Magnetic imaging by LEEM, X-PEEM, X-ray microscopy, and X-ray holography

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Introduction

Imaging of magnetic domains has contributed essentially to our present level of understanding of micromagnetic phenomena. A number of modern techniques is nowadays routinely used for magnetic imaging of magnetic materials and nanostructures. In my lecture I will present and explain magnetic imaging techniques that are based on electron emission microscopy or on synchrotron radiation. In electron emission microscopy the electrons that are emitted from the sample surface after excitation by electrons or photons are used to create an image of the sample. Two complementary approaches to magnetic imaging are used there, namely spin-polarized low energy electron emission microscopy (SP-LEEM), and x-ray photoelectron emission microscopy (X-PEEM). In SP-LEEM, spin-polarized low-energy electrons excite the sample surface. Magnetic contrast is achieved from the different reflection and absorption cross sections for majority and minority electrons due to the spin-split unoccupied electronic states a few electron volts above the vacuum level. In X-PEEM, the dependence of the absorption cross section for circularly polarized x-rays at elemental absorption resonances, the X-ray magnetic circular dichroism (XMCD) (see also: lecture of S. Pizzini), is used to obtain magnetic contrast in the local intensity of emitted secondary electrons. In both cases the intensity of the emitted electrons, which contains the information about the magnetism of the sample, is imaged by an electron optics.

The great advantage of X-ray-based magnetic imaging techniques is their elemental sensitivity. XMCD yields a signal that depends on the relative angle between the helicity of the circularly polarized X-rays and the local magnetization direction only if the wavelength of the X-rays is tuned to elemental absorption edges. This requires the use of synchrotron radiation, but makes imaging techniques based on XMCD ideal tools for the study of magnetic multi-layered systems. Many of today’s most fascinating discoveries are made in layered structures in which two or more magnetic layers are separated by non-magnetic spacer layers. The fundamental investigation of such layered magnetic structures calls for methods capable of delivering microscopic magnetic information for each of the magnetic layers separately. Due to the elemental sensitivity, XMCD-based magnetic imaging techniques can exactly do that. They allow the layer-resolved visualization of magnetic domain patterns at surfaces and in buried layers under static conditions, and, taking advantage of the pulsed nature of the synchrotron radiation, also during the dynamic response of the magnetic system to short magnetic field pulses.

Besides X-PEEM I will also present X-ray microscopy, the other of the two most frequently used approaches to XMCD-based magnetic imaging. It combines magnetic contrast by XMCD with X-ray microscopy in transmission, either as a parallel imaging technique or by scanning a finely focused X-ray beam across the sample.

A somewhat alternative approach is pursued if the diffraction pattern after transmission of coherent resonant X-rays through the sample is converted to provide a real space image of the sample. Also here the magnetic contrast is due to XMCD. I will discuss the advances that have been achieved recently by that holographic technique, and explain the experimental implementation.

Electron emission microscopy

Parallel imaging of emitted electrons by electron lenses dates back to 1933 [1, 2]. In contrast to transmission electron microscopy, where the direction of the electrons used for imaging the sample are defined by the incoming electron beam (see also lecture of B. Warot-Fonrose), emitted electrons propagate into different directions. For electron emission microscopy therefore usually so-called cathode lenses are used in order to obtain reasonable intensity in a parallel imaging process. A high voltage is applied between sample and objective lens in a cathode lens, so that the sample becomes part of the electron optics. This allows a higher solid angle of emitted electrons to be used for the imaging, and increases the intensity significantly. I will discuss the factors limiting the spatial resolution of cathode lenses, and present the attempts that are currently under way to overcome their inherent resolution limit by aberration-correction schemes [3].

Spin-polarized low-energy electron microscopy (SP-LEEM)

SP-LEEM is a variant of LEEM, a method for the imaging of single crystal surfaces and thin film growth by back-reflected electrons, pioneered by E. Bauer and coworkers [4-6]. The magnetic contrast in SP-LEEM is achieved by replacing the LEEM electron gun by a spin-polarized electron source with selectable polarization direction [7]. SP-LEEM has the advantage that at the same time with the magnetic image all the topographic and structural information of LEEM can be obtained, and that by changing the spin polarization direction of the electron source vectorial magnetic information is obtained. The magnetic contrast in SP-LEEM is realized by the spin-dependent reflection coefficient for low-energy electrons, which is biggest at spin-dependent gaps of the unoccupied part of the band structure. I will explain this mechanism for the magnetic contrast in SP-LEEM, present a typical experimental set-up, and discuss some recent examples of magnetic imaging [8-10].

X-ray photoelectron emission microscopy (X-PEEM)

In photoelectron emission microscopy with x-ray excitation of the sample (X-PEEM), electrons that leave the sample as a consequence of the photoexcitation process are used to obtain a magnified image of the sample. The local intensity in this image represents the local electron yield, and thus the local X-ray absorption cross section. The combination with XMCD is consequently straightforward, and was successfully demonstrated more than ten years ago [11]. X-PEEM is routinely used as a technique for magnetic imaging since about 1997 [12-15]. I will present the instrumentation for this type of magnetic imaging, and demonstrate how the magnetic contrast is obtained and separated from the topographic information. Then I will present some examples of X-PEEM investigations where the element-selectivity was turned into a layer-selectivity [16-20], and discuss the limits of the probing depth for the investigation of buried magnetic layers. XMCD as an integral method is widely used in connection with a set of sum-rules [21, 22], which allow to extract quantitative magnetic information like the effective spin moment or orbital moment per atom (see also lecture of S. Pizzini). Using X-PEEM, it is also possible to obtain this information with lateral resolution by quantitative analysis of a microspectroscopic data set, in which a stack of PEEM images is acquired for many different energies around the absorption edges for both helicities. The result is microscopic maps of the spin and orbital moments [23, 24].

Transmission x-ray microscopy

Magnetic X-ray transmission microscopy is the transmission counterpart to X-PEEM for the laterally resolved detection of XMCD. In x-ray transmission microscopy, x-ray lenses based on the zone plate principle are used to magnify the x-ray transmission image of the sample. Alternatively, zone plates are used to obtain a finely focused x-ray beam at the sample plane, and the transmission image is generated by scanning the sample position. Here also the combination with XMCD is straightforward, since the transmitted y-ray intensity is directly linked to the absorption in the sample. I will briefly explain the working principle and resolution of zone plate x-ray lenses, and present a typical set-up of an x-ray microscope for magnetic imaging [25]. This will be followed by some examples of magnetic imaging [26-30]. I will compare PEEM and transmission x-ray microscopy, and point out the complementarity and the specific strengths and weaknesses of each technique.

Time-resolved experiments

The dynamic behavior of small magnetic structures is becoming more and more important, especially with respect to the increased data rate in magnetic data storage. The pulsed nature of synchrotron radiation allows the study of dynamic magnetization processes. This is usually achieved in a stroboscopic way. Periodically applied magnetic field pulses are synchronized to the synchrotron x-ray pulses with a certain delay time between the two. Varying this delay time yields the opportunity to record elementally resolved domain images at certain times during periodic dynamic magnetization processes. I will present some examples of time-resolved magnetic imaging by X-PEEM [31-35] and transmission x-ray microscopy [36]. The element-selectivity of XMCD is an advantage also for time-resolved measurements, since magnetization reversal dynamics of the different layers in a magnetic trilayer can be studied separately [37]. Compared to a laser pulse the typical width of a synchrotron radiation pulse is much larger, typically about 50 ps, but still smaller than typical rise times in stripline-generated magnetic field pulses. Significantly shorter X-ray pulses are expected for future free-electron laser X-ray sources [38].

Holographic reconstruction of resonant coherent X-ray scattering

Although strictly speaking it is not an imaging technique, but belongs to the class of diffraction experiments, I will also discuss the holographic reconstruction of magnetic domain images from resonant X-ray scattering experiments using coherent radiation in combination with XMCD. In a recent experiment performed by a collaboration of researchers from BESSY and the ALS/Stanford University, the diffraction pattern of a small reference hole next to the sample was superimposed for phase retrieval to the transmitted X-ray pattern from a thin film with out-of-plane magnetization [39, 40]. It is expected that this way of lensless magnetic imaging will greatly benefit from the availability of free electron laser based sources of extremely brilliant and ultrashort X-ray pulses [38].

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