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Photoemission microscopy study of picosecond magnetodynamics in spin-valve-type thin film elements

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ABSTRACT

Exploring ultimate time scales of magnetic switching processes is an important issue in spin electronics. In spin valves or magnetic tunnelling junctions magnetic anisotropies and coupling phenomena alter the magnetodynamic response of the entire system. Understanding the role of these interactions is a key to the design of optimized devices. We have employed time-resolved X-ray photoemission microscopy to address the magnetodynamics in spin-valve-type model systems in the ns- and ps-regime. In Co/Cr/Fe(0 0 1) single crystal elements we find a strong influence of the magnetocrystalline anisotropy, which tends to suppress rotation processes. In addition, we observe a dynamic "decoupling" of the layers. In low-anisotropy FeNi/Cr/FeCo trilayers, the interlayer coupling character determines the dynamic response. Particularly, rotational processes in the FeNi and FeCo layers are temporarily shifted to each other, which can be related to different coercivities of the individual layers. By contrast, the domain wall motion in both layers closely agrees, caused by an enhanced coupling due to the domain wall stray fields. Our examples demonstrate that the detailed magnetodynamics in coupled magnetic layers is quite complex and depends strongly on the timescale under consideration.

1. Introduction

Exploring the ultimate time scales governing magnetic switching processes is currently a hot topic in nanomagnetism and spin electronics. The continuous progress in high density magnetic storage leads to smaller and smaller bit sizes [1]. To this end also the size of the read head has to shrink and the read/write times have to be reduced to allow for higher data transfer rates. In spin electronics, magnetic tunnelling junctions (MTJ) become very important for applications, in particular, in connection with high-density magnetic random access memory. A very elegant way to switch MTJs in such structures is provided by passing a high-density spin-polarized current through the element—a process which works the better the smaller the MTJ. Understanding the dynamics of the magnetization reversal processes in such elements on the nanosecond and picosecond timescales is very important for future optimization of the reversal mechanism and the materials. Moreover, the dynamic behavior of the magnetization on such short timescales still raises considerable fundamental questions, particularly if we consider complex coupled magnetic structures.

After the discovery of X-ray magnetic dichroism [2,3], polarized soft X-rays have found increasing use in the characterization of magnetic materials and systems. The first imaging experiments on static magnetic structures have been performed in 1993 using photoemission microscopes with circularly polarized synchrotron radiation [4,5]. The soft X-ray photoemission electron microscopy (XPEEM) combines high lateral resolution and element selectivity with a high magnetic sensitivity and became quickly a method of choice for the study of magnetism at surfaces and in thin film systems. It is also one of the few techniques which provides access to both ferro- and antiferromagnets [6]. Time-resolved XPEEM experiments on magnetization dynamics became available in 2003 [7–9] using the very regular time-structure of the synchrotron radiation for pump-probe approaches.

So far, most of the imaging studies of magnetodynamics have concentrated on permalloy ($Ni_{80}Fe_{20}$) as a material with very low magnetic anisotropy. In many of the structures of interest in spintronics, however, we encounter layer stacks composed of different magnetic and nonmagnetic materials. Moreover, these layers are usually magnetically not independent, but tied to each other by magnetic coupling effects (interlayer coupling, edge coupling, etc.) [10,11]. Studying the magnetization dynamics in such systems represents therefore a considerable challenge. Thus, only few investigations have been carried out so far concentrating on the dynamics of the top layer in spin-valve devices [12,13]. However, the tunability of the photon energy allows us to study the dynamics of individual layers independently. In the following, we will describe and discuss first results which we have

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obtained on magnetic trilayer systems with controlled interlayer coupling.

2. Experimental details

The studies were carried out at the beamlines UE56/1-SGM (BESSY-II, Berlin) and ID08 (ESRF, Grenoble) providing elliptically polarized soft X-rays using a photoemission microscope based on the electrostatic FOCUS IS-PEEM design [14]. The electron-optical system has been modified to allow for a gating of the electron beam in the microscope in order to select only electrons excited by specific light pulses coming from the synchrotron [15]. In this way, we can exploit the hybrid-bunch mode at BESSY-II, which allows us to probe the system with 50 ps X-ray pulses at a repetition rate of 1.25 MHz. The samples comprise lithographically defined elements on top of 25 μm coplanar waveguides. The magnetic excitation is achieved by passing short current pulses (FWHM 300 ps to 1 ns) down the coplanar waveguides, thereby creating an Oersted field acting on the magnetic elements. The current pulses are synchronized to the X-ray pulses via an electronic delay generator allowing for an adjustable delay between pump (current) and probe (X-ray) pulses.

The magnetic elements were grown on the Ag/GaAs(0 0 1) waveguide structures by means of molecular beam epitaxy and comprised two trilayer structures: (i) Co/Cr(0 0 1)/Fe(0 0 1) and (ii) NiFe/Cr(0 0 1)/CoFe(0 0 1). In both layer types epitaxial growth was achieved up to the upper Cr/ferromagnet interface. The Cr interlayer was grown with a thickness gradient across the sample surface, resulting in a Cr-thickness wedge. In this way, different magnitudes and orientations of the interlayer exchange coupling could be conveniently investigated on the same sample. A 2 nm Au cap layer served as oxidation protection. Before insertion into the microscope, the samples were demagnetized in an oscillating magnetic field in order to obtain the ground state domain structure.

3. Co/Cr/Fe(0 0 1)

3.1. Static domain structures

One of the open questions in magnetodynamics concerns the influence of the magnetocrystalline anisotropy on the dynamic behavior. This can be studied best in single-crystal structures. The Ag(0 0 1) coplanar waveguide provides an ideal template for the epitaxial growth of the Fe/Cr/Co trilayers. We should note, however, that cobalt does not grow epitaxially on Cr and the top layer is very likely polycrystalline with some texture. By varying the Cr interlayer thickness, the role of the magnetic anisotropy and the interlayer coupling can be investigated simultaneously. This is demonstrated in the static XPEEM images displayed in Fig. 1. The images have been acquired by means of X-ray magnetic circular dichroism (XMCD) at the Fe and Co absorption edges and show the elementally resolved magnetic domain structure in the bottom Fe layer (acquired at the Fe L_3 absorption edge) and the top Co layer (acquired at the Co L_3 absorption edge), respectively. The measurements on both layers have been carried out on the same trilayer structures on one rectangular and two quadratic elements comprising different interlayer thickness values.

The XMCD images in the bottom row show the magnetic domain structure in the bottom Fe layer. The magnetization direction in each domain has been determined from the XMCD contrast level and is indicated by the arrows. The domain structures in the rectangle (*E*1) and left-hand square (*E*2) are quite unusual, because they do not follow a simple flux closure scheme, which requires the magnetization to be aligned with the boundary of the element [16]. In this case the domain walls are expected to run almost parallel to

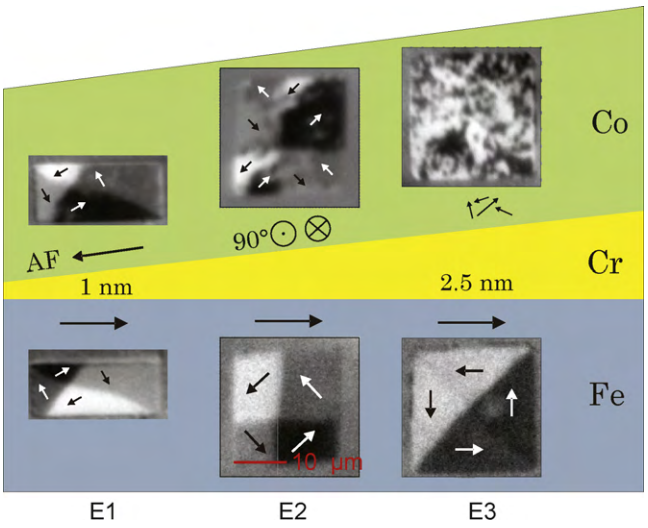

Fig. 1. Static domain patterns in the epitaxial Fe/Cr/Co elements for the bottom Fe layer and the top Co layer. Arrows indicate the local direction of magnetization. Magnetic coupling character can be directly deduced by comparing the contrast distribution at the Fe and Co absorption edges for the same element. Elements are numbered from left to right as *E*1 to *E*3.

the edges of the element. Only the right-hand square element (*E*3) fulfills this flux closure requirement and consequently exhibits a different magnetization pattern in agreement with earlier observations on permalloy or cobalt films [17].

The reason for the particular domain structure in the elements *E*1 and *E*2 is the magnetocrystalline anisotropy of the Fe layer. In single-crystalline iron the magnetization is known to point preferably along the $\langle 1\,0\,0 \rangle$ directions in the absence of an external field. In our samples these so-called easy axes are oriented under different angles to the boundaries of the elements ($E1 \equiv [30^\circ; 60^\circ]$, $E2 \equiv [45^\circ]$, $E3 \equiv [0^\circ]$). The local magnetization direction is therefore determined by a competition of two interactions: the magnetocrystalline anisotropy preferring an alignment along the easy axes and the dipolar anisotropy trying to minimize the magnetic stray field energy. At all three sample positions the domain structure is dominated by the alignment along the easy axes. The dipolar anisotropy, however, leads to the development of four domains minimizing the stray field of the structure. Only in image *E*3 the magnetocrystalline easy axes and the preferred alignment axes parallel to the structure edges coincide and the energetically most preferable Landau state consisting of four triangular domains is created [16].

The domain patterns obtained for the Co top layer (top row) by means of Co L_3-XMCD exhibit the same structure, but a contrast inversion for element *E*1, i.e. the local magnetization direction is reversed with respect to the bottom layer. This indicates the presence of a strong antiferromagnetic interlayer exchange coupling mediated by the Cr spacer [18]. Note that also the top layer is subject to the dipolar anisotropy and – being polycrystalline—has only a random magnetocrystalline anisotropy. We must therefore conclude that the interlayer coupling which can also be considered as an effective anisotropy is stronger than the dipolar anisotropy in the top cobalt layer in element *E*1. The magnetic configuration changes, when we go to element *E*2 where the coupling has a biquadratic or 90° character, i.e. the local magnetization vectors in the top and bottom layer enclose an angle of 90° [19]. It is important to note that this coupling creates two energetically equivalent configurations. This is likely the reason why each square domain breaks up into two domains with antiparallel magnetization orientation. In addition, this configuration also reduces the dipolar energy of the entire structure. This is an interesting feature, because the magnitude of the biquadratic coupling is usually small, which reflects