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INVESTIGATING SPINTRONICS THIN FILM SYSTEMS WITH SYNCHROTRON RADIATION

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I. Introduction

Complex layered structures and and nanomagnets are the main building blocks for current and future spintronics applications. The electronic, magnetic and magneto-transport properties of these layered systems are determined not only by the characteristics of the individual layers, but even more so by the boundaries between them. Magnetic coupling phenomena and spin-dependent transport are sensitively affected by the atomic arrangement, electronic states and the magnetic nanostructure of the individual constituents at the interfaces. In addition, not only the static magnetic properties are of interest, but also the dynamic response. A controlled and fast magnetization reversal determines the functionality of magnetic devices and therefore, the details of the magnetic switching mechanisms and the limiting timescales involved are of great interest.

Synchrotron radiation provides a convenient and versatile approach to the study of magnetism. Magnetic sensitivity can be achieved by a proper choice of circular or linear polarization. The synchroton light also combines element selectivity with time-resolution due to the broad tuning range and intrinsic time-structure. It is therefore ideally suited to address both static and dynamic issues in thin film and nanomagnetism on the basis of a variety of spectroscopy and microscopy techniques. In the following, we will focus on the application of photoelectron spectroscopy and microscopy techniques with synchrotron radiation to magnetic thin films.

In the first part of this contribution, we will discuss recent results of our studies on the electronic and magnetic states in two spintronic model systems: MgO/Fe(001) and $NiO/Fe_3O_4(011)$. A particular emphasis is laid on the role of the interfaces. The second part is devoted to pump-probe investigations of the magnetodynamics in magnetic microstructures by means of time-resolved photoemission microscopy.

II. Electronic States in MgO/Fe(001)

The Fe/MgO system is well known by now for its high tunneling magnetoresistance effects [1,2], presumably caused by coherent tunneling through matched electronic states across the interfaces. Little is known, however, about the electronic states at the MgO/Fe interface and the influence of the chemical composition and defects, respectively. Using spin-polarized photoemission spectroscopy, we have studied the spin-split electronic states in Fe(001) upon deposition of ultrathin MgO films of variable stoichiometry [3,4]. The band gap of MgO ensures that the Fe-related spectral features can still be observed through the MgO overlayer (Fig. 1). In our experimental geometry we are sensitive to electronic states of both Δ_1 and Δ_5 spatial symmetry. We find that for stoichiometric MgO overlayers the Fe spectral features and the spin polarization at the Fermi level remain unchanged.

On the other hand, overoxidation of the Mg leads to a clear reduction of the Fe spin polarization, caused by the formation of interfacial FeO. This can also be confirmed by the evolution of an exchange-splitting in the O 2*p* states. An oxygen deficiency in the MgO layer, however, causes a significant increase of the Fe spin polarization, which may be explained through the electronic interaction with O vacancies and the resulting charge transfer.

III. Magnetic proximity effects in $NiO/Fe_3O_4(001)$

The interface between antiferromagnets (AF) and ferromagnets (FM) gives rise to the phenomenon of exchange bias, which is often used to define a magnetic reference in spintronics. The combination NiO (AF) and Fe_3O_4 (FM) represents an interesting model system, as oxidic interfaces promise higher structural and magnetic quality than metallic ones. In our studies we addressed the magnetic coupling of ultrathin NiO overlayers on Fe_3O_4 single crystal surfaces by means of soft x-ray photoemission microscopy. By exploiting circular (XMCD) and linear (XMLD) magnetodichroic contrast mechanisms, we can address the magnetic microstructure of the ferrimagnet and the antiferromagnet separately (Fig. 2). From a comparison of the domain structures and a detailed analysis of the angular dependence of the XMLD contrast we can deduce the details of the coupling at the interface.

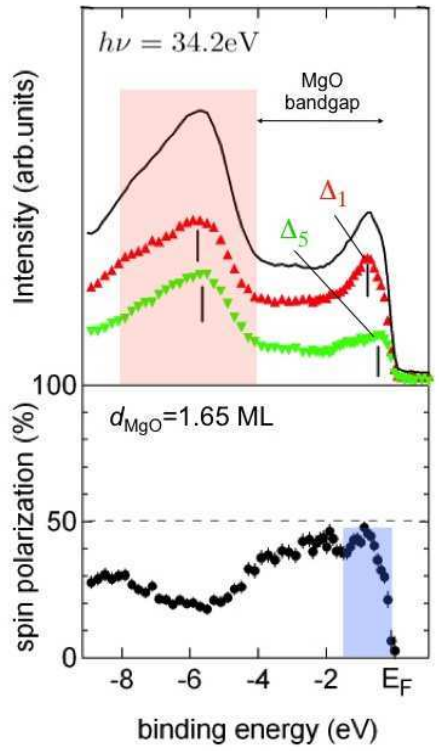

Figure 1. Spin-resolved photoemission spectra of a 1.65 monolayer (ML) MgO-films on Fe(001) at 34.2 eV photon energy. The spin-up (red) and spin-down (green) spectra can be interpreted in terms of the Fe bulk band structure. The broad feature below -4 eV binding energy results from MgO. The spin polarization (bottom) of ~50% close to the Fermi level corresponds to that of clean Fe(001) at the same experimental parameters.

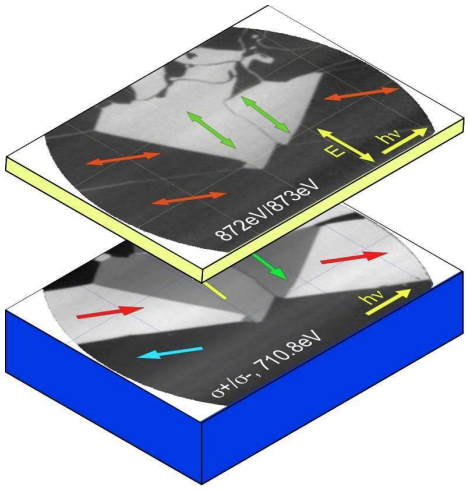

Figure 2. Element-selective magnetic domain imaging in the $NiO/Fe_3O_4(011)$ system exploiting XMCD at the Fe L_3 and XMLD at the Ni L_2 edges. The magnetic domain structure in the ferrimagnet (FM) Fe_3O_4 (bottom) is characterized by four magnetization axes (arrows). In the NiO film the micromagnetic structure is replicated, but exhibits only two different contrast levels, corresponding to two different spin quantization axes in the antiferromagnet (AF). This corresponds to a collinear coupling of FM and AF.

The ideal (011)-surface of NiO is spin-compensated, *i.e.* there is no net magnetic moment in this lattice plane. According to the theoretical considerations of Koon [5], this situation should lead to a 90° (spin-flop) coupling between AF and FM For the (011)-oriented interface, we find clear evidence for a spin-flip coupling, which may be mediated through the superexchange interaction across the interface. In addition, we observe a proximity effect on the NiO-side of the interface, leading to a sizable ferromagnetic response and XMCD signal of the interfacial NiO layer [6].

A similar behavior, *i.e.* spin-flip coupling is found for the (111) axis. The (001) orientation, which in the ideal case is also spin-compensated behaves differently and exhibits the expected spin-flop coupling. The difference of the interfacial coupling between the various crystalline orientations can be understood on the basis of the bonding mechanisms at the specific interface. Further analysis reveals that also magnetoelastic interactions have to be taken into account.

IV. Time-resolved studies of magnetization dynamics

Understanding the microscopic mechanisms and limits of fast magnetic switching processes is of high fundamental as well as of vital technological importance. This task asks for a real-space mapping of transient magnetization structures with high lateral and time resolution. Stroboscopic soft x-ray PEEM (XPEEM) studies exploiting the intrinsic picosecond time structure of the syn- chrotron light are ideally suited for this purpose by [7, 8]. In our pump-probe approach we excite the magnetic system with synchronized magnetic field pulses via a coplanar waveguide and probe the magnetodynamics via the transient state imaged by selected synchrotron light pulses. The time resolution obtained ranged between 10 and 70 ps, depending on the operational mode of the storage ring.

In our studies on small Permalloy and Co platelets we observe a variety of microscopic processes, which affect the reversal modes, for example, incoherent and coherent rotation events (Fig. 3). Domain magnetizations which are oriented perpendicular to the magnetic field pulse undergo a coherent rotation. Incoherent magnetization rotation occurs, if the driving pulse field opposes the sample or domain magnetization direction. These transient states are characterized by a strip-like domain pattern, which forms in selected domains along the rising edge of the pulse (region I in Fig. 3). Such a structure is associated with sizable magnetic stray fields, proving the importance of the magnetization torque in these fast processes. On the pulse plateau, the transient structure stabilizes and the system assumes a new dynamic equilibrium (region II). This has a peculiar consequence at the falling edge of the pulse. The reduction of the magnetic field is acting on the system like a magnetic field in the opposite direction. This leads to a formation of the strip-like domains also in other domains (region III). The domain walls, which have been created in this process, are rather stable causing the transient state to

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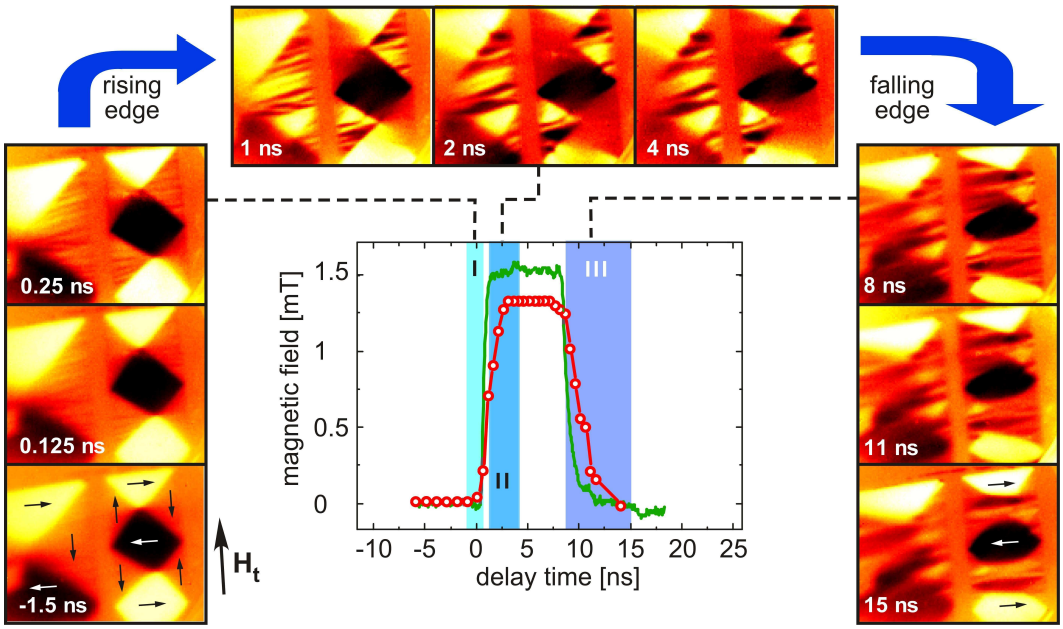

Figure 3. Time-resolved photoemission microscopy from rectangular Permalloy microstructures. The ground state (-1.5 ns) corresponds to a simple Landau flux closure pattern (magnetization directions marked by arrows). The images correspond to the transient domain configuration obtained from XMCD contrast along the field pulse (center) at different delay times (in ns).

relax only slowly (on the time scale of 20-30 ns) back into the ground state.

In addition to domain wall motion and rotation events, we also find collective excitations of the magnetization. These precessional modes have frequencies in the GHz regime and are determined by the shape of the platelets and the domain configurations [9]. By exciting the system close to the mode resonance, we can even generate quasistatic modifications of the magnetic domain structure.

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