Imaging nanoscale magnetic structures with polarized soft X-ray photons

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Abstract

Imaging nanoscale magnetic structures and their fast dynamics is scientifically interesting and technologically of highest relevance. The combination of circularly polarized soft X-ray photons which provide a strong X-ray magnetic circular dichroism effect at characteristic X-ray absorption edges, with a high resolution soft X-ray microscope utilizing Fresnel zone plate optics allows to study in a unique way the stochastical behavior in the magnetization reversal process of thin films and the ultrafast dynamics of magnetic vortices and domain walls in confined ferromagnetic structures. Future sources of fsec short and high intense soft X-ray photon pulses hold the promise of magnetic imaging down to fundamental magnetic length and time scales.

The magnetic properties of matter are one of the most vibrant research areas [1],[2], not only, because the phenomenon of magnetism itself is scientifically very attractive, it also has immense implications to modern magnetic storage and sensor device technologies. Nanomagnetism investigates magnetism approaching fundamental magnetic length scales which are given by material specific properties such as exchange lengths or anisotropy constants being in the few nm regime for common materials.

To minimize the competing magnetic interactions, e.g. exchange and anisotropy, in a ferromagnetic systems, the ground state is often not the single domain state, where all spins are aligned parallel, but breaks up into multiple magnetic domains [3]. The transition region between domains is referred to as domain wall (DW). In confined geometries, e.g. micron sized disk structures, the spin configuration forms a magnetic vortex (MV) [4],[5], with a singularity occurring at the center, the MV core, which overcomes shape anisotropy and points perpendicular to the disk plane. The sizes of domain walls and vortex cores are proportional to magnetic exchange lengths.

With a typical bit size of only a few tens of nm in high density magnetic storage media of 1Tb/in2 and the capability to artificially fabricate nanoscale magnetic structures either top-down or bottom-up, e.g. by state-of-the-art lithographical techniques [6], an abundance of analytical tools to characterize the magnetic behavior of these structures has been developed. Imaging methods are very attractive, since they give detailed and direct insight into the mechanisms involved.

There are several interaction mechanisms to control and manipulate the spin structure on a nanoscale. For example, reversal of the magnetic moments can be achieved by applying an external magnetic field pointing in opposite direction. Although discovered in the 1820's Oersted switching is still used in magnetic storage. In the realm of spintronics, where in addition to the charge also the electron spin is exploited, the torque created by a spin polarized current on the spins can be used to reverse the magnetization[7]-[9]. In the future the torque created by a photon onto the spins (opto-magnetics) is considered as the fastest way to switch the spins [10]-[11].

The functionality of a spin system is determined by its dynamic behavior and therefore the spin dynamics of nanoscale magnetic structures down to fundamental time scales, which are again determined by inherent magnetic interactions has received significant scientific interest recently [12]-[19].

Powerful imaging techniques have been developed utilizing various probes. To name but a few, there are optical Kerr microscopies, electron microscopies, e.g. SEMPA (SEM with polarization analysis) [20],[21], Lorentz TEM [22],[23], spin polarized LEEM [24],[25] or spin polarized STM [26],[27] as well as scanning probe microscopies, such as Magnetic Force microscopy (MFM) or Magnetic resonant force microscopy (MRFM) [28]-[30].

The counterpart to Kerr effect in the X-ray regime is X-ray magnetic circular dichroism (XMCD) [31], which describes the difference in X-ray absorption for circular polarized photons depending on the relative orientation between helicity and magnetization of the sample. XMCD serves as large and element specific magnetic contrast mechanism for several magnetic X-ray microscopies. Photoemission electron microscopy (X-PEEM) [32] detects the secondary electrons generated in the X-ray absorption process, while Fresnel zone plates [33] provide high spatial resolution optics for both scanning (STXM) [34]and full field transmission X-ray microscopy for magnetic imaging (MTXM) [35]. State-of-the-art zone plates have demonstrated a better than 12 nm spatial resolution [36]. While X-PEEM is surface sensitive, STXM and MTXM give access to the bulk and particularly to buried layers. External parameters such as magnetic fields or RF current pulses can be applied easily during the data acquisition process which enables studies of nucleation, swiching or DW motion upon spin injection [37].

Recently, MTXM has addressed the fundamental scientific question as to whether the magnetic behavior on the nanoscale exhibits a deterministic character in nanogranular thin magnetic films [38], DW depinning in nanowires [39] and in MV structures. A stochastic component has been identified in all those systems, which could be traced back to thermal fluctuations in the nanogranular system, geometrical and multiplicity effects for the DW depinning in the nanowires and a Dzyaloshinsky-Moriya coupling effect for the switching of magnetic vortex cores.

X-rays pulses from synchrotron sources have an inherent time structure with less than 100 ps length at typically MHz frequencies. This matches perfectly magnetization dynamics such as precession and relaxation time of MVs and DW motion. Due to the low intensity per photon pulse at 3rd generation sources, stroboscopic pump-probe schemes are used, which requires the dynamic processes to be fully repeatable [40]. Fine details of MV motion [41], switching of a MV core by a single pulse [42], dynamics of a constricted DW [43], but also quantitative measurements of the spin polarization of currents [44] have been reported. The excellent agreement with micromagnetic simulations [45] indicates that a description by micromagnetic theory is still valid at these length scales. While this is good news for potential applications of e.g. MV cores [46], there is increased interest to explore the non-linear regime of magnetization dynamics on the nanoscale [47].

Although the spatial resolution with X-ray microscopies is close to fundamental length scales, the fundamental fsec time scale is still far away. In the few psec regime, which is accessible already today e.g. with slicing sources, albeit at largely reduced photon intensities, first spectroscopic XMCD experiments have shown the evolution of orbital moments as function of time [48], which helps to understand magnetic anisotropies. On the fsec time scale, one expects to explore the very origin of exchange interaction. This will be the realm at X-ray FELs which are planned or have started operation very recently. HHG lab sources could serve as an alternative. Today they are already capable to address fsec dynamics at M edges in transition metals covering the transient regime between delocalized bands and localized atomic levels [49].

At these high brilliant and highly coherent fsec sources, lensless imaging techniques using XMCD [50],[51] hold great promise as a reciprocal space alternative to lens-based techniques for single shot and fsec magnetic X-ray imaging.

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Figure Captions

Fig. 1. Images of various magnetic nanostructures obtained with magnetic soft X-ray transmission microscopy.

(a) Magnetic domains of a nanogranular 50 nm thin $(Co_{82}Cr_{18})_{87}Pt_{13}$ alloy film exhibiting a pronounced perpendicular magnetic anisotropy during nucleation and reversal process []. Spatial resolution better than 15nm.

(b) Study of the field driven depinning process of a magnetic DW in a 450nm wide notched permalloy ($Fe_{20}Ni_{80}$) nanowire []. Spatial resolution better than 25nm.

(c) Circulating in-plane MV structure (chirality) of a 3x3 array of permalloy disks with a diameter of 850nm. Spatial resolution better than 25nm.

(d) In perpendicular geometry the images show directly the MV cores (polarity) in a 2x2 array of permalloy disks with a diameter of 850nm. Spatial resolution better than 25nm.