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ORIGINAL PAPER

Vortex Pinning by an Inhomogeneous Magnetic Field

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Abstract We discuss the transport properties of a superconducting film under the influence of a tesla range spatially alternating magnetic field created by magnetic nanostructures placed *outside* a superconducting film with an insulating barrier between both so that they interact *only* via the magnetic field. A simple model for pinning by the spatially periodic magnetic field from the magnetic nanostructure qualitatively describes the data.

Keywords Superconductivity · Hybrid · Magnetic nanorods · Vortex pinning · Critical field

1 Introduction

Several theoretical [1–4] and experimental [5–9] studies in recent years were focused on Ferromagnet-Superconductor Bilayers (FSB). Reviews of these studies are given in [10–12]. In almost all works the magnetic fields from a network of domain walls in the underlying magnetic film were in the millitesla range [5–13]. The single exception Ref. [14] where, instead of very thin (a few tens of nanometers) films, a bulk magnetic crystal was used as a source of the random alternating magnetic field in the superconducting film atop it. The typical length scale of the magnetic field inhomogeneity in these works is in the micrometer range [5–12]. Most studies of FSB have used films with strong anisotropy and with the easy axis perpendicular to the film plane, generating hysteresis phenomena in the superconducting resistivity of the film due to the large coercive field of the magnetic film. Nevertheless, the experimentally measured shift in the second critical field with respect to a control superconducting system was in the millitesla range [5–12]. The critical current, however, changed more strongly [5–12]. FSB hybrids have several scales. This includes the superconducting coherence length ξ, penetration depth λ, and the typical scale R of magnetic field variation. We discuss the situation when R is smaller than λ but larger than ξ. More information on FSB hybrids can be found in reviews [10–12]. We ignore the proximity effect which can be avoided with a thin insulating layer between the subsystems. Thus, the superconducting and ferromagnetic films interact only via the magnetic field. A homogeneous magnetic field cannot pin vortices; however, an inhomogeneous external magnetic field creates barriers for vortex motion. The study of this phenomenon can be of great importance for understanding vortex matter in superconductors and for practical applications. Theoretical predictions [1, 3–5] indicate pinning of vortices in the superconducting film by the magnetic field from domains or domain walls in magnetic films. Increase of pinning near the superconducting transition temperature has been observed [17, 18]. The relatively weak pinning can be due to the random nature of the domains/domain wall network and the weakness of the spatial variation of the magnetic field penetrating into the superconducting film. In this article we discuss results of studies of transport properties of a superconducting film in the strongly varying magnetic field created by an array of parallel ferromagnetic/nonmagnetic stripes.

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2 Magnetic Field Distribution

A sketch of magnetic field distribution from the magnetic nanostructure is given in Fig. 1. The applied magnetic field "channels" through the ferromagnetic stripes, as proposed earlier [19], thus creating a periodically varying magnetic field shown in Fig. 2. Figure 2(a) shows the distribution taken with a Scanning Hall Probe Microscope (SHPM) of the normal component of the magnetic field above the superconducting film surface. Figure 2(b) shows the normal component of magnetic field along the line indicated in Fig. 2(a). It is surprisingly close to a simple sinusoidal modulation with a period of 10 microns. To fabricate magnetic nanostructure, a silicon substrate was coated with a 15-nm thick Cr seed layer which was then spin-coated at 2000 rpm with SU-8 photoresist (from Microchem) and patterned to create 7.5 µm deep and 3.5 µm wide trenches to serve as a mold for subsequent electroplating of Co. After electroplating Co to fill the trenches, a 200-nm thick SiO_2 layer was deposited by e-beam evaporation to serve as an insulator. Finally, 100 nm of lead-bismuth ($Pb_{82}Bi_{18}$) alloy was thermally evaporated and quench-condensed onto the substrate at 77 K. Further experimental details will be published elsewhere. The phase diagram of a control superconducting film is shown in Fig. 2(c) and the dependence of the critical current on magnetic field at 4.2 K for current parallel to and perpendicular to the magnetic Co stripes is shown in Fig. 3. The very strong anisotropy is demonstrated here. Indeed, the magnetic field modulation provides barriers for vortex motion in the direction perpendicular to the magnetic stripes (i.e. for current parallel) and no barrier for vortex motion in the direction parallel to the stripes (i.e. for current perpendicular to the stripes). This results in a dramatically smaller critical current for current perpendicular to the magnetic stripes as compared to the current parallel to them. Previously a similar periodic field variation was created in a hybrid superconductor/magnet array of iron and brass stripes with a period of 275 microns [15, 16]. Despite such a large period, the system also produced an increase of the critical field and critical current (see Figs. 3 and 4, respectively in [15, 16]).

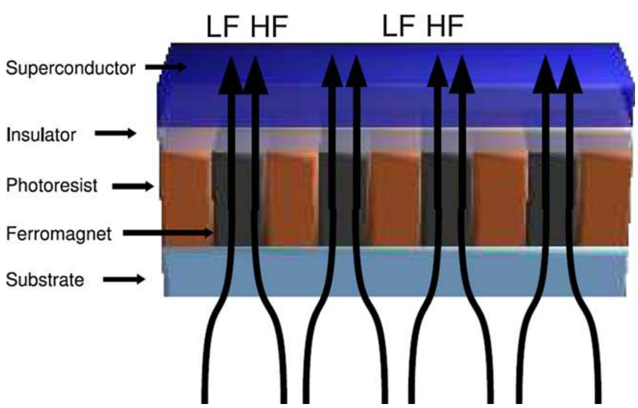

Fig. 1 Magnetic field pattern

3 Magnetic Pinning

Pinning techniques are commonly based on destroying superconductivity locally to attract a vortex core to that region. The core energy, however, represents only about 10% of the total vortex energy, which is 90% magnetic field energy. As a result, vortex pinning by an inhomogeneous magnetic field can use a larger part of the vortex energy. Although vortex pinning by magnetic domains was studied in theory [1–5] and experiment (see e.g. reviews [10–12]), the magnetic field normal to the film created by the network of magnetic domains is one–two orders of magnitude weaker than that observed here and in [15, 16].

The influence of the measured periodic field modulation on critical current can be estimated theoretically for comparison with the experimental values for the different magnetic field periods differing by a factor of 30 (10 micron

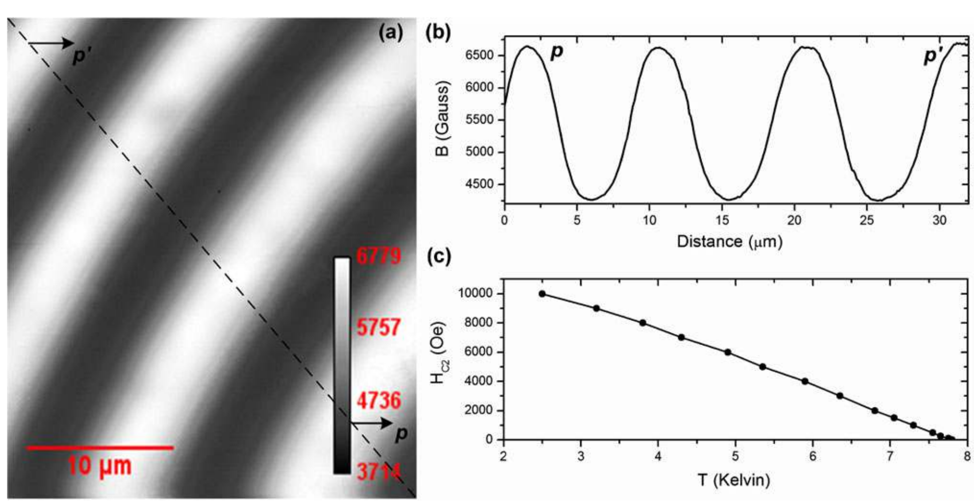

Fig. 2 (**a**) Scanning Hall Probe Microscope image of the sample at 300 K and 5 kOe applied field; (**b**) Magnetic field profile across the Co stripes; (**c**) $H_{C2}(T)$ plot of the $Pb_{82}Bi_{18}$ control film without Co stripes

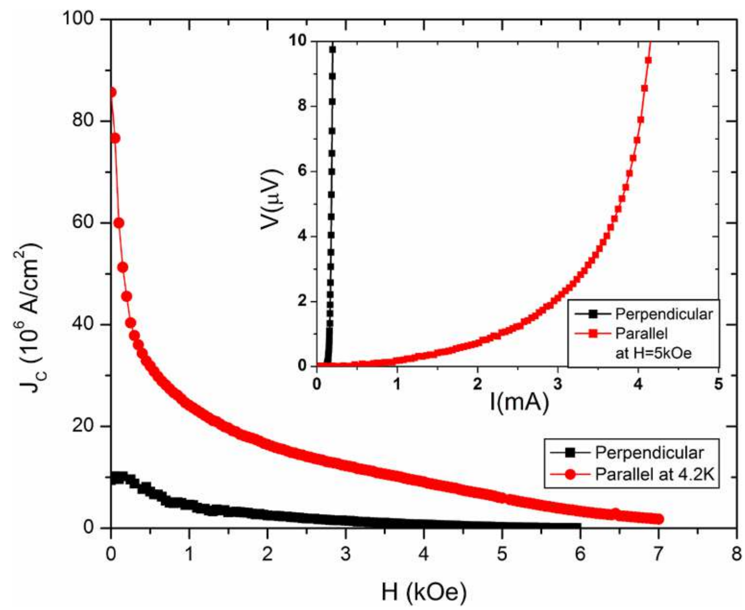

Fig. 3 Critical current density $J_C(H)$. *Inset 1*: I–V curves at 4.2 K and 5 kOe for both current directions. The difference in J_C at zero applied field is due to the remnant magnetization of the Co stripes

and 275 micron). The energy of interaction between a vortex and the magnetic structure with magnetization $M(x)$ modulated along the x-axis can be estimated as $\Phi_0 M$, where Φ_0 is a flux quantum. The pinning force due to the inhomogeneous magnetization is $\Phi_0\, dM(x)/dx = \Phi_0 \mu_0^{-1}\, dB/dx$, where $B(x)$ is the magnetic field created by the magnetization $M(x)$. This field is measured with the Scanning Hall Probe Microscope (SHPM). However, the Lorenz force acting on the vortex due to a current density J_C is given by $J_C \Phi_0$. This results in a simple estimate for the critical current density: $J_C \approx \mu_0^{-1}\, dB/dx$. This formula provides a convenient tool to estimate the validity of our magnetic pinning model. By comparing the ratio of critical currents in the two systems with different values of the magnetization gradient, we can roughly estimate the accuracy of this simple model. dB/dx is estimated to be 5×10^2 T/m in an external field 0.15 T from the data in Fig. 2b (Refs. [15, 16]). dB/dx is estimated to be about 4×10^4 T/m in an external field 0.5 T from Fig. 2b above, i.e. about 100 times larger than in [15, 16]. The critical current density at 4.2 K as a function of magnetic field is given in Fig. 3. In [15, 16] the critical current density at 4.2 K in a 0.3 T field is about 10^5 A/cm^2. From Fig. 3 above, the critical current density at 0.3 T is about 10^7 A/cm^2 which is 100 times larger than that found in [15, 16] in general agreement with the inverse of their periods (i.e. roughly the ratio of their field gradients). The results support this simple model of magnetic pinning in which the critical current density is proportional to the gradient of the magnetic field. The absolute value of critical current can also be checked. Indeed, substituting μ_0 and the field gradient we estimate $J_C \approx 0.3 \times 10^7$ A/cm^2, which is in order of magnitude agreement with the experimental result.

4 Conclusion

In summary, we have studied for the first time the magnetic pinning mechanism directly by creating a periodic magnetic field variation in superconducting films using two values of the magnetic field gradient which differs by roughly two orders of magnitude. The experimental results are in reasonable agreement with a simple theoretical model of magnetic pinning.

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