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Layer-selective studies of an anti-ferromagnetically coupled multilayer by resonant magnetic reflectivity in the extreme ultraviolet range

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ABSTRACT

A multilayer comprising a 5 nm $Ni_{80}Fe_{20}$ and a 10 nm $Co_{40}Fe_{60}$ layer separated by a 0.6 nm Cr layer was investigated by resonant magnetic reflectivity measurements of horizontally polarized light in the extreme ultraviolet spectral range (EUV). By exploiting the transversal magneto-optical Kerr effect (T-MOKE) at the *M* absorption edges of iron, cobalt and nickel (54 eV, 60 eV and 67 eV) a magnetic contrast as large as 30% can be obtained near a Brewster angle of about 45°. Energy dependent scans of the magnetic asymmetry as well as magneto-optical hysteresis loops were recorded to study the magneto-optical response and to determine whether the switching behavior of individual layers in the strongly anti-ferromagnetically coupled multilayer system can be probed.

1. Introduction

Exploiting the magneto-optical Kerr effect (MOKE) in a reflectivity experiment is a well-established technique for investigations of static and dynamic processes in magnetism [1]. At wavelengths above 250 nm, however, the effect is weak in most materials – less than a millirad of Kerr rotation upon a full magnetization reversal. Furthermore, the wavelengths employed in conventional MOKE experiments are large compared to the resolution required to image cutting-edge magnetic structures on the nanometer scale [2].

In the last decades these shortcomings have been overcome by performing magnetic investigations in the soft X-ray region. However, this increases the system complexity, since large synchrotron radiation facilities are needed for this purpose. By exploiting X-ray resonant magnetic scattering and X-ray magnetic dichroism at the *L* edges of transition metals at photon energies above 500 eV, not only a superior magneto-dichroic contrast of up to several tens of percent and a lateral resolution down to a few nanometers can be attained, but also element-selectivity can be gained by means of resonant excitations [3–5]. An entire suite of X-ray magneto-optical phenomena allows for magnetic investigations of individual constituents of heterogeneous ferromagnetic systems on a nanometer and on a femtosecond scale – the latter of which requires suitable light sources such as free electron lasers [6] or appropriate techniques such as femto-slicing [7].

In the last years several approaches to explore resonant magnetic reflectivity and magnetic dichroism in the extreme ultraviolet range (EUV) for magnetic contrast generation by addressing the *M* edges of transition metals have proven to be equally successful, attaining a magnetic contrast of up to 100% at photon energies around 50 eV [8–12]. Because the majority of synchrotron beamlines at third generation storage rings are optimized for photon energies in the soft X-ray region, investigating magnetic properties in the EUV region has not been in the focus of the magnetism community. However, recent developments justify a closer look into EUV magneto-optics, as laser-based light sources are able to produce photons with energies of up to 100 eV with moderate effort and a reasonable flux density. Advancements in laser amplifier technology have brought about reliable table-top light sources, which provide coherent and ultrashort EUV pulses by means of higher harmonic generation (HHG). They may serve as compact tools for element-selective investigations of magnetic properties on the femtosecond and nanometer scale in a laboratory environment [13–17].

Since only little attention has been paid to the EUV region, it is the purpose of this work to explore its potential as a magnetic contrast mechanism by tuning the photon energy to the *M* absorption edges of Fe, Co and Ni in a transversal MOKE reflectivity experiment that focuses on layer-selective investigations of an anti-ferromagnetically coupled multilayer.

2. Sample

The sample consisted of a magnetic bilayer structure and was prepared by thermal evaporation at a base pressure of 5×10^{-11} mbar [18]. In a first step a substrate system for the magnetic multilayer was manufactured comprising a 150 nm thick Ag(0 0 1) buffer layer [19], which was grown on an iron precovered

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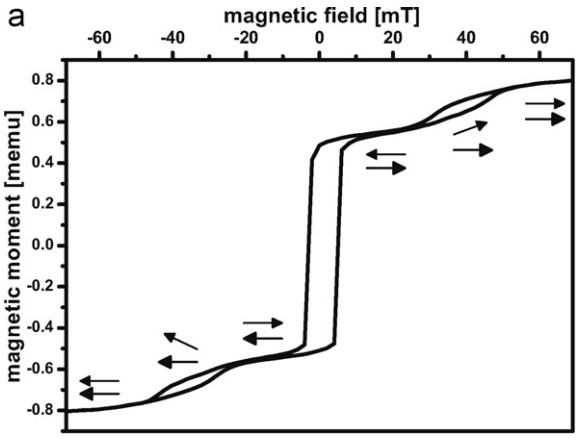

Fig. 1a. Hysteresis loop of the $Ni_{80}Fe_{20}$/Cr/$Co_{40}Fe_{60}$ multilayer measured with a SQUID at room temperature.

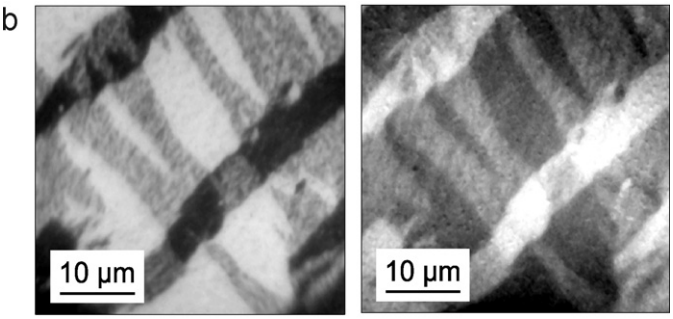

Fig. 1b. PEEM images of the top $Ni_{80}Fe_{20}$ (left) and the bottom $Co_{40}Fe_{60}$ (right) layer taken in remanence at the L_2 edge of Ni (854 eV) and Co (780 eV). The grey scale in both images represents the magnetic contrast in the plane of the sample.

GaAs(0 0 1) wafer at a temperature of 380 K. After postannealing at a temperature of 570 K, a 10 nm $Co_{40}Fe_{60}$ layer followed by a 0.6 nm Cr interlayer were deposited onto the buffer at room temperature. A 5 nm $Ni_{80}Fe_{20}$ layer was deposited on top of that and finally this multilayer was capped by 3 nm Al to prevent oxidation. For reference purposes single $Co_{40}Fe_{60}$ as well as $Ni_{80}Fe_{20}$ layers of 5 nm thickness were manufactured on the same buffer system.

The magnetic switching behavior in the plane of the multilayer system was first characterized by MOKE measurements in the visible range [20]. Recording hysteresis loops in a longitudinal MOKE (L-MOKE) setup for various angles of all three samples with respect to the external magnetic field revealed a fourfold magneto-crystalline anisotropy in the $Co_{40}Fe_{60}$ layer exhibiting an easy axis along the ⟨1 0 0⟩ direction and a hard axis along the ⟨1 1 0⟩ direction. Only a negligible magneto-crystalline anisotropy could be found in the presumably polycrystalline $Ni_{80}Fe_{20}$ layer. The anisotropy of both single layers was measured to be translated into the multilayer system.

In the following, we investigated the hysteretic behavior of all samples by applying a magnetic field only along their easy axes for the sake of simplicity. We employed a SQUID magnetometer in order to account for magneto-optical effects by referring to the absolute magnetic moment. Both single layers showed a rectangular hysteresis loop with a coercivity of less than 10 mT. The multilayer, on the other hand, produced a hysteresis loop which could be attributed to the anti-ferromagnetic coupling of the bottom $Co_{40}Fe_{60}$ layer and the top $Ni_{80}Fe_{20}$ layer, as can be clearly seen in Fig. 1a.

By taking into account the thicknesses of the top and bottom layer as well as the saturation magnetization derived from SQUID measurements of the individual layers, we can understand the switching behavior of the multilayer in detail. Above 50 mT the multilayer is saturated and both layers point into the same direction. As we decrease the magnetic field the top layer starts to reverse its magnetization until an anti-parallel alignment is reached around 10 mT. Once the magnetic field exceeds the coercive field of the bottom layer around −10 mT, its magnetization flips into the field direction followed by an immediate reversal of the top layer to maintain the preferred anti-parallel configuration. When the magnetic field is increased further, the top layer starts to reverse again until the multilayer saturates in a parallel state below −50 mT. We confirmed the anti-ferromagnetic configuration in remanence by XMCD images taken with a photoemission electron microscope (PEEM) tuned to the L_2 absorption edges of Ni and Co [21], which are displayed in Fig. 1b.

The complex domain structure indicates that the magnetization reversal proceeds mainly via domain wall nucleation and motion rather than magnetization rotation.

3. Experimental setup

We performed resonant magnetic reflectivity measurements in a T-MOKE geometry at the undulator beamline UE56/1-SGM of the synchrotron radiation facility BESSY II. The reflectivity of linearly *p*-polarized EUV light was measured across the *M* absorption edges of Fe, Co and Ni from 52 eV to 72 eV with an energy resolution of 0.1 eV and a degree of linear polarization exceeding 99%. Focusing mirrors enabled the synchrotron beam to be concentrated into a spot size of approximately $100 \times 100\,\mu m^2$. The multilayer stack was placed into a dedicated UHV reflectometer allowing for $\theta - 2\theta$ scans in a horizontal plane with the angle of incidence θ ranging from 0° to 90°. The intensity of the EUV light reflected off the sample was detected by a Schottky-type GaAsP photodiode (Hamamatsu G1127) directly connected to a sensitive amperemeter (Keithley 6517A). A set of coils was used to generate a static magnetic field of up to ±140 mT along the vertical axis of the chamber.

4. Theoretical considerations

In contrast to longitudinal or polar Kerr effects, where usually the change of polarization is analyzed to obtain information about the magnetic state of the sample, it is sufficient as well as convenient to record the change of reflectivity in a T-MOKE geometry. This is particularly true in the EUV regime due to the magnitude of the magneto-dichroic signal. Its strength originates from a large resonant enhancement of the reflected light if the energy of the incidence beam is tuned to the absorption edge of the material under investigation [22]. This strongly resonant behavior involves low order electric multipole transitions between core levels and unoccupied states of the valence band which results in both element selectivity and magnetic sensitivity in the presence of spin-orbit coupling and exchange splitting. For 3d transition metals, enhanced magnetic resonances occur at the $M_{2,3}$ absorption edges in the range of 50–75 eV by involving mainly $3p \rightarrow 3d$ transitions.

The strength of the T-MOKE signal is commonly denoted as the normalized difference of the reflected intensity *I* for two inverted directions of the sample magnetization, here referred to as ↑ and ↓. The latter can be achieved by an external magnetic field applied perpendicular to the scattering plane. This so-called magnetic asymmetry *A* is introduced to separate the non-magnetic from the magnetic contribution in the magneto-optical response of the sample. It is related to the Fresnel reflection coefficients r_{pp}, which describes the influence of a material on p-polarized light within the classical magneto-optical formalism [23]. If this mate-