Magnetic domain structure of Heusler/MgO/Heusler trilayer systems

A. Kaiser, C. Wiemann, S. Cramm, C.M. Schneider

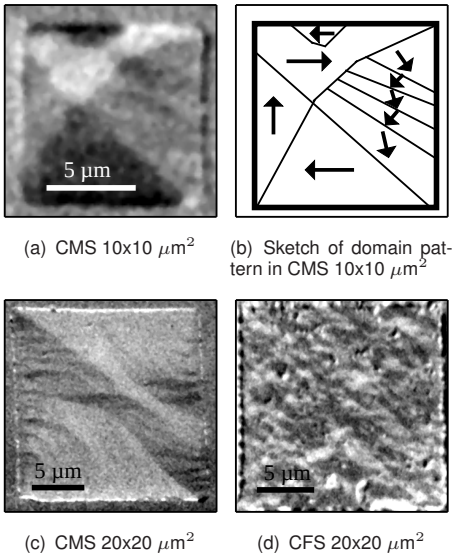
IFF-9: Electronic Properties

We have investigated the magnetic domain structure of magnetic trilayers consisting of the two Heusler compounds Co_2FeSi (CFS) and Co_2MnSi (CMS) and a thin MgO barrier by X-Ray Photoemission Electron Microscopy (XPEEM). The measurements revealed a parallel coupling of the two magnetic films and different micromagnetic properties depending on the layer sequence. The results are discussed in terms of the material properties and growth conditions.

Heusler alloys [1] are considered as interesting ferromagnetic electrode materials for magnetic tunnel junctions (MTJ). Due to their high spin polarization at the Fermi level they are expected to show extremely high tunnelling magnetoresistance (TMR) values. MgO as a tunneling barrier material has a comparable lattice constant and thus provides the possibility of epitaxial growth of trilayer systems. Due to the reduction of defects and the onset of resonant tunnelling mechanisms an increase of the TMR effect can be expected.

Co_2FeSi (CFS) and Co_2MnSi (CMS) are two protagonists of the class of half-metallic Heusler compounds. They have similar lattice constants providing structural compatibility to MgO. Both materials have high Curie temperatures around 1000 K and magnetic moments per formula unit of 5.07 μ_B (CMS) and 6 μ_B, respectively. Hysteresis measurements reveal clearly distinguishable coercive fields of 2.8 mT (CMS) and 6.5 mT (CFS). Single films and trilayer structures with asymmetric electrode configurations have been prepared by magnetron sputtering. The films have been subsequently microstructured by optical lithography and argon ion beam milling into squares with areas ranging from 2×2 to 100×100 μm^2. A more detailed description of the growth conditions and the experimental results can be found elsewhere [2].

The micromagnetic structure of the films has been studied by XPEEM exploiting the XMCD effect for the element-selective study of magnetic domain configurations [3]. The measurements have been carried out using an Elmitec PEEM III at the beamline UE56/1-SGM at BESSY-II. All measurements shown in this report have been generated by tuning the photon energy to the appropriate L_3 absorption edge and calculating the XMCD asymmetry value for each pixel.

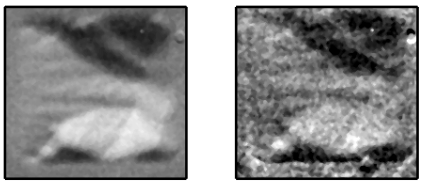


(a) CMS 10x10 μm^2 (b) Sketch of domain pattern in CMS 10x10 μm^2

(c) CMS 20x20 μm^2 (d) CFS 20x20 μm^2

FIG. 1: Magnetic domain structures in patterned CMS and CFS elements. The magnetic contrast has been obtained at the Co L_3 edge.

Fig. 1 shows the magnetic domain patterns from single CMS and CFS films. Under the influence of the shape-induced demagnetizing field, the magnetization configuration of elements of comparable size is distinctly different. The CMS film develops a so-called concertina or buckling pattern (fig. 1(c)). It is formed by alternating low-angle walls with the local magnetization direction varying around the average magnetization [4]. With decreasing element size the effect of the demagnetizing field becomes stronger and successively simpler flux-closure patterns reminiscent of Landau states start to form (Fig. 1(a) and 1(b)), which are still accompanied by buckling structures. The latter disappear for elements in the micrometer regime. However, the occurrence of the buckling state is not necessarily the magnetic ground state configuration, but may arise due to a local energetic minimum caused by neighbouring domains blocking each other. A completely different response is observed in the CFS films. Even under the influence of the demagnetizing field in small 10×10 μm^2 elements (Fig. 1(d)), the polycrystalline nature of the film is dominating the magnetization pattern and the fine-grained domain structure remains essentially un-



(a) Fe-L_3 (b) Mn-L_3

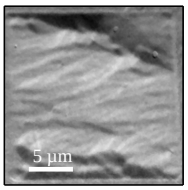
FIG. 2: Element-selective domain imaging in the layer system CMS/MgO/CFS, revealing a parallel magnetic coupling of the CFS and CMS films.

changed from that observed in the extended film (not shown). This result shows that the intrinsic anisotropy of the CFS-film is much stronger than the demagnetizing field of the square element.

In a second step the single Heusler films have been combined into trilayer structures with a MgO interlayer of 3 nm thickness. In order to separate the magnetic response of the individual layers in this stack, the full versatility of XPEEM is needed. By tuning the photon energy to the L_3-absorption edges of Fe and Mn the magnetization of both ferromagnetic layers can be investigated independently. Resulting domain images for a square element of CMS(20 nm)/MgO(3 nm)/CFS(2 nm) with 10 μm edge length are compiled in fig. 2. Due to the limited escape depth of the photoelectrons, the Mn signal is rather weak and had to be upscaled by a factor of five. Comparing the domain patterns of the Fe and Mn data reveals identical structures consisting of Landau flux-closure pattern superposed by concertina features in both films. The reasons for this coupling can be a roughness-induced Néel/orange-peel mechanism [5] or pinholes in the MgO layers, which favour a ferromagnetic contact between the CFS and CMS layer through a direct exchange interaction. The domain patterns of the trilayer film resemble the situation of the single CMS film (fig. 1a). Due to the difference in thickness in both films the micromagnetic structure is strongly dominated by the CMS bottom layer. For larger $20 \times 20\ \mu m^2$ elements (fig. 3a) the magnetic structure is no longer determined by the flux-closure but by local anisotropy fluctuations leading to a magnetization ripple due to the polycrystalline structure of the films is formed

In the inverse trilayer system the magnetic microstructures changes drastically. Instead of the ripple pattern we find a higher average domain size and the formation of a low-remanence magnetization pattern consisting of two antiparallel Landau domains (fig. 3b). Some of the 90°-walls have been replaced by an additional domain with two low-angle walls (known as "Tulip" state). The 180°-walls between neighbouring antiparallel domains are modified by a high density of cross-ties replacing 180°-walls by energetically more favorable 90°-walls.

In this trilayer structure we do not find a magnetic contrast at the Mn edge. This fact is surprising since the CMS film is the top layer and is expected to yield a higher intensity than in the reversed stack.



(a) CMS (20 nm)/ MgO (3 nm)/ CFS (2 nm)

FIG. 3: Comparison of magnetic domain patterns acquired at the Co L_3 edge of $20 \times 20\ \mu m^2$ square elements of both trilayers.

Thus we must conclude that the CMS film is nonmagnetic at room temperature. This behaviour may be attributed to a strong thickness dependence of the CMS magnetic moment that has been reported by other groups. The strongly reduced Curie temperature in the 2 nm CMS film may be explained by interdiffusion at the interface leading to a higher atomic disorder. Furthermore, this result seems to indicate that the MgO barrier in this layer has only a negligible density of pinholes, because a direct exchange coupling to the bottom CFS layer should also result in a common Curie temperature for both layers.

In conclusion our element-selective domain imaging experiments reveal the complexity of the magnetic microstructure in Heusler-based thin film systems. The results also show that the micromagnetic structure depends on fine details of the formation process of the Heusler phases. Analysis of the domain configurations shows that the ferromagnetic coupling observed in the dual-Heusler trilayers can be attributed to roughness-induced Néel coupling. This can be overcome by an improvement of the preparation conditions. The surprising difference of the magnetic behaviour between the CMS/MgO/CFS and CFS/MgO/CMS trilayer structures is due to a strong thickness dependence of the magnetic ordering in CMS and must be taken into account for the construction of magnetic tunnelling junctions.

We thank D. Rata and D. Banerjee for the deposition of the samples and hysteresis measurements. This work was financially supported by the DFG (SFB 491).

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