Magnetic reversal and domain structure in perpendicular antiferromagnetically-coupled Films

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Introduction

An exciting area of nano-science is the increased complexity and emergent behavior as one builds materials from the nanoscale [1]. That is, local interactions give rise to higher-level large-scale patterns, mesoscopic order and behavior that are not readily expected. This can arise from competing interactions or multiple phases with similar energies. Such behavior is often observed in the complex oxide materials such the colossal magnetoresistance (CMR) manganites materials [2].

To explore these rich physical phenomena it often proves useful to build model systems where the all the energy terms can be quantified and tuned. This is readily done in thin-film deposition of magnetic multilayers where the magnetization, anisotropy and exchange parameters are tunable and model layered magnetic materials can be designed. Recently we have demonstrated that Co/Pt-Ru multilayers structures are model systems for A-type antiferromagnets [3, 4]. The structure is shown schematically in Fig. 1a. The Co/Pt multilayer films have strong perpendicular anisotropy for thin Co layers resulting from the symmetry breaking at the Co-Pt layers. Strong ferromagnetic coupling across the weakly magnetic Pt layers yield a ferromagnetic (FM) film where local magnetization is either parallel or antiparallel to the film surface. Layering Co/Pt multilayers separated by Ru layers allows an indirect exchange between adjacent Co/Pt multilayers to be tuned to be antiferromagnetic (AF) such that the system has magnetic layers with strong interlayer FM exchange with weaker intralayer AF exchange. This system can be viewed layered Ising system that mimics a range of A-type antiferromagnets [5]. This model Hamiltonian has also been used to describe the ordering of multi-block achiral liquid crystalline molecules where at least one block contains a permanent dipole moment [6, 7]. In this presentation we describe the magnetic phase diagram of this model system with particular focus on the mixed behavior of AF and FM phases.

Methods and Materials

The multilayer structures used were $[[Co(4Å)/Pt(7Å)]_{X-1}/Co(4Å)/Ru(9Å)]_N$ where $2 \le X \le 10$ and $2 \le N \le 18$. The samples were deposited by magnetron sputtering onto ambient temperature Si_3N_x coated Si substrates and Si_3N_x membranes coated with 200-Å Pt seed layers. A series of [Co(4Å)/Pt(7Å)]X multilayers were also grown to characterize the magnetic properties of individual sublayer stacks. The average magnetic properties were determined by SQUID and Magneto-Optical Kerr Effect magnetometry while the domain structure was characterized by Magnetic Force Microscopy (MFM) and resonant soft x-ray Small-Angle Scattering (SAS) in a transmission geometry [8]. The SAS experiments were performed at the Advanced Light Source on undulator beamlines 4.0 and 8.0 with the photon energy tuned to the Co L3 resonant peak (778 eV) to maximize the magnetic scattering contrast.

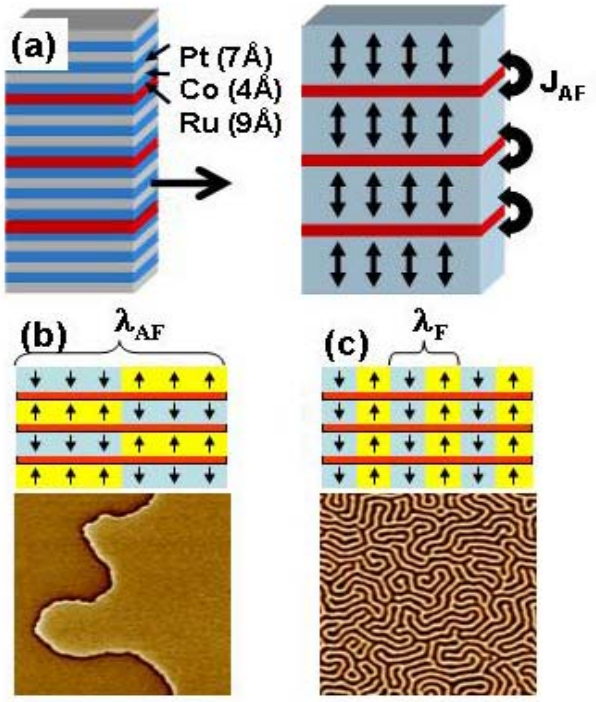

Fig. 1. (a) Schematic of the Co/Pt-Ru multilayer structure consisting of N $[Co(4Å)/Pt(7Å)]_{X-1}/Co(4Å)$ multilayers separated by 9-Å Ru interlayers. Each Co/Pt stack can be viewed as a single FM layer with perpendicular anisotropy coupled AF to the adjacent stacks. (b) Schematic of the AF ground state with corresponding experimental MFM image. (c) Schematic of the FM ground state with corresponding MFM image.

Results

The results of modeling and experiments show, in general, two phases depending on the balance of the exchange and dipolar energy as shown in Fig. 1b-c [3, 6, 7]. Figure 1b is the AF phase where the magnetization of adjacent layers are antiparallel which occurs for strong interlayer coupling and/or thin ferromagnetic layers. The AF phase can form domains (up-down-up-down *vs.* down-up-down-up) that are characterized by a periodicity λ_{AF}. For small magnetization layer thickness, λ_{AF} is expected to be large (infinite in the models) [7]. An experimental realization of this structure is shown in Fig. 1b which is an MFM image that shows large uniform regions are the AF domains and the strong contrast corresponds to the phase boundary between the two AF domains [4]. The domains are

large, microns on scale, as expected from the models and results from trapping these domains in the hysteresis process.

The second magnetic phase is a FM stripe domain pattern with a characteristic domain periodicity (Fig. 1c). The ferromagnetic order within each layer is correlated as a result of the strong dipolar fields. This phase is observed experimentally (Fig. 1c) by increasing the number of the Co/Pt layers (X) in the multilayers. This sample shows a characteristic λ_{FM} that results from the competition between the thin film dipolar energy and the interlayer layer exchange energy as originally outlined by Kittel [9]. The transition from the AF to FM phases can be quantitatively determined by comparing the energy of the AF phase (assuming $\lambda_{AF}=\infty$) with the FM phase [3].

To follow the transition between the AF and FM phases in detail it is useful to vary the dipolar fields continuously rather than in discrete steps with X and N. To achieve this we deposited several multilayer wedge samples where each of the Co layers within the multilayer varied continuously from 4.0 Å at one end of the sample to 4.4 Å at the other while keeping the Pt and Ru layer thickness constant. This change in Co layer thickness is sufficient to evolve the system from an AF to FM ground states. The number of Co blocks was chosen to be odd which gives a slight contrast between the two AF domains in the MFM imaging.

Shown in Fig. 2 are six remanent MFM images after out-of-plane demagnetization of the sample. For the thinnest Co thickness (Fig. 2a), the image is characterized by large AF domains (as seen in Fig. 1b) where one-dimensional stripe domains forms at the boundary between AF phases. These regions of FM order are stabilized at the boundary due to dipolar fields [4]. As the Co layer thickness increases Fig. 2b-f, one sees that the one-dimensional stripes broaden forming two-dimensional stripe domains characteristic of the FM phase. These regions of FM domains form at the boundary between the two AF domains. This is seen most clearly in Figs. 2c and d. One also sees that the stripes are normal to the boundary at the AF phases reflecting the one-dimension pattern at lower Co thicknesses. By Fig. 2e the FM phase has become the dominant phase with local regions are AF order. Again the stripe domains are normal to the phase boundary of the AF phases. In Fig. 2f, the entire film is in the FM phase.

Discussion

The complex behavior reflected in Fig. 2 arises from the competition between the dipolar and exchange energies, which we were able to tune by means of the individual sub-layer thickness or total film thickness. While such domain structures are not expected to occur in antiferromagnets where the exchange coupling dominates all secondary interactions (e.g. CoO or MnF_2), they may occur in A-type antiferromagnets, which exhibit anisotropic exchange coupling. This class of materials includes many of the Ruddlesden-Popper series of perovskites including the manganites, cobaltites, and nickelates where naturally layered, $La_{1.4}Sr_{1.6}Mn_2O_7$ being an example [5]. In such systems mesoscopic domain structures and separation of AF and FM phases are observed that arise from both intrinsic and extrinsic factors [2] that form complex structures. These present results provide insight into the complex magnetic domain structures that can occur. In particular these results highlight the role of AF domain boundaries on the two phase behavior.

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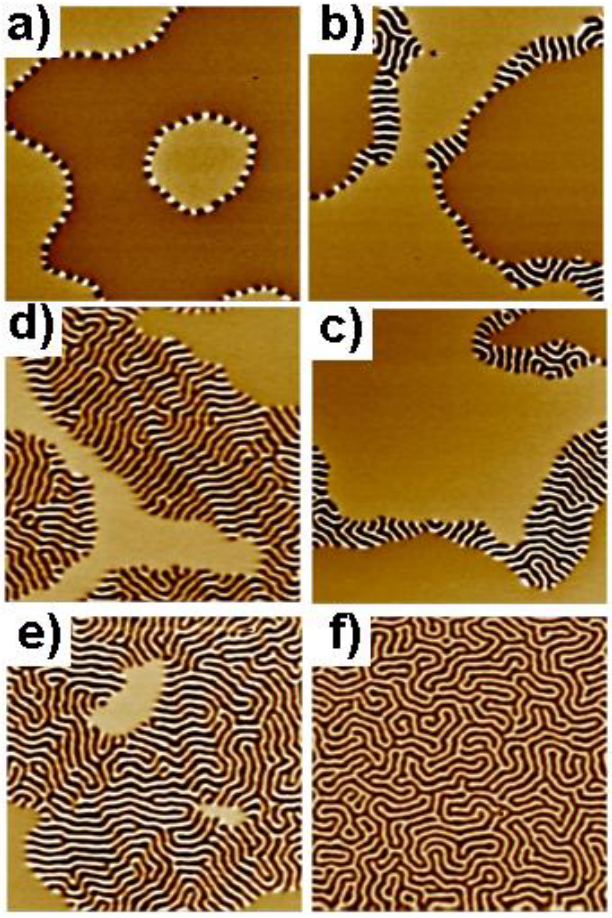

Fig. 2: Sequence of MFM images, (10 μm)2 each, along a wedge sample with N=15 and X=8 with increasing Co thickness from (a) to (f) showing the transition from one dimensional AF stripe domain walls (a) to 2-dimensonal stripe domains (f) after out-of-plane demagnetization.

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