Switching a magnetic vortex by interlayer coupling in epitaxially grown Co/Cu/Py/Cu(001) trilayer disks

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Abstract
Epitaxial Py/Cu/Co/Cu(001) trilayers were patterned into micron sized disks and imaged using element-specific photoemission electron microscopy. By varying the Cu spacer layer thickness, we study how the coupling between the two magnetic layers influences the formation of magnetic vortex states. We find that while the Py and Co disks form magnetic vortex domains when the interlayer coupling is ferromagnetic, the magnetic vortex domains of the Py and Co disks break into anti-parallel aligned multidomains when the interlayer coupling is antiferromagnetic. We explain this result in terms of magnetic flux closure between the Py and Co layers for the antiferromagnetic coupling case.

1. Introduction

Understanding the formation of various magnetic states in confined geometries is crucial to the development of spintronics technology. The magnetic vortex state in magnetic disks is an important example of magnetic state formation in nanostructures and has been a recent area of interest [1]. A magnetic vortex state is formed when the spin magnetization directions curl inside a disk to minimize the system's total magnetic energy [2]. While much effort has been devoted to the study of single layer vortex state such as the vortex dynamics [3] and vortex core reversal [4], multi-layer structures are less well understood. Recent studies have indicated that vortex states in trilayer disks exhibit many new interesting phenomena due to the magnetic coupling between vortices [5, 6]. For example, magnetic domain imaging reveals that the magnetization reversal in a trilayer structure involves a coordinated magnetic reversal of each magnetic layer [7]. Magnetic simulations also show that the vortex dynamics in a trilayer structure is highly non-linear, revealing nontrivial coupled vortex dynamics [8].

However, most previous work has studied vortex formation in polycrystalline films in which the two disks are strongly ferromagnetically coupled. In the limit of infinitely strong ferromagnetic coupling, the magnetic states in the two magnetic disks will be identical so a trilayer system should have no fundamental difference from a single layer system. On the other hand, layers that are antiferromagnetically coupled are not well studied. To investigate the formation of antiferromagnetically coupled magnetic domain states in these confined structures, we fabricated high quality single crystal trilayer disks in which the interlayer magnetic coupling can be tuned systematically between ferromagnetic coupling (FC) and antiferromagnetic coupling (AFC) by varying the thickness of a nonmagnetic spacer. Using element-specific x-ray magnetic circular dichroism (XMCD), we obtained the domain images for each the two coupled ferromagnetic microstructures and unexpectedly find that while FC coupled

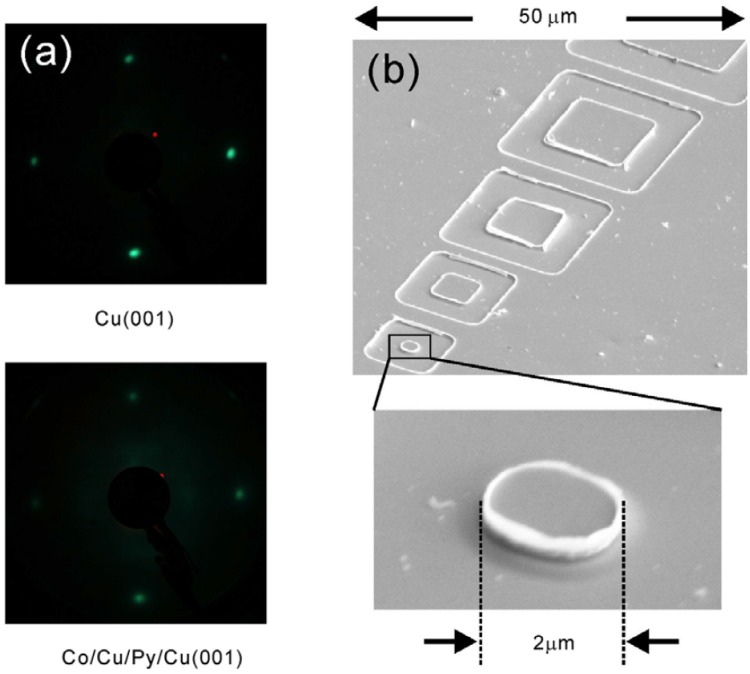

Figure 1. (a) LEED result shows the formation of single crystalline Co/Cu/Py/Cu(001) films. (b) SEM image of FIB fabricated disks from the Co/Cu/Py/Cu(001).

(This figure is in colour only in the electronic version)

microstructures favor the formation of magnetic vortex states, AFC coupled microstructures do not form vortex states.

2. Experiment

The microstructures were fabricated on a Cu(001) single crystalline substrate, which was cleaned in an ultrahigh vacuum system by cycles of Ar ion sputtering at 2 keV and annealing at 600 °C. Py, Cu, and Co films were grown epitaxially onto the Cu(001) substrate at room temperature to form Co(30 Å)/Cu/Py(120 Å)/Cu(001) trilayer structure. The Cu spacer layer was grown into a wedge (0–15 ML over 2 mm) to facilitate a continuous thickness variation. It is well known that a magnetic sandwich structure exhibits an oscillatory magnetic interlayer coupling across a spacer layer [9] due to the formation of quantum well states in the spacer layer [10]. Thus the interlayer coupling between the Py and Co layers in our sample should oscillate between ferromagnetic coupling (FC) and antiferromagnetic coupling (AFC) as a function of the Cu spacer layer thickness.

After capping the trilayer with a 20 Å Cu capping layer to prevent oxidation of the magnetic thin film, the sample was characterized by low energy electron diffraction (LEED). The sharp LEED spots from the trilayers are almost identical to that of the Cu(001) substrate (figure 1(a)), indicating that high quality epitaxial single crystalline Co/Cu/Py trilayers are formed on the Cu(001) substrate. The sample was then taken out of the UHV chamber and patterned using standard photolithography and ion milling. The resulting structure exhibits sharp edges and a complete removal of the trilayers from the designed area for the fabricated disks (figure 1(b)).

3. Results and discussions

To characterize the sample magnetically, we first performed XMCD measurements on an unpatterned area of the Co/Cu/Py/Cu(001) substrate. Photoemission electron microscopy (PEEM) was used to image the Co and Py domains at the PEEM-II beamline of the advanced light source. A circularly polarized x-ray beam is incident at a 60° angle relative to the sample surface normal direction. By tuning the x-ray energy to the Co and Ni 2p level absorption edge, we obtained the Co and Py magnetic domain images separately [11]. Figure 2 shows representative PEEM images for different Cu thicknesses (d_{Cu}). At $d_{Cu} = 3.5$ ML, the Co and Py magnetic domains have identical domain pattern and contrast, showing that the Co and Py magnetic spins are parallel to each other with ferromagnetic interlayer coupling between the Co and Py. At $d_{Cu} = 6.5$ ML, however, the Co and Py magnetic domains have identical domain pattern but have opposite magnetization contrasts, showing that the Co and Py magnetic spins are anti-parallel to each other with antiferromagnetic interlayer coupling. The above result was further confirmed by magnetic hysteresis loop measurements obtained using a standard magneto-optic Kerr effect (MOKE) setup. At $d_{Cu} = 3.5$ ML, the hysteresis loop exhibits square shape with a full remanence because the Co and Py switch together with the magnetic field (figure 2). At $d_{Cu} = 6.5$ ML,

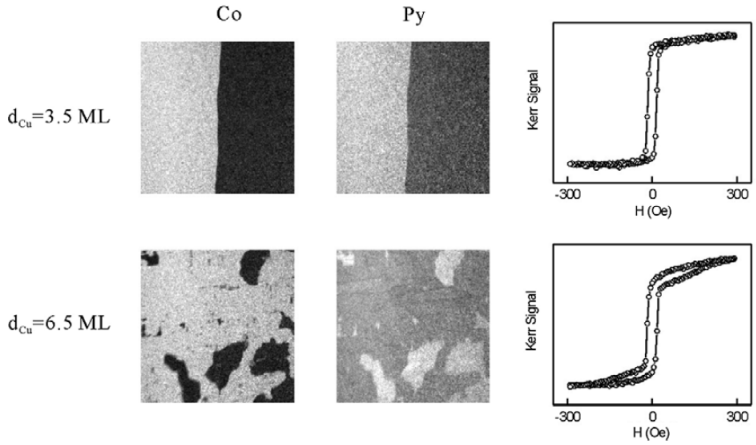

Figure 2. PEEM domain images (left) and MOKE hysteresis loops (right) show that the Co and Py layers are ferromagnetically coupled across 3.5 ML Cu spacer layer and antiferromagnetically coupled across 6.5 ML Cu spacer layer.

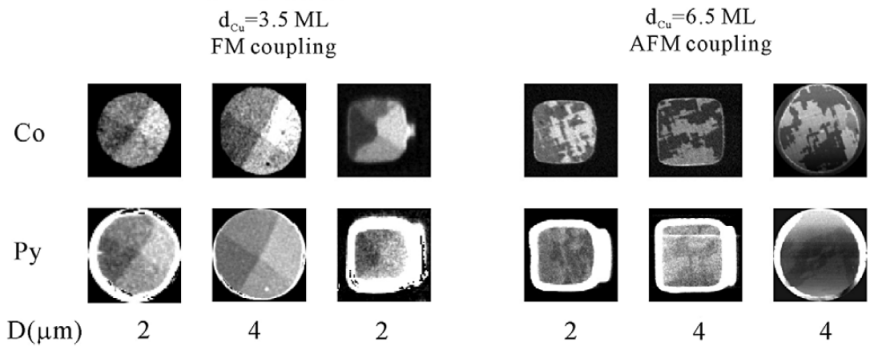

Figure 3. The Co/Cu/Py/Cu(001) trilayer disks exhibits magnetic vortex state for the ferromagnetic interlayer coupling case ($d_{\mathrm{Cu}} = 3.5$ ML), but multimagnetic domains for the antiferromagnetically coupled case ($d_{\mathrm{Cu}} = 6.5$ ML).

the magnetization does not have a full remanence due to the anti-parallel alignment of the Co and Py layers and is saturated at a much higher magnetic field compared to the $d_{\mathrm{Cu}} = 3.5$ ML measurement. This result is consistent with antiferromagnetic interlayer coupling between the Co and Py layers. Together, the PEEM and MOKE result confirms the ferromagnetic and antiferromagnetic couplings between the Co and Py layers across $d_{\mathrm{Cu}} = 3.5$ and 6.5 ML, respectively.

Element-specific domain images were next obtained on the patterned regions of the substrate at room temperature. In the $d_{\mathrm{Cu}} = 3.5$ ML region of the sample, where the Co and Py are coupled ferromagnetically, we observed a magnetic vortex state clearly (figure 3). Moreover, the vortex state exists in both circular and square structures of diameter/length 2 and 4 μm. Previous work studying ferromagnetic coupling in patterned polycrystalline thin films has shown that the magnetization vector curls around the center of the disk continuously. However, our results show that the magnetization vector is along the $[\pm 1, \pm 1, 0]$ axes and switches its direction by forming a domain wall. This is due to the four-fold magnetocrystalline anisotropy of the Co film, which results in an easy magnetization axis in the $[\pm 1, \pm 1, 0]$ axes. In a polycrystalline disk the magnetocrystalline anisotropy direction is averaged out due to the random alignment of the crystal grains. The Py layer lacks the four-fold magnetocrystalline anisotropy that the Co layer has, but we find the vortex structure to be oriented identically to the Co disk. An isolated Py disk should have a continuous change in the magnetization vector in analogy with a polycrystalline layer, but instead the domain wall pattern of the Co layer is imprinted into the Py disk as a result of the coupling between the two layers. Because Py has a weaker moment than Co, applying an external magnetic field should affect the two vortices differently. The application of an external field is problematic in PEEM due to the interaction of the magnetic field with the emitted electrons used to obtain the image, but work is underway to study this effect using x-ray transmission microscopy, which is more compatible with externally applied fields.

For the case of $d_{\mathrm{Cu}} = 6.5$ ML, where the Co and Py layers are antiferromagnetically coupled, we do not observe any vortex states. The sample was demagnetized using standard AC demagnetization techniques, but we always obtained either single domain or multidomain states, never a vortex state (figure 3). But regardless the domain shape, we always have the Co and Py magnetizations anti-parallel to each other. This result shows that the single and multidomain states are almost energetically degenerated, but have a lower

energy than the vortex state under this condition. The absence of the vortex state is not due to the absence of interlayer magnetic coupling because the Co and Py domains are always antiferromagnetically coupled no matter what the multidomain pattern looks like after the demagnetization. It is also not likely due to damage of the sample during patterning because the same patterning techniques were used for both the ferromagnetically and antiferromagnetically coupled structures and all of different the patterned structures are from the same substrate. The absence of the vortex in the antiferromagnetically coupled microstructures also doesn't depend on their size and shape. Both square and circular disks at 2 and 4 μm diameters fail to exhibit vortex state for the antiferromagnetic interlayer coupling. The small size of the multidomains suggests that the vortex state should be absent at even smaller sizes. Therefore, we conclude that the vortex state is not the ground state for antiferromagnetically coupled trilayer disks.

The magnetic ground state of a confined structure forms as a result of the interplay between the film's magnetostatic energy and exchange interactions. The lack of vortex states in antiferromagnetically coupled layers can be explained as a consequence of the minimization of the total energy due to these interactions. For a single ferromagnetic disk, the strong exchange interaction makes it difficult to change the spin direction in the surface normal direction so that the only way to minimize the magnetic field leakage is by curling the spin direction within the film plane, i.e., by forming a magnetic vortex within the disk. In an antiferromagnetically coupled trilayer disk, however, the magnetic field leaking out of one ferromagnetic disk can be converged back into the second ferromagnetic disk because of the anti-parallel spin alignment of the two ferromagnetic layers. Therefore the formation of a vortex state becomes less favored in an antiferromagnetically coupled trilayer disk. The above explanation could account for a certain thickness range but won't work for any thickness ratio of the two ferromagnetic layers. The reason is that the magnetic flux out of a single domain disk is proportional to the product of the magnetization and the film thickness so that the magnetic flux out of one ferromagnetic disk in an antiferromagnetically coupled trilayer disk cannot be totally balanced out by the second ferromagnetic layer. More theoretical work is needed to quantitatively explain our result, however.

4. Summary

We studied antiferromagnetic and ferromagnetic coupling in single crystalline Co/Cu/Py/Cu(001) trilayer disks. We find that while the ferromagnetically coupled disks form magnetic vortex state, the vortex state is absent in the antiferromagnetically coupled disks.

Acknowledgments

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