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Filling the seats:
Atomic-scale roughness of antiferromagnetic films

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Saturday afternoon: The first supporters arrive and fill the stand, but this stadium has peculiar rules. On the orange seats women and men are seated in a strict alternating order, while the blue stand has to be filled with either only men or only women. The gender of the supporters in the blue seats has to be selected such that at the interface between the orange and blue seats preferably couples of men and women are placed. This makes the filling of the seats an interesting problem, which very much depends on the details of how the border line between orange and blue exactly runs. This is pretty much the situation of the interaction at the interface in a stack of ferro- and antiferromagnetic films. These multilayers are important ingredients of many devices like hard disk read heads, magnetic sensors, or magnetic random access memories [1,2]. Their widespread use in commercial applications is, however, not paralleled by a detailed fundamental understanding of the interaction between antiferromagnetic and ferromagnetic materials. While in ferromagnets all the atomic magnetic moments are pointing in the same direction (i.e. are all male or female in the stand), the magnetic order in antiferromagnets is more complex. In antiferromagnets the atomic moments align such that the total moment vanishes if averaged over a few neighbor atoms. In the simplest ones every other atom has its spin pointing into the opposite direction. To achieve understanding of the magnetic interaction between an antiferromagnetic and a ferromagnetic material, it is thus vital to characterize and control the interface structure and roughness on the atomic level.

We used the technique of magnetic domain imaging by x-ray magnetic circular dichroism photoelectron emission microscopy (XMCD-PEEM) [4] to study the dependence of the magnetic interface coupling on thickness and layer filling of both the ferromagnetic and antiferromagnetic films [3]. The absorption of circularly polarized synchrotron radiation from the elliptic undulator beamline UE56-2 PGM 2 was used to obtain magnified images of the sample by means of the emitted secondary electrons. In these images, regions of different intensity represent different magnetization directions. The XMCD effect occurs only in resonance at elemental absorption lines, thus magnetic domain images of different layers at different depths of the single-crystal heterostructures can be acquired separately if they contain different elements. Crossed-wedge samples, in which the thickness of a ferromagnetic and an antiferromagnetic layer vary along perpendicular directions, were prepared, and allow the simultaneous visualization of the magnetic coupling as function of two different layer thicknesses.

Fig. 1 shows an example of a trilayer on a Cu(001) substrate in which antiferromagnetic FeMn is sandwiched by two ferromagnetic layers, a Co layer at the bottom, and a Co/Ni hybrid layer at the top. Panel (a) shows a sketch of the wedge geometry. The thickness of the bottom Co layer (blue) increases from left to right up to 8 atomic monolayers (ML), and then stays constant. The thickness of the antiferromagnetic FeMn layer (red) varies from bottom to top. Panel (b) shows the magnetic domain image of the as-grown Co bottom layer, panels (c) and (d) the domain images obtained at the Co and Ni absorption resonances, respectively, after deposition of the complete structure. Because both the bottom and top ferromagnetic layers contain Co, image (c) is a superposition of the magnetic domain patterns (b) and (d), while panel (d) represents the top layer only. Alternating regions of parallel and antiparallel coupling across the FeMn layer are indicated by couples of parallel and antiparallel arrows in (c). They alternate with a 2-ML period as a function of FeMn thickness, but also exhibit an interesting saw-tooth-like behavior on the thickness of the bottom Co layer. The latter represents the dependence on the interface morphology. It is modulated by the thickness, and hence the atomic layer filling, of the bottom Co layer.

From these measurements and supporting magneto-optical Kerr effect experiments, the following picture could be deduced [3]: First, to have a significant magnetic interaction between the ferromagnetic and the antiferromagnetic layers, steps of single atom height at the interface are required. Perfectly flat regions do not contribute. This follows from

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Acknowledgments:

We thank B. Zada and W. Mahler of the UE56-2 beamlines for their help.

Supported by the BMBF

the absence of 90° coupling, which would otherwise be expected at FeMn thicknesses close to n + 0.5 ML thicknesses with n an integer number [6]. Also the influence of the Co bottom layer thickness on the sign of the coupling is not compatible with flat regions being the dominant source of the antiferromagnet/ferromagnet coupling. Second, the coupling is higher if these monatomic steps are laterally confined at small islands. Larger islands or elongated steps mediate a weaker coupling. The strength of the coupling can only be deduced from the Kerr measurements.

The observed saw-tooth pattern is surprising. The interface roughness has maxima at around 50% atomic layer fillings and decreases towards both sides, for higher and lower fillings, leading to the sine-like oscillations typically observed in the diffracted electron intensity [7]. In the present case, however, a 20% filling is completely different from an 80% filling, although the number of monatomic steps and thus the roughness may be equal. This leads to the third conclusion, that the amount of antiferromagnetic material needed to complete the outmost atomic layer of the ferromagnets is not contributing to the sign of the coupling.

The coupling is mediated by uncompensated spins of the antiferromagnet at monatomic step edges at the interface. A sketch of a possible interface spin configuration at such a monatomic step edge is shown in Fig. 2. Black and gray bullets with arrows represent atomic moments of next-level atomic planes of the non-collinear antiferromagnetic spin structure [5] of FeMn. Ellipses at the step edges indicate regions in which the antiferromagnetic spins do not cancel, but follow the magnetization direction M_{FM} of the ferromagnetic layer. These uncompensated atomic moments are responsible for the magnetic coupling to the ferromagnet.

Our results indicate that, in general, the interface coupling can be enhanced by the controlled incorporation of atomic-level roughness features with small lateral size. This would be like designing the border line between the orange and blue seats in the stadium in a particular rough zig-zag shape such as to provide a very clear-cut decision about the gender of the supporters in the blue stand. With the forthcoming advent of atomic-scale manipulation in nanotechnology, this may be a feasible way to controllably modify the coupling strength in ferromagnetic–antiferromagnetic systems.

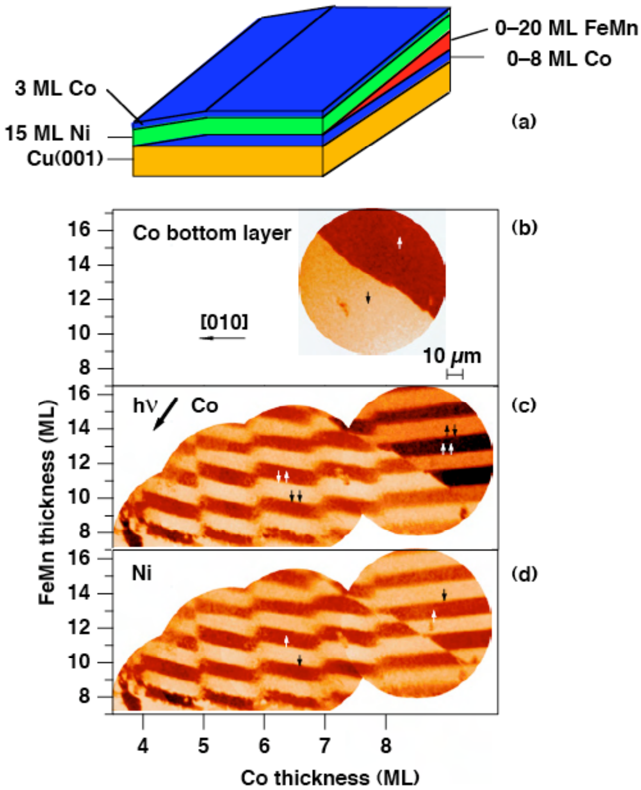

Fig. 1:
(a): Geometry of a crossed double-wedge sample. Antiferromagnetic FeMn of varying thickness is sandwiched between ferromagnetic layers consisting of Co at the bottom and Co/Ni at the top.
(b): Domain pattern of the Co bottom layer. Bright and dark regions correspond to magnetization direction down and up, respectively.
(c): Element-selective domain image of the complete sandwich structure, acquired at the Co L_3 edge. Bright and dark regions result from a superposition of magnetization directions of Co in the bottom and top layer, indicated by couples of arrows.
(d): Element-selective domain image of the top layer, acquired at the Ni L_3 edge. Bright and dark regions correspond to magnetization direction down and up, respectively.

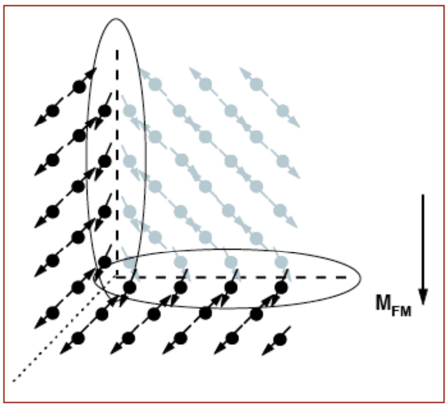

Fig. 2:
Sketch of a possible interface spin structure of the antiferromagnetic FeMn layer. Uncompensated atomic moments at monatomic step edges (ellipses) mediate the magnetic coupling to an adjacent ferromagnetic layer.

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