Photoemission electron microscope for the study of magnetic materials

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INTRODUCTION

Photoemission electron microscopy (PEEM) using ultraviolet (UV) radiation was first developed in the 1930's, and has since become a well-established technique. The resolution of modern PEEM instruments approaches 10nm, within a factor of two of the theoretical limit for uncorrected microscopes of 5nm [1, 2]. Our motivation in developing the instrument reported here was to construct a system for spectromicroscopic imaging of magnetic surfaces near the theoretical resolution limit for this type of microscope. One key target was to achieve sufficient positional stability so that the theoretical resolution could be achieved while acquiring spectroscopic data; as series of images are required high stability over tens of minutes is needed. A second goal was to provide this high level of performance in a beamline and endstation environment dedicated to microscopy.

PEEM PRINCIPLE

In PEEM photons incident on a sample cause photoelectron emission if the energy of the photons is larger than the work function of the sample. These photo-emitted electrons are extracted into an electron-optical imaging system by a large electric field that is applied between the sample and the first electrode of the electron optical system. This field is the first lens of the microscope. Several electron-optical lenses are used to form a full field image of the emitted electrons onto a detector such as a phosphor that converts electrons into visible light.

Two contrast mechanisms are available in UV-PEEM, topological contrast and workfunction contrast. Topological contrast is due to distortion of the electric field around surface topological features. The field distribution distortions disturb the electron trajectories which produces image contrast. Workfunction contrast is manifest in the intensity modulation of the photo-emission intensity due to the different emission probability in regions of different workfunction. Additional imaging modes are available when x-ray photons are used to stimulate photoelectrons. Elemental contrast is achieved by tuning the incident x-ray wavelength through absorption edges of elements. X-ray absorption and the resulting photo electron emission intensity is strongly enhanced at absorption edges. Areas on the surface containing the corresponding element emit more photoelectrons and thus appear bright in the PEEM image at a given absorption edge x-ray energy. The fine structure in the energy dependence of the x-ray absorption can be characteristic of the chemical bonding state of surface atoms. Near Edge X-ray Absorption Fine Structure (NEXAFS) spectroscopy [3] can be applied to two-dimension image formation to obtain chemical contrast. Linearly and circularly polarized x-rays can be used to study the orientation of molecules. In orientation contrast linearly polarized x-rays are strongly absorbed when the electrical vector of the light and the orientation of a

bond in the molecule are parallel, and the absorption is weak for a perpendicular orientation [4]. Furthermore, x-ray magnetic circular dichroism (XMCD) can be utilized to study magnetic materials [5] since the absorption of left and right handed circularly polarized radiation varies with the relative orientation of the magnetic moment in the sample. XMCD permits the determination of spin and orbital moments using sum rules [6]. Finally, x-ray magnetic linear dichroism can be utilized to study the properties of antiferromagnetic materials.

BEAMLINE AND PEEM2 LAYOUT

The new instrument called PEEM2 is installed at the bending magnet beamline 7.3.1 which was specifically designed for XMCD microscopy. The spherical grating monochromator is entrance slitless and delivers monochromatic radiation in the energy range of 175-1300 eV. Since the vertical source size at the center of this bending magnet is less than 30 μm and corresponds to the typical field of view of the microscope, the source can be directly imaged onto the sample at unity magnification. The low line density of the grating (200 lines/mm) leads to a very slow variation of the focal length with the wavelength, therefore the monochromator can work with a fixed imaging distance [7]. As the magnification of the PEEM determines the required field of view and hence illumination, the sample is placed in the monochromatic focal plane, without the use of exit slits as typical for conventional systems. This results in an energy dispersed vertical line. Over the typical field of view however of 30 μm the wavelength is essentially fixed. The photon flux is very high for a bending magnet beamline because the minimum number of optical components are used, and the field of view and spectral resolution are optimized for XMCD-PEEM. The photon flux is $3x10^{12}$ photons/s in a 30 μm spot when the storage ring is operated at 1.9 GeV with a ring current of 400 mA in a design band pass of 1 eV at 1000 eV. A mask upstream from the monochromator is used to select above plane (left circularly polarized), in plane (linearly polarized), or below plane (right circularly polarized) radiation. The resolving power of the beamline is $E/\Delta E=1800$.

The objective lens of PEEM2 is an electrostatic tetrode lens with a stigmator/deflector assembly located in its backfocal plane. A transfer lens produces a 1:1 image and a second objective backfocal plane outside the lens where an aperture is located. Four different apertures are mounted on a small flexure stage and can be easily exchanged in vacuum (2mm, 50 μm, 20 μm, and 12 μm diameter). The intermediate lens (with another deflector) and projector lens form the final image on a phosphor screen deposited on a fiber optic plate. This fiber optic plate scintillator serves also as the vacuum interface, and is directly coupled through a second fiber optics taper to a slow scan cooled CCD camera. This detector arrangement is about 5 times more efficient than a lens coupling of the camera.

The typical distance between the objective lens and the sample is 2 mm, and the maximum operating voltage is 30 kV. The sample is held at high negative potential. The center electrodes of the lenses are biased to focus the electrons. All other electrodes and the detector are held at ground potential. The CCD camera can operate in two different modes with a maximum image acquisition rate of 4 images per second. This rate is

sufficient for focusing and adjustment of the microscope. The camera accommodates variable exposure times, with typical image acquisition times of a few to tens of seconds. The microscope is shown in Figure 1.

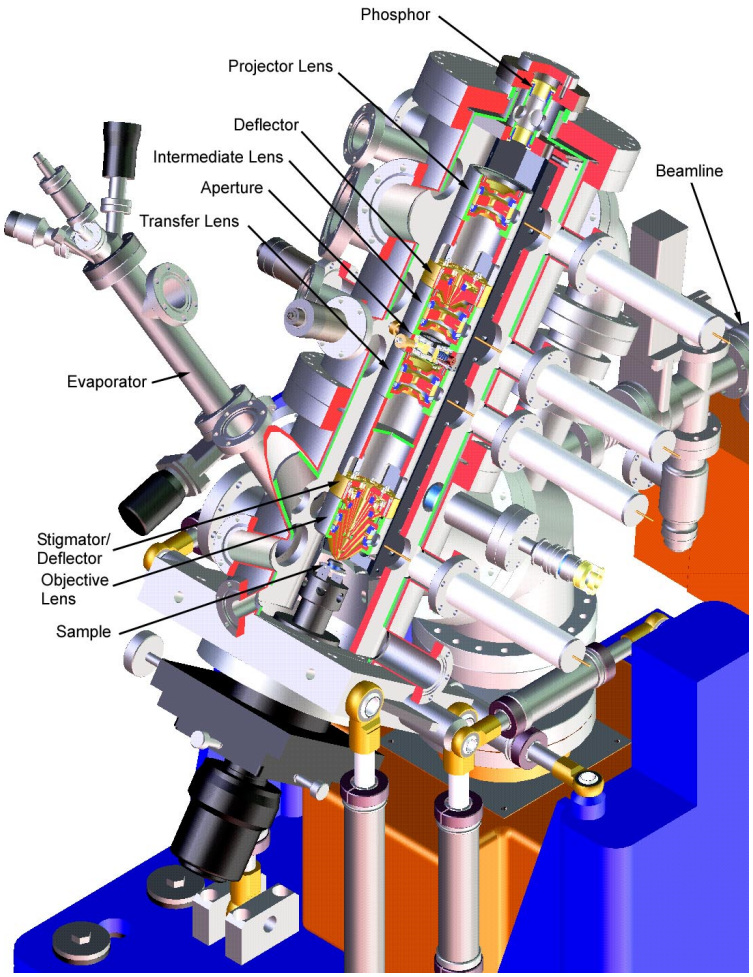

Figure 1: Drawing of PEEM2.

The theoretical resolution limit of PEEM2 was calculated by taking the complete angular and energy distribution of the photo-exited secondary electrons into account. The theoretical resolution limit considering all relevant aberrations is about 20nm obtained using an aperture of 10μm and a sample voltage of 30 kV. The transmission for such a small aperture is around 5 %. All these values depend on the work function of the sample material (we assumed 4 eV as a typical value for metals). The resolution of a PEEM using x-rays is dominated by the aberrations of the accelerating field.

EXPERIMENTAL RESOLUTION TESTS

PEEM2 has been in operation since December 1997. Most of the experiments have been dedicated to the study of magnetic materials. Here we demonstrate the spatial resolution of PEEM2. Figure 2 shows a low resolution and a high resolution image of a surface discharge track on a $LaFeO_3$ sample acquired at the La M_5 edge.

The operation voltage was 18kV, the 12 μm aperture was used, the exposure time was 60 s, and the estimated resolution is 20 nm. Magnetic imaging presents a greater challenge because the contrast based on the XMCD effect is typically only on the order of 5-30% whereas it can be up to factors of 5-10 for elemental contrast. Despite of the low contrast in XMCD imaging the highest resolution we have achieved so far for magnetic imaging is 25 nm. This result was obtained on Co stripes exhibiting stripe domains of a typical size of 100 nm.

This resolution for imaging using x-rays is very close to the theoretical limit for x-ray operation. Better resolution can only be obtained by correcting for the aberrations of the microscope. The most promising approach to an aberration corrected PEEM seems to be the application of an electrostatic mirror. Aberration corrected PEEMs might achieve a spatial resolution in the few nanometer range.

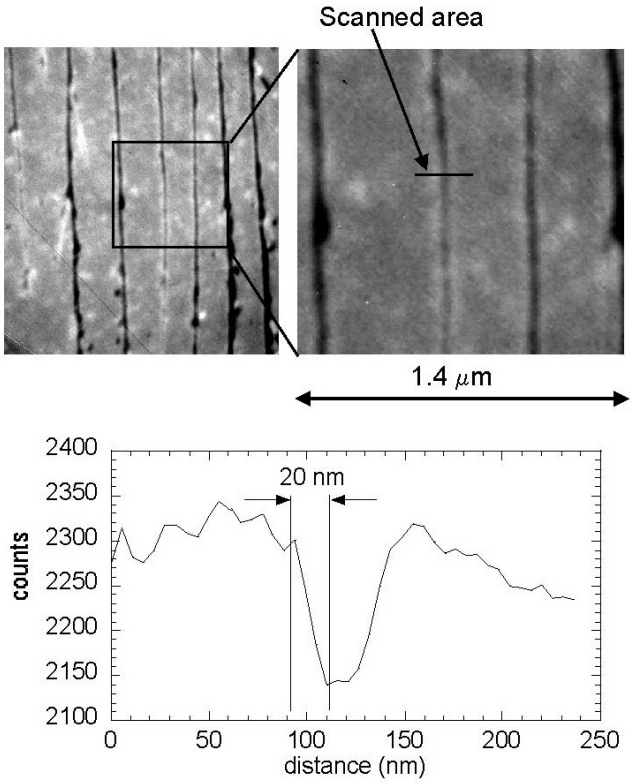

Figure 2: Low resolution and a high resolution PEEM image of a discharge track on a $LaFeO_3$ sample acquired at the La M_5 edge. Estimated resolution 20 nm.

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