Investigating magnetization dynamics in permalloy microstructures using time-resolved x-ray photoemission electron microscope

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We present results of a direct imaging approach to visualize the dynamics of magnetic domains on the nanosecond scale. The experiments are carried out by means of an x-ray photoemission electron microscope (X-PEEM) in a stroboscopic mode and exploit the intrinsic time structure of the synchrotron radiation delivered by the storage ring facility ESRF (Grenoble). In this way we combine the high lateral resolution of a PEEM with a subnanosecond time resolution. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1687531]

Controlling the dynamic behavior of the magnetization in the nanosecond and subnanosecond regime becomes a critical issue in magnetic data storage and spin-electronics applications. Imaging the magnetic domain structure and the magnetization reversal on this time scale with a high lateral resolution poses a considerable experimental challenge. Until recently, only time-resolved Kerr microscopy in scanning or direct imaging mode was available for this purpose.[1–4] These experiments were carried out with pulsed laser sources. The first experiments on magnetization dynamics exploiting the intrinsic time structure of synchrotron radiation probed the time dependence of the surface spin polarization[5] or the magnetic x-ray circular dichroism (MXCD) signal in spin valve structures.[6] The MXCD approach yields a unique combination of element selectivity, magnetic sensitivity, and time resolution. First time-resolved MXCD-based imaging experiments using an x-ray photoemission electron microscope (X-PEEM) were demonstrated by Krasyuk *et al.*[7] and Vogel *et al.*[8]

In this contribution, we report about stroboscopic pump-probe X-PEEM experiments addressing the magnetization dynamics in Permalloy microstructures. We obtained a subnanosecond time resolution and observed dynamic processes of the magnetization on different time scales.

The experiments have been performed at the elliptical undulator beamline ID-08 of the European Synchrotron Radiation Facility (ESRF) in Grenoble using a dedicated photoemission electron microscope based on the IS-PEEM design.[9] The instrument features a dual imaging detector system comprising a phosphor screen/CCD camera (CCD, charge-coupled device) combination and a two-dimensional delay line detector[10] for low photon flux applications. Both detectors are interchangeable *in situ*. The data discussed below were recorded with the CCD camera setup. During the experiments the ring was operated in the ‘‘16-bunch’’ mode, which produced light pulses of about $\Delta t = 105$ ps width (FWHM) at about $\Delta T = 176$ ns repetition time. A bunch marker generated from the rf accelerating the electrons in the ring was used to trigger the magnetic field pulse. The time delay between the bunch marker and the magnetic field pulse was controlled by a switchable cable delay.

The samples comprised a microstrip line geometry (Fig. 1). The microstrip lines ranged from 20 to 100 μm in width and were defined by optical lithography and subsequent wet chemical etching of a 200 nm thick Cu film on a SiO_x/Si substrate. On top of this microstrip line, a bilayer (30 nm NiFe, 2 nm Cu) was deposited by dc magnetron sputtering and microstructured by optical lithography and ion milling.

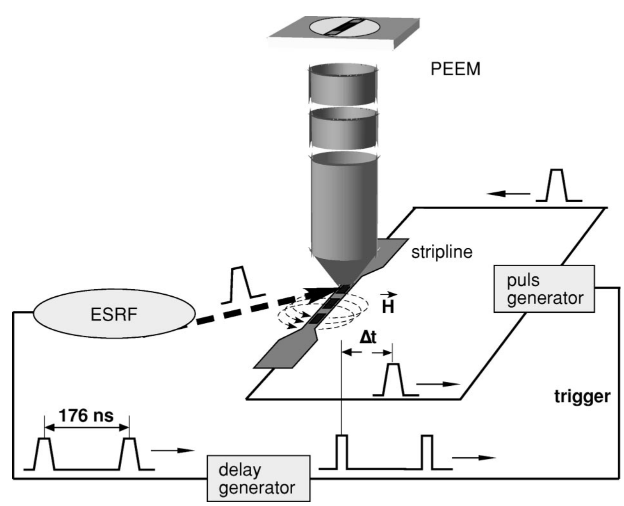

FIG. 1. Experimental setup of the time-resolved X-PEEM using the 16-bunch operational mode at the ESRF (photon pulse width $\Delta t = 105$ ps, pulse separation $\Delta T = 176$ ns).

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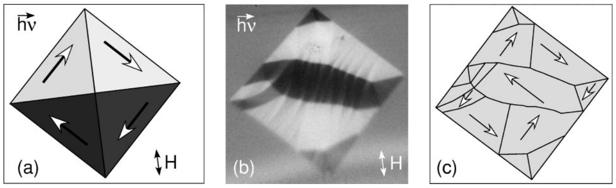

FIG. 2. Metastable static domain configuration of a 50-μm-sized diamond-shaped microstructure (b) after a sequence of field pulses in comparison to the corresponding Landau pattern (a). (c) Graphical reconstruction of the domain pattern.

The Cu protection layer was removed by mild ion bombardment after introducing the sample into the microscope. A fast pulse generator (KenTech) was used to feed a unipolar or bipolar current pulse into the microstrip line. Taking into account the jitter of the ESRF synchronization signal and of the pulse generator we estimate the total time resolution in these experiments to about 130 ps. The circularly polarized light impinged at an angle of 20° with respect to the surface plane along the stripline axis and was thus oriented perpendicularly to the magnetic pulse field. In the stroboscopic mode, each image represents an average over 10^9 pulses.

The first important finding of our experiments concerned the starting domain configuration in the pump-probe experiments. Prior to any magnetic field pulsing the Permalloy microstructures usually exhibited simple flux-closure governed Landau domain configurations indicating a fully relaxed state. This was verified in static X-PEEM domain imaging experiments. After a series of field pulses, however, the system remained in a more complicated metastable domain configuration, which eventually relaxed to the Landau structure on a time scale of minutes. One of these metastable configurations is shown in Fig. 2 for the example of a diamond-shaped Permalloy structure. The graphical reconstruction of the domain pattern after analysis of the gray-level distributions yields an ''S''-like domain configuration with edge domains. Clearly visible are the crosstie walls, which are well-known to occur in Permalloy films of this thickness.[11] Note that the magnetic pulse field axis is such that it includes an angle of 45° with the local magnetization direction $\vec{M}$ of every other pair of domains of the Landau pattern [Fig. 2(a)]. The direction of light incidence $\vec{q}$ was somewhat inclined with respect to the diamonds diagonal (3°–4°). As a consequence, the projection of the local magnetization vectors in the Landau pattern onto $\vec{q}$ results in four different contrast levels. These can be used to reconstruct the magnetization directions from a single image [Fig. 2(c)].

The starting situation in the stroboscopic imaging experiments again differs. Apparently, the time between the field pulses, $\Delta T = 176$ ns, is too short to allow the system to reach the metastable state shown in Fig. 2. In Fig. 3 we compile the data for an experiment in which the system was driven with a bipolar pulse. Analyzing the domain pattern right before the field pulse (time delay $\Delta t = 0$ ns), we note both similarities and distinct differences to Fig. 2. The domain structure in the left-hand corner is almost preserved, whereas the ''V''-shaped area in the bottom corner has grown. The major change occurs in the center of the diamond, which appears bright now. Obviously, the dark center domain in Fig. 2 has moved towards the top corner, thereby also changing the magnetization configuration in the top-hand and right-hand corners of the diamond.

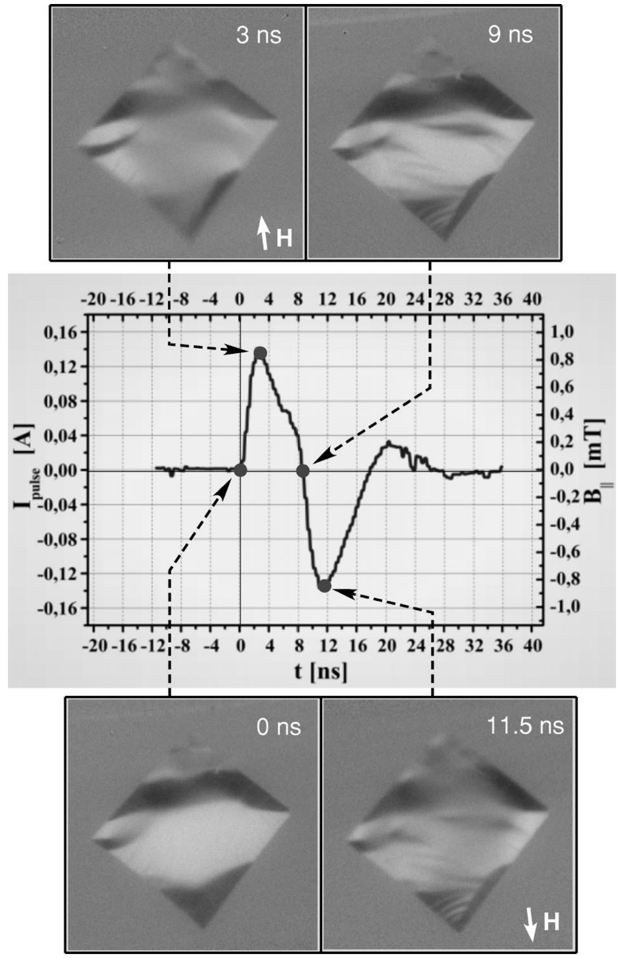

FIG. 3. Time-resolved response of the magnetization pattern during a bipolar magnetic field pulse. (center) Shape of the magnetic field pulse with representative domain patterns at delay times of $\Delta t = 0,3,9,11.5$ ns (top, bottom).

Inspecting the domain pattern at $\Delta t = 0$ ns in more detail reveals two other important findings. First, compared to the static images the domain boundaries appear slightly ''blurred.'' Second, within the experimental uncertainty it is more difficult to distinguish those domains where the projection of the local magnetization vector differs only by a small amount. We believe that both findings are caused by the same microscopic mechanism, namely, local irreproducibilities in the magnetization reversal process. As mentioned above, each of these images represents the average over about 10^9 field pulses or reversal events. Obtaining a sharp domain image under these circumstances requires the magnetic microstructure to relax into the same configuration *within the lateral resolution of the instrument* after each field pulse. If this is not the case, the measurement will average over different configurations, resulting in a blurring of the domain boundaries and a washing out of the distinct contrast levels. Because of this we cannot unambiguously assign local magnetization vectors to the center area of the diamond.

This blurring effect becomes much more pronounced when we move into the field pulse, for example, to the positive maximum ($\Delta t = 3$ns). The overall appearance of the domain pattern appears to be preserved, but we observe a distinct change of the magnetic contrast in the central and bottom area of the diamond. Two processes may lead to this contrast change: (i) a rotation of the local magnetization vector into the direction of the external field, and (ii) a nonreversible domain formation and domain wall motion under the influence of the field pulse. Following the temporal development of the domain pattern, however, there is a strong indication for the presence of the second mechanism. Comparing the image taken at the zero-point crossing of the bipolar pulse ($\Delta t = 9$ ns) with the reference image at $\Delta t = 0$ ns we note the appearance of fine stripe like magnetization structures mainly in the central part of the sample. In particular, the V-shaped area in the bottom corner of the diamond has partially converted into a block-domain pattern. This is one of the prominent regions, which showed a strong blurring at $\Delta t = 3$ ns. It is thus reasonable to assume that this blurring is related to the formation and motion of the blocklike domains, which occurs on a subnanosecond time scale. It is interesting to note that the image at $\Delta t = 9$ ns appears quite sharp again, which suggests a quite stable magnetization configuration.

Moving the time delay to the maximum of the opposite magnetic field at $\Delta t = 11.5$ ns, we again observe an increased blurring of the image. This time the blurring is most prominent in the upper part of the diamond. Nevertheless, many of the stripelike structures survive, in particular, the block-domain structure in the bottom corner. This is surprising as the peak values of the positive and negative magnetic field are almost the same ($\mu_0 H \approx 0.85$ mT). Apparently the negative field pulse is not strong enough to instantaneously remove this block pattern. After the negative maximum, the field pulse goes through a much smaller positive maximum and quickly drops to zero. On the other hand, the block-domain pattern and the other fine structure have certainly relaxed before the start of the next field pulse. We are therefore led to conclude that the relaxation takes place on a time scale longer than the pulse length. It is thus much slower than the processes during the formation of this pattern.

In summary, we performed time-resolved X-PEEM studies on Permalloy microstructures. We were able to follow the magnetization dynamics with a subnanosecond time resolution in a stroboscopic imaging mode. While the magnetic field acts on the magnetic microstructure the domain images exhibit a characteristic blurring which is partly attributed to an averaging over a large number of fast nonreproducible remagnetization processes.

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