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Time-resolved measurements of $Ni_{80}Fe_{20}$/MgO/Co trilayers in the extreme ultraviolet range

R. Adam*, P. Grychtol, S. Cramm, C.M. Schneider

Institute of Solid State Research IFF-9 & JARA-FIT, Research Center Jülich, D-52425 Jülich, Germany

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ABSTRACT

We performed an element-selective magneto-optic characterization of $Ni_{80}Fe_{20}$/MgO/Co magnetic trilayers employing the resonant magnetic reflectivity of extreme ultraviolet (XUV) radiation tuned to the *M* absorption edges of cobalt (60.2 eV) and nickel (67.5 eV). Static reflectivity shows a large magnetic contrast of up to 80% for the top Co and 20% for the buried $Ni_{80}Fe_{20}$ layers. The magneto-dynamic response of the trilayers to the ultrashort field pulse exhibits oscillations in a frequency range of up to 6.5 GHz associated exclusively with magnetization dynamics of the top Co layer. The presented results demonstrate the feasibility of element-specific magneto-dynamic studies of magnetic multilayers employing resonant XUV reflectivity at the *M* absorption edges.

1. Introduction

During the past decade, magnetization dynamics in magnetic systems has been studied extensively because of its high relevance for both fundamental research and technology [1]. Various magneto-dynamic processes, including domain wall propagation [2], precessional switching [3], vortex core dynamics [4], or ultrafast demagnetization [5,6] have been actively examined for their potential in magnetic recording. To study ultrafast processes in ferromagnetic materials, a pump-probe experimental technique based on femtosecond pulsed lasers in combination with the magneto-optic Kerr effect (MOKE) has been the technique of choice due to its unmatched temporal resolution. At the same time, the properties of ferromagnetic thin films have been successfully studied by a variety of techniques at higher photon energies using synchrotron radiation, taking advantage of element selectivity, strong magnetic dichroism and nanometer (<20 nm) lateral resolution [8,9]. Element selectivity originates from the characteristic core-level to valence-band transitions (2p → 3d and 3d → 4f) excited by soft X-rays. These transitions are also responsible for a strong dichroic signal, exploiting a large spin-orbit splitting in the core states as well as a large exchange interaction of the valence bands. The most prominent magneto-optic effects at high photon energies are the X-ray magnetic circular and linear dichroism (XMCD, XMLD) [10,11].

While the dichroic contrast has been routinely employed for element-selective magnetic measurements in the soft X-ray range (∼250 eV to few keV) [12], the neighboring spectral region of the extreme ultraviolet (XUV, ∼30–250 eV) has received only little attention. However, quite recently synchrotron-based experiments revealed an impressively strong magnetic signal of up to 94% relative reflectivity change in XUV resonant reflectivity experiments at the *M* edges of Fe, Co and Ni [13–15]. This huge magnetic contrast at the *M* edges makes studies in XUV energy range extremely attractive for measurements of small-angle magnetization dynamics which yields only weak modulation of the dichroic signal. Furthermore, resonant reflectivity in the XUV range exhibits a number of very attractive features including the compatibility with external magnetic fields, the deep (>20 nm) sub-surface probing depth and the ability to test 'as-fabricated' magnetic films, i.e., there is no need for ultrathin membrane substrates which are necessary for transmission experiments. As an added advantage, the XUV reflectivity signal is much less sensitive to interferences and surface roughness which often aggravate the data analysis in the soft X-ray regime, since structural interferences can often be superimposed on the magnetic signal.

A strong appeal of element-selective measurements in the XUV range is even more enhanced by the fact that element selectivity can be translated into a layer selectivity in multilayer stacks [16]. This provides an entirely new way of extracting detailed information about magnetization dynamics in spatially separated but magnetically coupled layers with a varying degree of coupling. This issue is of utmost importance for the understanding of magnetization dynamics and switching in complex multilayer magnetic devices. Furthermore, the significance of the XUV regime has increased dra-

* Corresponding author. Tel.: +49 2461 61 6670.
E-mail address: r.adam@fz-juelich.de (R. Adam).

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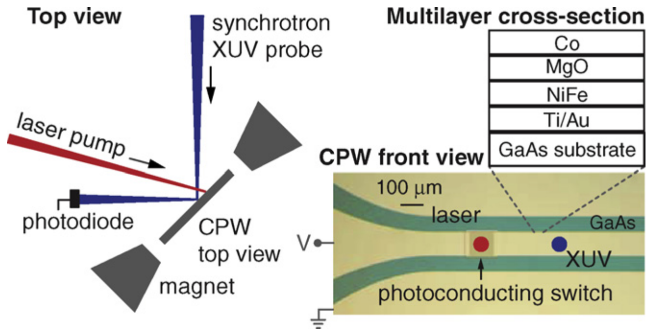

Fig. 1. Schematics of the experimental setup and the sample layout. The vertical coils and the vacuum chamber have been omitted for clarity.

matically since the table-top XUV sources became available [17], offering a convenient laboratory tool for element-selective investigations of magnetic properties on nanometer and femtosecond scales.

In this paper we address magneto-static and dynamic properties of magnetic trilayers by employing resonant XUV reflectivity at the *M* absorption edges using synchrotron radiation.

2. Experimental details

The schematics of the experiment and the sample layout are shown in Fig. 1. We have chosen $Ni_{80}Fe_{20}$ (50)/MgO(3)/Co(*h*) trilayers (with Co top layer) as a model system for magnetic tunnel junctions. The numbers in brackets indicate the film thickness in nanometers and h = 5 nm, 10 nm, and 20 nm for three separate samples (termed as PMC5, PMC10 and PMC20, hereafter). Samples were deposited on top of a GaAs/Ti(5)/Au(150) substrates using ion sputtering technique. A reference $Ni_{80}Fe_{20}$ (50) film (Py50, hereafter) with a 2-nm Au capping layer has been fabricated as well to compare its response with the buried $Ni_{80}Fe_{20}$ layers. After the film deposition, each sample was patterned to form a 4 mm long coplanar waveguide (CPW) comprising a 150 µm wide central line and extended ground planes to allow high-frequency measurements. An integrated photoconductive switch, patterned near the end of the central line, served as a picosecond pulse generator.

The samples were placed in a dedicated high-vacuum reflectometry chamber allowing θ–2θ scans, with the scattering angle θ ranging from 0° (grazing) to 85° (near normal incidence). Two sets of coils generated static magnetic fields of up to 80 mT and 50 mT in the vertical and the horizontal configurations, respectively.

The reflectometry chamber was connected to the BESSY synchrotron UE56/1-SGM beamline producing polarized light from 57 eV up to 1.5 keV. During the experiment a *p*-polarized beam was used and the photon energy was varied from 57 eV to 72 eV with a resolution better than 0.1 eV. Adaptive focusing mirrors enabled the XUV beam to be focused to approximately 100 µm in both vertical and horizontal directions. The synchrotron was operating in the single-bunch mode generating ~50-ps pulses at a repetition rate of 1.25 MHz. The XUV pulses were aimed at the surface of the CPW center line and the intensity of the reflected light was detected by an avalanche photodiode (APD) featuring a 10 ns response time. The electrical signal from the APD was then recorded using a 2-MHz digital lock-in amplifier locked to the 1.25 MHz reference signal derived from the synchrotron bunch clock.

The experiment was arranged in a transversal MOKE geometry in which only the magnetic components perpendicular to the scattering plane contribute to the measured signal and changes of the sample magnetization translate directly to an intensity modulation of the reflected light.

3. Results on magnetostatics

As indicated by earlier static experiments, see, e.g. [15], the intensity of the XUV light (R) measured in reflectivity experiments varies strongly, depending on the sample magnetization ($\vec{\boldsymbol{M}}$), the photon energy (E) and the scattering angle (θ).

The magneto-dichroic signal is often defined in terms of a normalized asymmetry ratio $A = (R_+ - R_-)/(R_+ + R_-)$ representing the normalized intensity of the reflected XUV light. Here, R_+ and R_- refer to the intensities of the reflected light for two opposite orientations of the external magnetic field $\vec{H}_+$ and $\vec{H}_-$ applied along the sample surface and perpendicular to the plane of incidence.

The lower and the upper limits of the energy scans in our measurement were determined by the minimum undulator gap (yielding 56 eV) and the absorption edge of the Al filter (72.5 eV) placed in front of the photodiode to block the intense 1.55 eV light of the femtosecond laser applied to trigger the photoconductive switch.

Fig. 2(a)–(c) show the color maps of the measured $E-\theta$ scans of magnetic asymmetry A for the PMC trilayer stacks with a Co thickness of 20 nm, 10 nm and 5 nm. The scans display pronounced maxima reaching up to 80% at the scattering angle of ~42° at the energy near the *M* absorption edge of cobalt. Horizontal dashed lines indicate the energy scans of A at $\theta = 42°$. Fig. 2(d)–(f) display the evolution of magnetic asymmetry and sample reflectivity along the dashed lines. We note that we detected no static magneto-dichroic signal in absence of magnetic field ($\vec{H} = 0$) or when the external field has been applied parallel to the plane of incidence.

Fig. 3(a) and (b) show the $E-\theta$ color map of A and a single energy-scan at 42° for the Py(50) sample displaying a resonance peak near the *M* edge of Ni (67.5 eV). A comparison of the peak intensities at 67.5 eV for all trilayers allows a simple analysis of the depth sensitivity. While the magnetic asymmetry reaches up to 20% for Py(50) and for PMC5 samples, the signal drops to about 25% of the Py(50) level for PMC10 and the signal decreases further to approximately 1.5% for PMC20, pointing to a strong signal attenuation in the top Co layer. We note that although the photon-in/photon-out XUV magnetooptics is expected to yield larger probing depth compared to the surface sensitive photoemission techniques, the intensity of the reflected light can be substantially affected by a strong absorption in the top layer, especially at XUV energies near or above the absorption edge of the top layer.

4. Results on magnetodynamics

To obtain information about magnetization dynamics we have first set the incidence angle and the probe beam energy to the maximum of the magnetic contrast near the absorption edge of a targeted element. We then aimed 20 fs laser pulses (1.55 eV) at the photoconducting switch to trigger a train of current pulses. A characterization of the switch by photoconductive sampling [18] revealed that a 20 fs laser pulse generates a photocurrent with a pulse length of about 10 ps (FWHM). This current pulse, which is accompanied by a magnetic field of the same temporal structure, propagates with a group velocity of 105 µm/ps and a damping of 1.2 dB/mm along the CPW, perturbing the magnetization of the films deposited on top of the CPW. To probe the system response, we reflected synchronized XUV pulses (60.2 eV or 67.5 eV) from the central line of the CPW and recorded the XUV intensity as a function of the optical delay time. A precise synchronization of the laser pump and the synchrotron probe pulse trains was achieved by setting the repetition rate of the laser to 100 MHz – an integer multiple of the synchrotron pulse sequence frequency – and by employing dedicated electronics [19] for the synchronization of the laser cavity.