Magnetic domains in epitaxial nanomagnets with uniaxial or fourfold crystal anisotropy

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In order to prepare submicron sized particles with strong magnetocrystalline anisotropies high quality epitaxial bcc-Fe films were grown on GaAs(110) and GaAs(001) by molecular beam epitaxy. Whereas Fe(110) on GaAs(110) is a model system with uniaxial in-plane anisotropy, Fe(001) on GaAs(001) has a strong fourfold anisotropy for films thicker than \( \sim 5 \) nm. Various shapes like circular, square, or rectangular elements with sizes from 200 nm up to 6 \( \mu \)m were fabricated by electron beam lithography and ion beam etching. The remanent states after saturation along different directions or ac demagnetization along the easy axis were examined by using magnetic force microscopy. The experimental results clearly reflect the interplay of the different magnetocrystalline and shape anisotropies depending on the different magnetic histories. © 2002 American Institute of Physics. [DOI: 10.1063/1.1453339]

The control of the magnetic structure of nanoscale ferromagnetic elements, e.g., in magnetic tunnel junctions, is of central importance for their functionality. While the static magnetic properties of nanopatterned polycrystalline magnetic films of different shape were intensively investigated during the last few years less information is available about the magnetization behavior of nanoscale magnetic elements fabricated from epitaxially grown films. On the other hand, magnetic tunnel junctions involving single crystalline iron contacts on single crystal semiconductor barriers like GaAs or ZnSe, e.g., promise very high magnetoresistance effects. 1,2 Very recently it was also shown that spin polarized electrons can be injected from epitaxially grown iron films into GaAs (Ref. 3) or AlGaAs. 4 Here we report on magnetic properties of nanopatterned epitaxial iron films on GaAs. By growing on differently oriented GaAs substrates epitaxial layers with different magnetic anisotropies can be realized: Fe(110) on GaAs(110) exhibits a uniaxial anisotropy, 5 thick Fe(001) on GaAs(001) a magnetocrystalline anisotropy of fourfold symmetry. 6, 7 Nanopatterned elements fabricated out of the two types of epitaxial iron films display strikingly different magnetization patterns in their remanent and demagnetized state.

High quality bcc Fe films were grown at room temperature by molecular beam epitaxy (MBE) on GaAs(110) and GaAs(001) substrates. The substrates were prepared by an annealing in UHV at 900 K for 1 h, Ar+ ion etching (500 eV) at 900 K for 30 min, and further annealing for 1 h at 900 K. On GaAs(110) 34 nm thick Fe(110) films and on GaAs(001) 25 and 30 nm thick Fe(001) films were grown. The Fe films were finally covered with a 4 nm thick Au layer to prevent oxidation. Details of the epitaxial growth can be found in previous publications: Ref. 8 for GaAs(110) and Ref. 7 for GaAs(001).

For bulk bcc Fe the magnetic easy axis of the cubic anisotropy is aligned along the [001] direction. In addition to the cubic anisotropy a strong uniaxial contribution \( K_u \) with the easy axis also aligned in [001] direction is found in thin Fe(110) films. Hence, our films display essentially uniaxial behavior. 8 The anisotropy constants were determined by alternating gradient magnetometer (AGM) measurements 9 as \( K_1 = 3.5 \times 10^5 \) erg/cm\(^3\) and \( K_2 = 2.4 \times 10^5 \) erg/cm\(^3\). Using the in-plane anisotropy energy density

\[ \epsilon_K(\varphi) = \frac{1}{4} K_u (\sin^2 2\varphi + \sin^4 \varphi) + K_u \sin^2 \varphi, \]

where \( \varphi \) is the angle between the magnetization and the [001] direction we find a maximum value of \( \epsilon_K(\varphi) \approx 3.3 \times 10^5 \) erg/cm\(^3\).

The Fe(001) films, on the other hand, show a transition from a uniaxial to a fourfold magnetocrystalline anisotropy for films thicker than \( \sim 5 \) nm. The in-plane anisotropy of our 25 and 30 nm thick Fe(001) films behaves like bulk material \((K_1 = 4.8 \times 10^5 \) erg/cm\(^3\)) with the easy axes orientated along [100], [010] and the hard axes along [110], [110]. 7 For these films the maximum anisotropy energy density is \( \epsilon_K(\varphi) = 5 \times 10^5 \) erg/cm\(^3\).

From the films we prepared elements with different shapes and sizes between 5 \( \mu \)m and 150 nm. Here we focus on circular disks and rectangular elements. In a first step Ti etch masks were prepared on the Fe films by electron beam lithography (EVL) and liftoff technique. After etching the ferromagnetic elements using 500 eV Ar+ ion beam etching (IBE) the structures were coated with a 10 nm Ti layer. This was done by rotating the tilted sample (tilt angle 60°) around its surface normal to also cover the edges of the elements. The Ti layer reduces the interaction between the MFM tip and sample especially during the topography scan.

For the MFM investigations we used a Digital Instruments Multimode AFM in non contact mode and phase detection of the magnetic force gradients. Commercial MFM tips from nanosensors with \( \sim 40 \) nm CoCr coating were used. The lift height was set to 30 nm. All MFM measurements were carried out at ambient conditions.

Circular disks are an ideal shape to study the intrinsic magnetocrystalline anisotropy because the shape anisotropy has no preferred in-plane direction. The shape anisotropy of

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disks made of polycrystalline ferromagnetic material without any intrinsic anisotropy forms a flux-closed in-plane vortex to minimize the stray field. To approach the ground state of the Fe disks they were demagnetized with a slowly decreasing ac in-plane field along an easy axis.

Figure 1 shows demagnetized Fe(110) and Fe(001) disks of different sizes. The magnetization pattern of all Fe(110) disks investigated with diameters between 200 nm and 5 μm is a two domain state. In the larger disks the two antiparallel domains are separated by cross-tie-like walls. In the smaller disks the wall contains only one Bloch line in its center [see right-hand side image of Fig. 1(a)]. In contrast, the demagnetized Fe(001) disks with diameters above 1.5 μm, displayed in Fig. 1(b), show a flux-closed four-domain state. This pattern looks like a typical Landau–Lifshitz domain configuration. However, here the Landau–Lifshitz structure is caused by the magnetocrystalline anisotropy in contrast to the shape anisotropy in squares. Disks with diameters below 1.5 μm show no distinct wall structure. For the fourfold Fe(001) disks no dependence of the remanent state on the direction of saturation was found. The disks show the same type of domain pattern as the ac-demagnetized states shown in Fig. 1(b). This result agrees with previous investigations of Fe dot arrays, but in contrast to Ref. 12 no single domain state was found for the Fe(001) disks with diameters between 200 nm and 5 μm.

An other interesting shape is represented by rectangles with an additional high shape anisotropy. The domain patterns obtained after ac demagnetization along different crystallographic axes are shown in Fig. 4. The magnetization of the 30 nm thick Fe(001) rectangles always lies parallel to the long axis independent of their orientation and their magnetic history [see Fig. 4(a)]. This means that the shape anisotropy dominates the magnetization of these particles. If we approximate our smallest rectangle by an ellipsoid (length 1500 nm, width 300 nm, thickness 30 nm) we find a magnetostatic energy density of $\sim 3 \times 10^5$ erg/cm$^3$ for the system magnetized in-plane perpendicular to the long axis. This value is larger than the maximum anisotropy energy density of $e_{K(001)}^{\max} = 1.2 \times 10^5$ erg/cm$^3$. The two energy densities are equal for elements with a length of about 750 nm. This is consistent with the fact that the magnetization of the shorter
The magnetization state occurs for side lengths between 900 and 800 nm. The size of the two largest squares is 1100 nm. The transition of the magnetization state is always displayed the same remanent magnetization pattern. This is in contrast to the Fe$_{110}$ elements which always displayed the same remanent magnetization pattern.

In summary, we have shown that it is possible to switch from a dominating magnetocrystalline anisotropy to a dominating shape anisotropy and vice versa by varying the shape and size of a particle. For the Fe$_{110}$ elements we found a strong dependence of their remanent state on the magnetic history. This is in contrast to the Fe$_{001}$ elements which are in multidomain states (not shown).

The Fe$_{110}$ rectangles, in contrast, are magnetized along the long axis only if the easy axis [001] of the intrinsic uniaxial anisotropy is also aligned in this direction [see left-hand side image of Fig. 4(b)]. If the easy axis is perpendicular to the long axis a periodic domain pattern is found in the ac-demagnetized state and also after saturation along the easy axis of the intrinsic anisotropy [see central image of Fig. 4(b)]. After saturation along the [110] direction the shortest rectangle displays a regular pattern with smaller domains [see bottom of the right-hand side image of Fig. 4(b)]. This behavior has been reported previously.$^{14,15}$ The longer rectangles display a strong magnetization component parallel to the long axis (see dark–bright contrast at the edges of the rectangles) caused by the shape anisotropy. With increasing length of the rectangles, the magnetostatic energy density becomes higher than the magnetocrystalline energy density: $e_{\text{stat}}=4.3 \times 10^5 \text{ erg/cm}^3$ (for a length of 2 $\mu$m) > $e_{K(110)}^{\text{max}}=3.3 \times 10^5 \text{ erg/cm}^3$.

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