AIP | Journal of Applied Physics

# Domain wall modulated superconductivity in Nb/Y3Fe5O12 hybrids

Zhaorong Yang and Victor V. Moshchalkov

Citation: J. Appl. Phys. **109**, 083908 (2011); doi: 10.1063/1.3572270

View online: http://dx.doi.org/10.1063/1.3572270

View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v109/i8

Published by the American Institute of Physics.

JOURNAL OF APPLIED PHYSICS **109**, 083908 (2011)

# Domain wall modulated superconductivity in Nb/$Y_3Fe_5O_{12}$ hybrids

Zhaorong Yang[1,2,a)] and Victor V. Moshchalkov[1]
[1]*INPAC - Institute for Nanoscale Physics and Chemistry, K. U. Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium*
[2]*Key Laboratory of Materials Physics, Institute of Solid State Physics, Chinese Academy of Sciences, Hefei 230031, People's Republic of China*

(Received 16 November 2010; accepted 3 March 2011; published online 19 April 2011)

In superconductor/ferromagnet hybrids, the stray field and inhomogeneous exchange field coming from magnetic domain walls have opposite influence on the superconductivity if the ferromagnet displays in-plane anisotropy. In this paper, we investigate modulation of superconductivity by the stray field of Bloch walls in Nb/$Y_3Fe_5O_{12}$ hybrids where the proximity effect is excluded. By applying in-plane magnetic field, we show that the resistance as a function of magnetic field displays two dips precisely at the saturation field $H_s$ of $Y_3Fe_5O_{12}$. The superconducting transition temperature $T_c$ at $H_s$ is higher than that at lower fields, suggesting the suppression of superconductivity by the stray fields of Bloch walls. By effective controlling of the domain walls, the superconductivity can be switched either on or off. © *2011 American Institute of Physics*. [doi:10.1063/1.3572270]

## I. INTRODUCTION

During the past few years, intensive research efforts have been devoted to hybrid superconductor-ferromagnet (S/F) systems aimed at controlling superconductivity by magnetic subsystem.[1–8] In the S/F hybrids, the superconducting order parameter can be modulated by both exchange and electromagnetic interactions. For ferromagnet with perpendicular anisotropy, superconductivity is favorable to nucleate above magnetic domain walls due to the lowest stray fields or inhomogeneous exchange fields in those areas. The experimental realizations of domain wall superconductivity have been reported by different groups.[9–11] On the other hand, if the ferromagnet has in-plane anisotropy, the exchange interaction still favors superconductivity above domain walls while the stray field does oppositely. The coexistence of exchange interaction and stray field effect results in contrary experimental observations, e.g., spin switch and inverse spin switch.[12–16] In addition to pure magnetically quenching of superconductivity, theoretical investigations show that the stray field from domain wall creates a weak link and can trap vortex.[17,18] Manipulation of vortices by the magnetic domain walls has been reported recently by Goa *et al*.[19–21] Clearly, the superconductivity in the S/F hybrids can be modulated by the magnetic domain wall in different ways.

In this paper, we investigate domain wall modulated superconductivity Nb/$Y_3Fe_5O_{12}$ (Nb/YIG) hybrids by excluding the proximity effect. The YIG (yttrium iron garnet) substrates we used have in-plane anisotropy. The resistance of the Nb film as a function of in-plane magnetic field shows two dips precisely at the saturation field $\pm H_s$ of YIG, indicating the suppression of superconductivity by the stray field from domains walls. The critical temperature $T_c$ of the superconducting transition in Nb is enhanced at $H_s$ as comparing with that at lower fields. These results suggest that the superconductivity can be modulated by effective controlling of the magnetic domain walls.

a)Author to whom correspondence should be addressed. Electronic mail: zryang@issp.ac.cn.

## II. EXPERIMENTAL RESULTS AND DISCUSSION

The sample of Nb/YIG has been prepared by depositing 50 nm Nb film on the single crystal YIG (111) substrate ($3 \times 2 \times 0.5$ mm$^3$) by molecular beam epitaxy. A 10 nm Si layer was used as buffer between Nb and YIG to exclude the proximity effect. The magnetic properties of YIG (111) substrate were studied by using a quantum design SQUID magnetometer. Figure 1 shows the magnetization loops at 5 K with magnetic field $H$ applied perpendicular and parallel to the sample surface, respectively. With increasing field from zero, the magnetization with $H$//(111) increases abruptly and reaches saturation at $H \approx 300$ Oe. In contrast, the

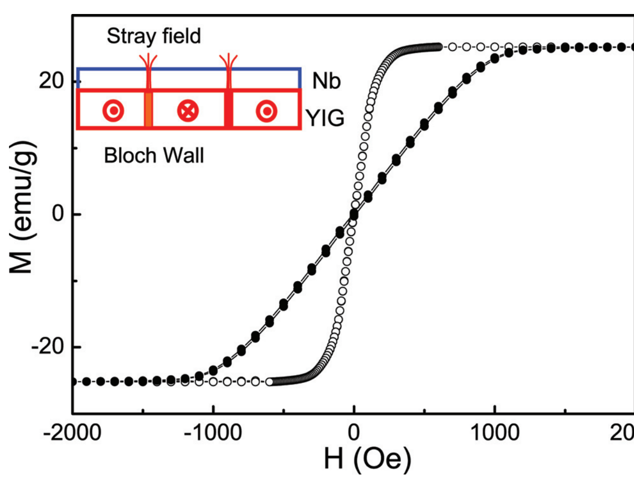


FIG. 1. (Color online) Magnetic hysteresis loops of YIG (111) substrate at 5 K with magnetic field applied in plane (open circles) and perpendicular to (111) (solid circles), respectively. The inset shows schematic illustration of the sample Nb/YIG with Bloch wall as the source of stray field.

 

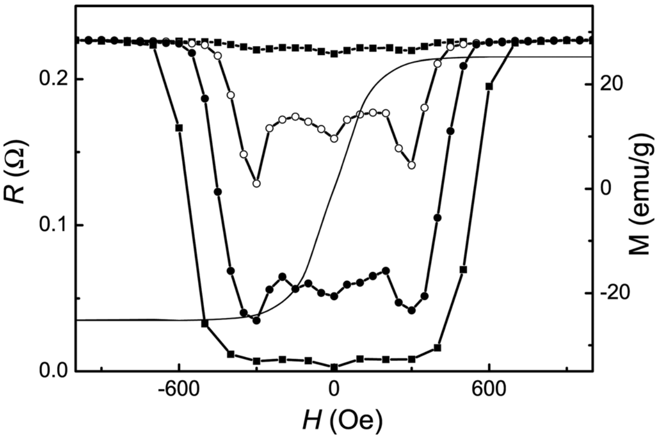


FIG. 2. Field dependence of resistance $R$ of the Nb/YIG hybrid system at different temperatures: 8.435, 8.43, 8.425, 8.42 K (from top to bottom). Dotted line displays the magnetic hysteresis loop of YIG (111) substrate at 5 K with magnetic field applied in plane.

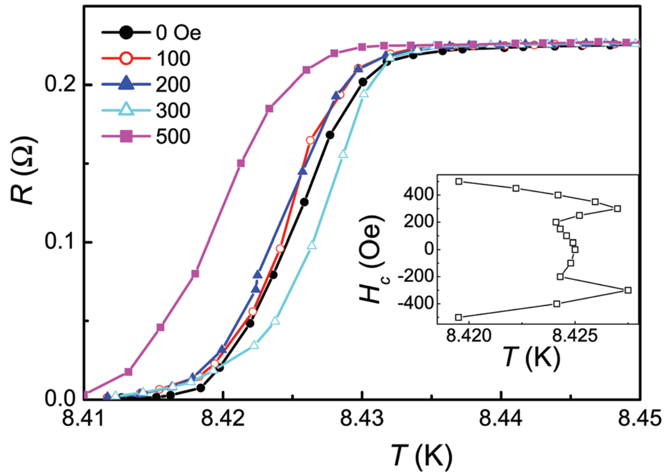


FIG. 3. (Color online) Temperature dependence of resistance $R$ for Nb/YIG at different in-plane magnetic fields. The inset shows the $H$-$T$ phase diagram.

magnetization with $H \perp (111)$ reaches saturation at a relatively higher field (1100 Oe), suggesting an in-plane anisotropy in YIG (111). For ferromagnet with in-plane magnetization, Bloch walls exist at the surface separating the magnetic domains with opposite magnetization direction, which are the source of the stray field, see a schematic illustration of the sample in the inset of Fig. 1. A typical domain image of YIG with in-plane anisotropy can be found in Ref. 22. The domain walls can move freely in response to the variation of the external field since no hysteresis is observed here.

The resistance $R$ of the Nb film deposited on YIG was measured in a Physical Properties Measurement System (Quantum Design) applying a four-probe ac technique with an ac current of 10 $\mu$A at a frequency of 19 Hz. Figure 2 shows the resistance as a function of magnetic field at various fixed temperatures. $H$ is applied parallel to the sample surface in the sequence from $-2$ to 2 kOe. At $T_0 = 8.435$ K, the resistance $R(H, T_0)$ displays minima at 300, 0, and 300 Oe. As the temperature is decreased, three dips develop at the corresponding fields and are clearly visible at 8.43 and 8.425 K. The resistance at $\pm$300 Oe is even lower than the zero field resistance. When the field is swept back from 2 kOe, no clear hysteresis is observed and the $R(H)$ curves are almost symmetric with respect to $H = 0$. These dips exist only in a narrow temperature range. Above 8.435 K and below 8.42 K, the resistance does not change between $\pm$300 Oe.

To get a clear picture of the resistive transition at different in-plane fields, we show $R(T)$ curves in Fig. 3. By defining superconducting transition temperature $T_c$ with a criterion of $R_{cri} = 50\%\ R_n$, we construct the magnetic field ($H$) - temperature ($T$) - phase diagram, as shown in the inset of Fig. 3. $T_c$ at zero field is about 8.425 K. The resistive transition is sharper, with a width of 20 mK. In agreement with the dips in $R(H)$, $T_c$ measured at 0 and 300 Oe are higher than that at 100 and 200 Oe. Moreover, $T_c$(300 Oe) is about 2 mK higher than $T_c(0)$, i.e., the application of 300 Oe provides an enhancement of superconductivity in the Nb film. For a pure Nb film, as we know, $T_c$ always shifts monotonously to lower temperature as $H$ is increased.

In order to understand the field enhancement of superconductivity in the Nb/YIG hybrids, we shall have a close look at the domain state of YIG substrate. The magnetization loop of YIG with magnetic field applied in plane is also shown in Fig. 2 for comparison. It is clear that the dips in $R(H)$ curves occur precisely at the saturation field ($\pm$300 Oe) of YIG, suggesting that the domain state of YIG is involved in controlling the superconducting transition of Nb film. For YIG with in-plane anisotropy, Bloch walls exist at surface at fields below the saturation field, and give rise to stray field acting perpendicular to the Nb film, see the inset of Fig. 1. The total magnetic field in Nb film is a superposition of the perpendicular stray field and the external parallel field. In contrast, at 300 Oe, Bloch wall disappears due to the saturation of YIG, so does the stray field. The total field felt by the Nb film is therefore the pure external field. This is the reason why Nb film has the highest $T_c$ at field corresponding to the saturation field of YIG substrate. With increasing field from zero, the first stage of the magnetization process in YIG corresponds to the reversible movements of magnetic domains, and the total number of the Bloch walls does not change. In this stage, the total magnetic field in the Nb film should increases with the applied field. As a result, the measured resistance at 8.435 K increases with field (Fig. 2). Further increase of the applied field results in the expansion of positive magnetic domains in YIG and the gradual disappearance of Bloch walls. As a consequence of the decrease of the total magnetic stray field in Nb film, the resistance decreases with increasing field followed by a dip at the field (300 Oe) corresponding to complete switching off the Bloch walls.

Above 300 Oe, the magnetization in YIG substrate is oriented along the external magnetic field and generates fringe field from the magnetic poles along the surface antiparallel to the applied external field. The fringe field compensates the applied field and should also affect the superconductivity in Nb film. However, the calculated fringe field in the major area of the Nb film is about 20 Oe. This value is much lower than 300 Oe and should not be the main cause of the resistance dip at 300 Oe.

In Nb/YIG hybrids, by switching the Bloch walls either on or off, the superconductivity in Nb film can be effectively modulated. In our case, a globe resistance is measured, the voltage contacts covers numerous Bloch walls. If we can capture a single Bloch wall and make the contacts, a pronounced switching effect can be expected. Based on effective controlling of the Bloch wall, it is possible to use this effect for new devices like the superconducting switch. Finally, it should be noted that the modulation of superconductivity by Bloch walls in Nb/YIG is contrary to the recent observation of domain wall superconductivity in $Nb/Ni_{0.8}Fe_{0.2}$ bilayers, although both have in-plane anisotropy in the ferromagnetic layer.[12] In $Nb/Ni_{0.8}Fe_{0.2}$ bilayers, the domain wall is found to favor the superconductivity rather than do the opposite due to the proximity effect. In the Nb/YIG hybrids, the proximity effect can be excluded and the superconductivity is only influence by the stray fields.

## III. CONCLUSIONS

In conclusion, the modulation of superconductivity by Bloch walls has been studied in Nb/YIG hybrids. The superconductivity is enhanced by switching off the Bloch walls. Based on effective controlling of the Bloch wall, it is possible to use the effect for new devices like the superconducting switch.

## ACKNOWLEDGMENTS

This work is supported by the FWO, GOA, and IAP projects and the ESF-NES Research Networking Programme. Z.Y. thanks the support from the National Key Basic Research of China Grant Nos. 2007CB925001, 2011CBA00111, and the National Nature Science Foundation of China Grant No. 10774147.

[1]For recent reviews, see I. F. Lyuksyutov and V. L. Pokrovsky, Adv. Phys. **54**, 67 (2005); A. I. Buzdin, Rev. Mod. Phys. **77**, 935 (2005); A. Yu. Aladyshkin, A. V. Silhanek, W. Gillijns, and V. V. Moshchalkov, Supercond. Sci. Technol. **22**, 053001 (2009).
[2]L. N. Bulaevskii, E. M. Chudnovsky, and M. P. Maley, Appl. Phys. Lett. **76**, 2594 (2000).
[3]S. Erdin, I. F. Lyuksyutov, V. L. Pokrovsky, and V. M. Vinokur, Phys. Rev. Lett. **88**, 017001 (2002).
[4]R. B. G. Kramer, A. V. Silhanek, J. Van de Vondel, B. Raes, and V. V. Moshchalkov, Phys. Rev. Lett. **103**, 067007 (2009).
[5]M. V. Milošević, W. Gillijns, A. V. Silhanek, A. Libál, F. M. Peeters, and V. V. Moshchalkov, Appl. Phys. Lett. **96**, 032503 (2010).
[6]A. Mani, T. G. Kumary, D. Hsu, J. G. Lin, and C.-H. Chern, Appl. Phys. Lett. **94**, 072509 (2009).
[7]C. Visani, N. M. Nemes, M. Rocci, Z. Sefrioui, C. Leon, S. G. E. te Velthuis, A. Hoffmann, M. R. Fitzsimmons, F. Simon, T. Feher, M. Garcia-Hernandez, and J. Santamaria, Phys. Rev. B **81**, 094512 (2010).
[8]A. Singh, C. Sürgers, and H. V. Löhneysen, Phys. Rev. B **75**, 024513 (2007).
[9]A. Yu. Aladyshkin, A. I. Buzdin, A. A. Fraerman, A. S. Mel'nikov, D. A. Ryzhov, and A. V. Sokolov, Phys. Rev. B **68**, 184508 (2003).
[10]Z. R. Yang, M. Lange, A. Volodin, R. Szymczak, and V. V. Moshchalkov, Nature Mater. **3**, 793 (2004).
[11]L. Y. Zhu, T. Y. Chen, and C. L. Chien, Phys. Rev. Lett. **101**, 017004 (2008).
[12]A. Yu. Rusanov, M. Hesselberth, J. Aarts, and A. I. Buzdin, Phys. Rev. Lett. **93**, 057002 (2004).
[13]M. van Zalk, M. Veldhorst, A. Brinkman, J. Aarts, and H. Hilgenkamp, Phys. Rev. B **79**, 134509 (2009).
[14]D. Stamopoulos, E. Manios, and M. Pissas, Phys. Rev. B **75**, 184504 (2007).
[15]G. Carapella, F. Russo and G. Costabile, Phys. Rev. B **78**, 104529 (2008).
[16]R. Steiner and P. Ziemann, Phys. Rev. B **74**, 094504 (2006).
[17]E. B. Sonin, Pis'ma Zh. Tekh. Fiz. **14**, 1640 (1988); Sov. Tech. Phys. Lett. **14**, 714 (1988).
[18]L. E. Helseth, P. E. Goa, H. Hauglin, M. Baziljevich, and T. H. Johansen, Phys. Rev. B **65**, 132514 (2002).
[19]P. E. Goa, H. Hauglin, Å. A. F. Olsen, D. Shantsev, and T. H. Johansen, Appl. Phys. Lett. **82**, 79 (2003).
[20]V. Vlasko-Vlasov, U. Welp, G. Karapetrov, V. Novosad, D. Rosenmann, M. Iavarone, A. Belkin, and W.-K. Kwok, Phys. Rev. B **77**, 134518 (2008).
[21]J. I. Vestgården, D. V. Shantsev, Å. A. F. Olsen, Y. M. Galperin, V. V. Yurchenko, P. E. Goa, and T. H. Johansen, Phys. Rev. Lett. **98**, 117002 (2007).
[22]J. Basterfield, J. Appl. Phys. **39**, 5521 (1968).