Influence of Domain Width on Vortex Nucleation in Superconductor/Ferromagnet Hybrid Structures

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We have investigated the effect of spatially inhomogenous magnetic fields on vortex nucleation in magnetically coupled superconductor/ferromagnet hybrid structures. Using low temperature scanning tunneling microscopy and spectroscopy (LT-STM/STS) we have studied Pb/[Co-Pd] systems with slightly inhomogeneous magnetic domain width throughout the sample. Visualization of the underlying magnetic template structure is achieved through field dependent conductance maps. In the case of zero applied fields these maps reveal the absence of vortices below a threshold domain width. At those locations with insufficient domain width to support generation of vortices in zero applied fields, nucleation can be restored through the application of an external magnetic field, with vortices nucleating above the domain parallel to the external field. For the magnetic domain width studied in this work local tunneling spectroscopy reveals uniform superconducting critical temperature as a function of location, despite of local differences in the stray field experienced by the superconductor.

Keywords: Superonductor-Ferromagnet Hybrids, Vortices and Nanostructured Superconductors, Low Temperature Superconductors

Introduction

Superconductor/ferromagnet (S/F) systems have been widely studied in recent years [1,2]. If a thin layer of oxide is placed between the superconductor and the ferromagnet the stray field of the ferromagnet affects locally the superconductivity. In this case the interaction is orbital in nature, and can give rise to a variety of new phenomena such us domain wall superconductivity and reverse domain wall superconductivity [3]. Additionally, these types of S/F systems also hold the potential to increase the critical current density of the superconducting layer through the interaction of the vortices with the magnetic moment of the underlying magnetic domain [4,5]. Furthermore, if the ratio of magnetic domain width to superconductor thickness is properly tuned vortex-antivortex pairs are formed in zero applied magnetic field [6,7,8]. If the magnetic domain width, instead, is below the minimum threshold to allow the formation of spontaneous vortex-antivortex pairs vortices can still be induced in the superconducting layer when applying an external magnetic field [8,9].

In this work we study the effect of an unbalanced size distribution of positive and negative magnetic domains in the ferromagnetic layer on the vortex nucleation in the superconducting layer.

2. Samples

The superconductor/ferromagnet system investigated consists of a *30* nm ultrathin film of Pb deposited on top of a multilayer Co-Pd ferromagnet. The multilayer Co-Pd system was made by successive deposition of *2* nm Co and *2* nm Pd onto a Si(100) substrate using dc magnetron sputtering with an in-plane magnetic field of a few hundred Oe applied to the substrate to help promote perpendicular magnetic anisotropy [10]. A *10* nm insulating layer of Al_2O_3 was immediately deposited onto the Co-Pd multilayer system prior to removal from vacuum by rf sputtering of aluminum in a partial pressure of oxygen. This insulating layer prohibits proximity effects between the superconducting and ferromagnetic films. Ultrathin films of Pb were deposited in situ in a vacuum of better than 1×10^{-11} Torr onto the Co-Pd/Al_2O_3 system using e-beam evaporation from a Mo crucible at a rate of approximately *0.2* nm/min. The substrate was held at *150* K during deposition, and then gradually allowed to warm to room temperature over a few hours before being transferred to the already cold scanning tunneling microscope.

Magnetic characterization of the domain structure of the Co-Pd/Al_2O_3 multilayer system was carried out using room temperature magnetic force microscopy using silicon cantilevers coated with a layer of Co-Cr alloy (MESP MFM probes by Bruker Corporation, Santa Barbara). These probes have a spring constant of *1-5* N m^{-1}, a resonant frequency of *60-90* kHz, and a coercive field of nearly *400* Oe. Images were taken using a Bruker Multimode *8* atomic force microscope in the lift-mode regime at a lift height of *30* nm.

3. Results

Low temperature scanning tunneling microscopy and spectroscopy (LT-STM/STS) measurements were carried out in a UHV low temperature STM combined with sample preparation for *in situ* fabrication of thin films (Unisoku USM-1300 and RHK electronics). Tunneling spectroscopy was performed using the standard lock-in technique with an *ac* modulation of 0.2 mV at 373 Hz. The conductance maps were acquired while scanning the tip over the sample surface at high voltage (-20 mV), periodically pausing scanning to disable height feedback, and acquiring the lock-in signal at the Fermi energy. Topography was always acquired simultaneously to ensure the location where the spectroscopic information was recorded. All differential conductance spectra (dI/dV) were taken with the same tunneling parameters with the junction stabilized at V=-10 mV, I=100 pA.

Although STM is not sensitive to stray fields, the information of the underlying magnetic template is imprinted in the vortex configuration in the superconducting layer, which will be effected by the presence of an external magnetic field. Indeed, above each magnetic domain the stray field will either be compensated or strengthened by the external field and therefore the density of vortices will reflect the underlying magnetic pattern.

Figure 1(a) shows a *20* μm x *20* μm room temperature magnetic force microscopy image, which exhibits the characteristic domain structure of our samples. Domains of opposite polarity have slightly different widths throughout the image, with an average width of about *200* nm. Ultrathin films of Pb grown in UHV on the oxide coated ferromagnet have surfaces with large areas of atomically flat terraces, as shown in figure 1(b). A zero bias conductance (ZBC) map acquired concurrently with the topography of figure 1(b) in zero applied external magnetic field is shown in figure 1(c). Regions of higher conductance (more normal) in this ZBC map represent Abrikosov vortices. The image shows the presence of only a few vortices due solely to the ferromagnet stray field.

In order to understand the underlying magnetic domain structure we performed magnetic field dependent ZBC map acquisition. In figures 2(a)-(c), ZBC maps in the presence of magnetic fields H=0 and ±500 Oe are reported. The maps clearly show that vortices arrange preferentially along stripes, with an increasing density for higher applied magnetic fields. For the opposite polarity, vortices are located along previously unoccupied stripes. Evidently, the vortex configuration reflects the nature of the underlying stripe magnetic domains of the ferromagnet. When an external magnetic field is applied, the domains anti-parallel to the external field will be at least partially compensated, and as a result the effective region of magnetic stray field variation above each of these domains will decrease. On the other hand, domains parallel to the applied field will experience an increase in the effective region of magnetic stray field variation.

Tunneling spectroscopy acquired far from vortices above opposite polarity domains, as well as at the position corresponding to the domain wall (positions A, B, C in Figure 2(a)), shows a slightly inhomogeneous superconducting state. This inhomogeneity is represented through the zero bias conductance values extracted from dI/dV spectra acquired at different values of magnetic field, which are reported in figure 2(d). As expected from the field dependent maps, this inhomogeneity grows with increasing field as the vortex density increases in stripes parallel to the applied field. This inhomogenous superconducting state also persists with increasing temperature. In figures 3(a-c) the temperature dependence of the tunneling spectra acquired above the two opposite magnetic domains (position A and C), as well as above the domain wall (position B), are reported. The behaviors of the temperature dependent evolution of the spectra are similar in the three locations. Again, the ZBC extracted from the dI/dV can be used to characterize the inhomogenous superconducting state. In this case, the inhomogeneity decreases with increasing temperature, and eventually the curves all converge to the same value at the transition. Thus, the critical temperature extracted from these data is homogeneous with the location despite the different local stray field.

4. **Discussion and Conclusions**

We have investigated the effect of inhomogeneous magnetic domain size on the superconducting properties of Pb/(Co-Pd) systems. Such local variations of spectroscopic behavior in the superconducting state are inaccessible to many other techniques widely used in studies of S/F systems, such as magnetic force microscopy or transport measurements. Our results show that in zero applied field only a few vortices are present due to the stray field of the ferromagnet, which are located in regions where the stripe width meets the criteria for vortex nucleation. Moreover, in applied external fields, it will be energetically favorable for vortices to nucleate above the domains with the same polarity as the external field. The ability to understand and control the formation of vortex-antivortex pairs in S/F structures can have far reaching impact going well beyond the fundamental understanding of vortex matter in superconductors. Many applications of superconductors in sensors are limited by noise believed to be due to dissipation from vortex-antivortex dynamics, yet no conclusive evidence of the mechanism causing this dissipation has been obtained thus far. These results show that it is possible to engineer these systems to avoid formation of vortex-antivortex pairs and that it is possible to locate vortices at different locations by changing the polarity of the applied magnetic field.

Acknowledgments

Work at Temple University was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering under Award DE-SC0004556. Work at Argonne was supported by the U.S. Department of Energy (DOE), Office of Science, Basic Energy Sciences (BES) under Award # DE-AC02-06CH11357.

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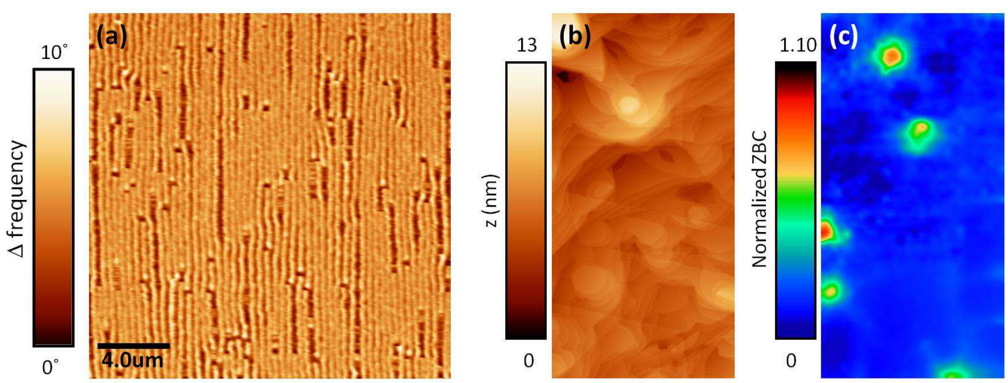

Figure 1 (a) *20* μm x *20* μm room temperature magnetic force microscopy image taken in lift height mode showing the magnetic domain structure of our samples. (b) *1.13* μm x *0.57* μm low temperature scanning tunneling microscopy topography showing the morphology of the ultrathin Pb film. Tunneling conditions during scanning were V=*-10* mV and I=*100* pA. (c) 1.13 μm x 0.57 μm zero bias conductance map taken concurrently with the topography in zero applied field showing a low density of vortices (red) generated by the stray field of the underlying ferromagnet, and surrounded by large superconducting regions (blue).

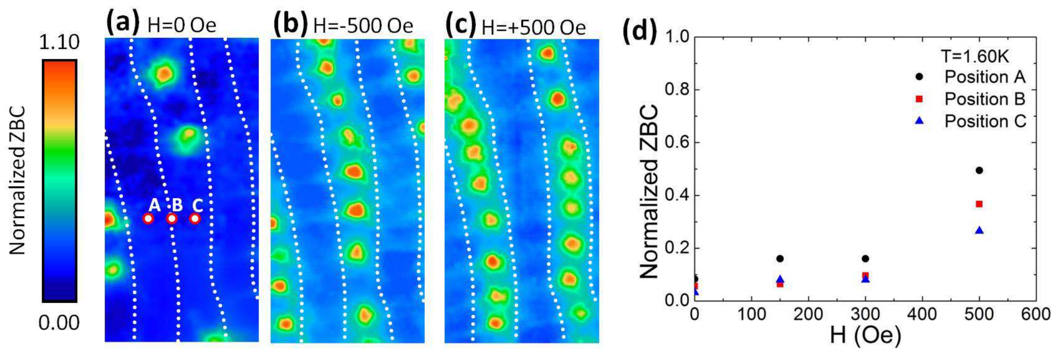

Figure 2 (a-c) 1.13μm x 0.57 μm zero bias conductance maps taken in the same location as a function of applied fields showing the evolution of the vortex configuration, which reveals the nature of the underlying magnetic template. Points A, B, and C are points above the positive domain, the domain wall, and the negative domain, respectively. The white dotted lines indicate the approximate locations of the domain walls. (d) Spatial dependence of the normalized zero bias conductance values as a function of applied magnetic fields taken in positions near points A, B, and C.

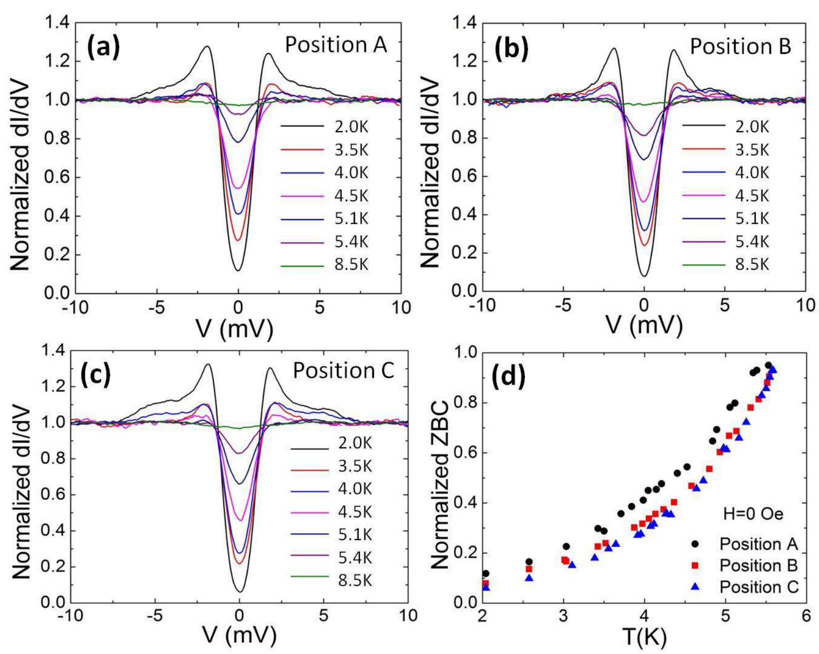

Figure 3 (a-c) Characteristic temperature dependent conductance spectra taken in zero applied magnetic field in positions A, B, and C indicated in figure 2(a). These spectra show that superconductivity is more pronounced (lower zero bias conductance) above the domain wall and negative domains. (d) Spatial dependence of the normalized zero bias conductance values (in positions A, B, and C) as a function of temperature. Although superconductivity decreases more quickly above the positive stripe (position A) with reduced width, the transition temperature is uniform in all regions.