DOI: 10.1017/S1431927606067596
Microsc Microanal 12(Supp 2), 2006

Magnetic Nanostructures: In-Situ Assembly and Exploration of Low-Dimensional Systems by Spin-Polarized Low-Energy Electron Microscopy.

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Spin-polarized low-energy electron microscopy (SPLEEM) is a powerful tool to reveal details of sample morphology and spin-resolved electronic structure in nanostructured materials. By illuminating sample surfaces with spin-polarized electrons and monitoring spin-dependent electron reflection to form images, we can probe sample structure as well as electronic and magnetic properties during *in-situ* preparation [1,2,3].

Magnetic properties of materials can change in interesting ways when one prepares structures with nanoscale dimensions. For example one can ask, what might be the minimum size of thermally stable magnetic domains in a material? Measuring minimal domain size is important, both to understand basic magnetic phenomena and to guide the development of materials for spin-electronics applications.

Using SPLEEM to study magnetization in single-crystalline layered structures, we discovered that magnetic domains and domain walls in the top Fe layer of Fe/NiO/Fe/MgO(100) structures are dramatically smaller than the corresponding domain structures observed in bulk-like Fe/MgO(100) films [3]. The patterns include many domains that are topolocically unconnected ("bubbles") and narrow elongated domains ("channels"), and the domain wall widths are roughly one order of magnitude smaller than what is observed in Fe layers grown on non-magnetic substrates.

Our structures were build on top of clean MgO(100) crystals, using *in-situ* preparation techniques. Freshly fabricated NiO/Fe/MgO(100) samples (thickness: MgO = bulk, Fe ≈ hundreds nm, NiO ≈ 1 nm) were UHV-transferred into the specimen chamber of our spin-polarized low-energy electron microscope (SPLEEM), where we grew the top Fe layer (thickness ≈ 1nm) under conditions of very good vacuum and very low stray-magnetic field. We imaged the resulting, 'virgin', magnetic domain microstructure in the top Fe layer *in-situ* during and after deposition. When the thickness of the NiO spacer is small (of the order of 1 nm), the remarkable topology of the magnetic domains in the Fe capping layer results. Large regions of the samples are covered with intricate patterns of domains that are all magnetized along one easy axis. The domains are separated by 180° domain walls and have complex, meandering structures. The widths of the domain walls are so small that, given the resolution of our images, we can only estimate an upper limit of < 20 nm wall-width.

The topologies of the observed domain microstructures share many features with the predictions from two-dimensional Ising-models with only short-range interactions. For example, unconnected topologies with domain size distributions that include very small bubbles and narrow channels, as well as spanning-domains that extend across the entire sample, are a natural feature of two-states systems. What's puzzling is that, in principle, our system has four-fold symmetry, and one might have guessed that observed topologies should be closer to predictions from 4-states Potts models. (4-states models would predict compact domains and very rare bubbles or channels, this is clearly not our observation.) The observation that the top Fe layer “chooses” one of the two degenerate easy axes and “ignores” the other one can be understood as a result of the strong coupling of the ultrathin ferromagnetic top Fe-layer, through an antiferromagnetic spacer, to the much thicker ferromagnetic substrate [4]. The thick, ferromagnetic substrate has very large magnetic domains (typically mm-scale), magnetized along either [010] or [001] directions. The antiferromagnetic easy axis of NiO grown on top of such a domain latches onto the Fe magnetization direction via exchange coupling. As a result, antiferromagnetic domains in the NiO spacer scramble the coupling direction with respect to the subsequently deposited top Fe-layer, but conserve their axis with respect to the underlying domain in the Fe substrate.

The other puzzling feature in our observations is the extremely small width of domain walls. Again, this can be understood as a consequence of exchange coupling between ferromagnetic and antiferromagnetic layers [4]. In pure ferromagnets, domain wall width is often relatively large, because it is governed by the competition between the stronger exchange interaction (favoring greater width) and normally relatively weak anisotropy (favoring smaller width). The situation can be very different at interfaces with antiferromagnets. In this case, frustrated exchange forces at interfaces also favor narrow domain walls, and can be far greater than anisotropy forces [4].

The discovery of nanoscale domains in Fe/NiO/Fe/MgO(100) is important both fundamentally and because the stability of small magnetic domains in this type of single-crystal layered structures is potentially useful to enable miniaturization of spin-electronics devices such as coherent spin-tunnel junctions [5,6]. It is interesting to note that the stability of our observed nanodomains coincides with perfect remanence, as we demonstrated by magneto-optic Kerr measurements [3]. This indicates that remanent single-domain states spanning the sample are possible, and one might envision to “write” individual, stable, “bubble”-nanodomains into such trilayer structures.

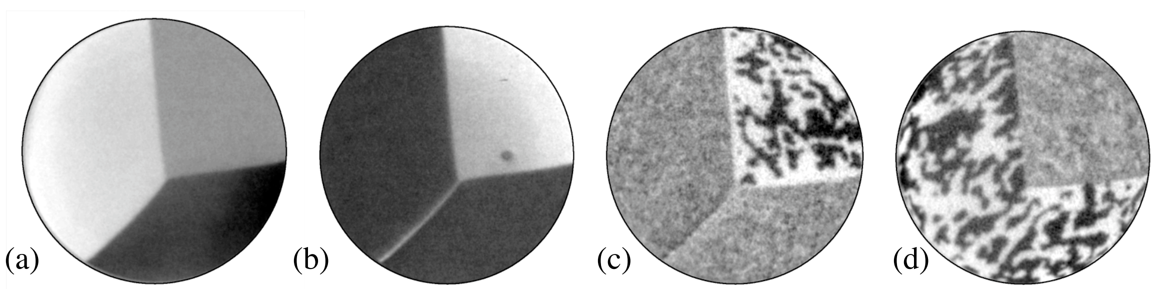

Figure: SPLEEM images (field of view 7 μ) in panels (a) and (b) (electron beam spin parallel [010] and [001], respectively) show magnetic domains in Fe/MgO substrate prior to growth of trilayer structure. Large domains are magnetized along [010] or [001] easy axes. 180º domain walls are ≈ 120 nm wide (see bright linear feature in lower part of b). Panels (c) and (d) show corresponding images of domain structures in the top Fe-layer after completion of the Fe/NiO/Fe/MgO trilayer. Delicate, Ising-like domain structures include very small “bubble”- and “channel”-domains with width as small as 70 nm. Width of 180° domain walls is smaller than 20 nm, below resolution of these images.

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https://doi.org/10.1017/S1431927606067596 Published online by Cambridge University Press