focusing on such a magnetostatic interaction have suggested that the magnetostatic interaction plays an important role for the determination of the magnetic domain configuration in the hybrid films [3)-5)]. The experimental result of the magnetostatic interaction has been already investigated in bulk samples [6)]. Additionally, an electric current switch consisting of a superconducting and a ferromagnetic layer was produced as an application of the hybrid system [7)]. In this device, the suppression of the superconductivity by the local magnetic field from the ferromagnetic layer was utilized for the switching. Therefore, it is of importance to investigate the magnetic properties of the ferromagnetic-superconducting hybrid films.

In this paper, the magnetic properties of ferromagnetic and superconducting hybrid films consisting of Fe/Si/Nb are presented. The magnetization process of the hybrid films is different from those of individual Fe and Nb films, suggesting the existence of the magnetostatic interaction between the ferromagnetic and the superconducting layers.

2. Experimental

Samples with trilayered structure consisting of Fe/Si/Nb were prepared on silicon substrates using RF sputtering process progressed in an argon gas pressure of 5.0×10^{-3} Torr. The Si layer is inserted so as to eliminate the superconducting proximity effect and to investigate only the magnetostatic interaction. The thickness of Nb layer was varied from 60 nm to 400 nm, while that of Fe and Si layer were fixed to 100 nm and 10 nm, respectively. Both Fe and Nb layers have enough thickness to keep their intrinsic ferromagnetic and superconducting properties. Nb and Fe films were also prepared to investigate the effect of the hybridization. All samples were patterned with a circular structure 5 mm in diameter using metallic

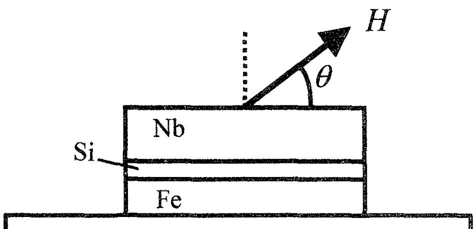

Fig.1 Trilayered structure of Fe/Si/Nb hybrid film. θ is the angle between the applied magnetic field and the sample plane.

masks. Magnetization measurements were performed by a vibrating sample magnetometer (VSM) at 4.5 K and 15 K, which are below and above the superconducting temperature $T_C \sim 8.4$ K, respectively.

3. Results and Discussion

Figure 2 shows the magnetization curves for the sample consisting of Fe(100 nm)/ Si(10 nm)/Nb(400 nm) at 4.5 K. After the sample had been demagnetized at 15 K, it was cooled down to the measuring temperature in the absence of the magnetic fields. The magnetization was measured as functions of external magnetic field and the angle θ between the external field and the sample plane. The magnetization curve in the magnetic field perpendicular to the sample plane (θ=90°) exhibits a typical magnetization curve of type II superconductors. The large magnetization of the hybrid films at θ=90° is mainly caused from the shape effect of the

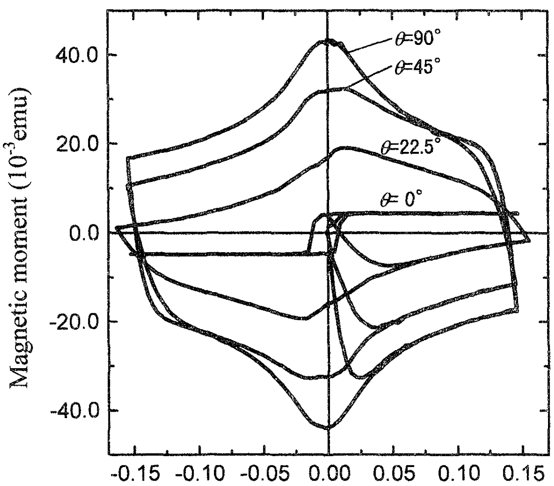

Fig.2 Magnetization curves of Fe(100nm)/Si(10nm) /Nb(400nm) at 4.5K.

superconducting film. In this configuration, the fluxoids are hard to penetrate into the center of the sample because of the pinning effect of the Nb layer [8]. Therefore, its magnetization curve changes as if the volume of the superconductor were increased. As rotating the applied field parallel to the sample plane, the hysteresis loop becomes smaller and finally the magnetization curve at θ=0° shows the same hysteresis as that of an Fe film, since the superconductor does not contribute to the in-plane magnetization curve.

Figure 3 shows the three magnetization curves at θ=45° for the Fe(100 nm)/Si(10 nm)/Nb(400 nm) hybrid film [solid line], the Nb (400 nm) film [broken line] and the Fe (100 nm) film [dotted line]. If there is no interaction between the Nb and Fe layers in the hybrid film, the magnetization of the hybrid film should be equal to the simple sum of the magnetization of the Nb and the Fe film; $m_{\mathrm{hybrid}} = m_{\mathrm{Nb}}+m_{\mathrm{Fe}}$, where m_{hybrid}, m_{Nb} and m_{Fe} are the magnetization of hybrid, Nb and Fe films, respectively. As seen in Fig. 3, however, it is obvious that $m_{\mathrm{hybrid}} > m_{\mathrm{Nb}}+m_{\mathrm{Fe}}$ at the decreasing process of the magnetic field from ±0.1 kOe to zero. In general, in terms of the critical state model, the larger magnetization in the hysteresis loop at the decreasing process of magnetic field reflects the larger pinning force in superconductors. Therefore it is considered that the hybrid film has the pinning force larger than that of the single Nb film. The increase of pinning force in the hybrid film is possibly due to the pinning of the fluxoids in the Nb layer, enhanced by the neighboring Fe layer.

The in-plane magnetization curves for the hybrid film consisting of Fe(100 nm)/ Si(10 nm)/Nb(160 nm) at 4.5 K are shown in Fig. 4; one is the magnetization curve (solid line) measured in the low magnetic field (0.15 kOe) after the cooling from 15 K without magnetic fields, and the other was the curve (broken line) obtained in the high magnetic field (12 kOe). It should be noted that the magnetization curve measured subsequently at 15 K after measuring the magnetization curve in the high field exhibited the same square hysteresis loop as that of high field at 4.5 K. As seen in Fig. 4, the magnetization reversal process measured in the high field has three significant differences in comparison with that measured in the low field. Firstly the onset field of magnetization reversal, H_r, is in the positive direction. Secondly the magnetization reversal is progressing slowly. Thirdly the magnetization is hardly saturated, and the absolute value of the saturation field (H_s) becomes larger than that in the low field.

Here the relation to the magnetization process of the hybrid films is discussed. Figure 5 shows the Nb thickness dependences of H_r (triangles) and H_s (circle), where the open and solid marks respectively represent the values obtained in the low (0.15 kOe) and high (12 kOe) magnetic fields. The values H_r and H_s measured in the low magnetic fields are almost independent of the thickness of the Nb layer, while H_r and H_s after applying the high field depend on the Nb thickness. That is, H_r increases and H_s decreases with thickness of the Nb layer. It is known that the critical field H_{c1}, above which the fluxoids penetrate into the superconducting Nb layer, is about 1.3 kOe at 4.5 K. In the low magnetic fields below H_{c1}, the Nb layer, cooled without magnetic fields, is in the Meissner state and exhausts the fluxoids. As the Nb layer is so thin, the magnetic field acting on the Fe layer is not much different whether the Nb layer is superconducting or not. Therefore, the magnetization curve of the hybrid film is unchanged below and above T_c of the Nb layer.

When high magnetic fields beyond H_{c1} are applied to the superconducting Nb, the fluxoids penetrate into the Nb layer and are pinned along the external field. The remnant fluxoids pinned in the Nb layer produce a local magnetic field at the Fe layer. As this local magnetic field oppositely directs towards both the remnant fluxoids and the magnetized field, the effective field on the Fe layer is weakened. As a result, the magnetization reversal of the hybrid film magnetized in the high magnetic field starts in early stage during the demagnetizing process.

The strength of the local field can be estimated as the

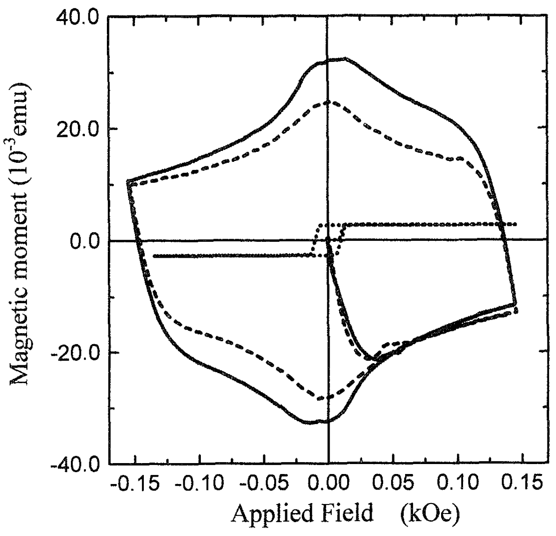

Fig.3 Magnetization curves of Fe(100nm)/Si(10nm) /Nb(400nm) [Solid line], Nb(400nm) [Broken line] and Fe(100nm) [Dotted line] at 4.5K and θ=45° .

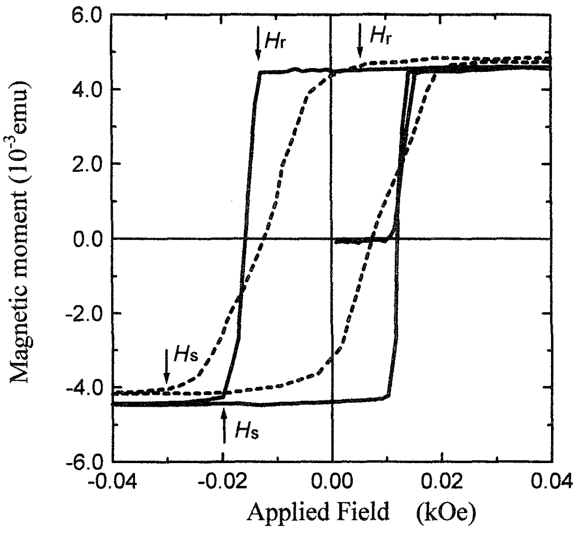

Fig.4 In-plane magnetization curves of Fe(100nm)/ Si(10nm) /Nb(160nm) at 4.5K. The solid and broken lines are the magnetization curves obtained in the magnetic field up to 0.15kOe and 12kOe, respectively.

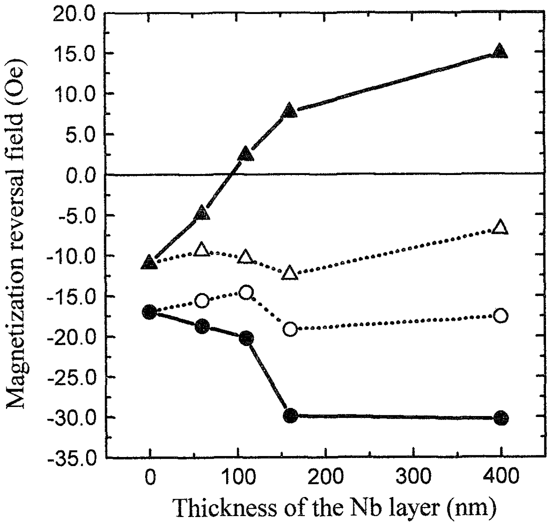

Fig.5 Magnetization reversal field H_r and H_s as a function of the thickness of the Nb layer. The open and solid marks indicate the values obtained in the field up to 0.15kOe and 12kOe, respectively, and the triangle and circle show H_r and H_s, respectively. (see Fig.4)

difference between H_r obtained in the low and high magnetic fields. As shown in Fig. 5 which shows the Nb thickness dependences of the H_r and H_s, the difference linearly varies with thickness of the Nb layer, suggesting that the strength of the local field from the Nb layer linearly depends on the volume of the Nb layer. This is consistent with the idea described above in which the local field results from the remnant fluxoids pinned in the Nb layer, since the quantity of the remnant fluxoids should be proportional to the volume of the Nb layer.

The detailed mechanism why the magnetization reversal process gradually progresses and the magnetization is harder to saturate after the application of the high magnetic field is not clear at this stage. It is sure, however, that the magnetostatic interaction between the remnant fluxoids in Nb layer and the Fe layer results in the change of the magnetization reversal process of the hybrid films, as H_s measured in the high magnetic field depends on the thickness of the Nb layer. The magnetic domain structure in the Fe film, together with the magnetostatic interaction between the remnant fluxoids and the magnetic fluxes at the magnetic domain wall, plays an important role in the magnetization reversal process of the hybrid system.

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References

1) K. Kawaguchi and M. Sohoma: *Phys. Rev.*, **B46**, 14722 (1992).
2) Th. Mühge, K. Westerholt et al.: *Phys. Rev.*, **B55**, 8945 (1997).
3) A. Stankiewicz, S.J. Robinson et al.: *J. Phys.: Condens. Matter*, **9**, 1019 (1997).
4) G. M. Genkin, V. V. Skuzovatkin and I. D. Tokman: *J. Magn. Magn. Mater.*, **130**, 51 (1994).
5) G. M. Genkin, V. V. Skuzovatkin and I. D. Tokman: *J. Magn. Magn. Mater.*, **149**, 345 (1995).
6) Y. Tsuyama, Y. Otani et al: *J. Mag. Soc. Jpn*, **20**, 449 (1996).
7) T. W. Clinton and M. Johnson: *Appl. Phys. Lett.*, **70**, 1170 (1997).
8) H. Theuss, A. Forkl and H. Kronmüller: *Physica C*, **190**, 345 (1992).