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*Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung (BESSY)*

# Looking beneath the surface in nanodevices: standing-wave and hard x-ray photoemission and microscopy

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Modern technological devices, as for example, the integrated circuits which carry out the logical operations in a computer or the device which reads magnetically-stored information from a computer hard drive, consist of multilayer structures whose dimensions have shrunk into the nanometer regime. The Nobel Prize in Physics for 2007 was in fact shared by a German scientist for work that led to the development of the current devices for reading information. For reference, one nanometer (nm) is about the length of five atoms in a row. Such “nanodevices” consist of complex sandwiches of different materials. The individual layers and the interfaces between these layers are crucial to arriving at the desired performance. It is thus key in developing the next generation of high technology to be able to measure the properties of the different layers and interfaces in such structures, including their chemical composition, magnetic character, and precise electronic structure (e.g. metallic, semiconducting, or insulating).

Although many techniques have been developed in the past few decades for studying the first few surface layers of materials, the number of methods which can penetrate below the surface to look at buried layers and interfaces is quite limited. In this research at BESSY, we have explored, and combined, two new approaches for exploring such sub-surface structures. Both are based on photoemission (photoelectron spectroscopy) in which an x-ray is absorbed and excites a photoelectron from the sample. Photoemission is a well known and very powerful tool for studying materials, but in its usual implementations, its probing depth is limited to the first few layers near a solid surface. However, it has recently been demonstrated in the BESSY “HIKE” experiment and elsewhere [1] that, by exciting the photoelectrons with x-rays of significantly higher energies (hard x-rays up to ca. 4,000-10,000 electron volts, as compared to past studies with soft x-rays at ca. 20-1,500 electron volts) one can increase the average probing depth from ca. 1 nm up to about 10 nm or roughly 50 atomic layers. Various applications for such hard x-ray photoemission have been explored and suggested [1].

In addition, some recent soft x-ray studies at the Advanced Light Source in Berkeley have shown that, by growing the sample on top of a nanometer-scale multilayer (ML) mirror, the exciting radiation field can be "tailored" into an oscillatory standing wave that has the same nanometer scale [2]. The maxima and minima of this standing wave (SW) can then be moved up and down in the sample layers on top of the ML in three ways: by scanning the incidence angle of the radiation around that satisfying the condition for strong reflection from the ML (the Bragg condition), by scanning the incident radiation energy around that satisfying the Bragg condition for reflection, and/or by sitting at the Bragg condition and moving the sample in the synchrotron radiation beam. The latter method requires one layer of the sample to be specially grown in a wedge configuration; a schematic drawing of this standing wave/wedge ("swedge") method is shown in Fig. 1(a) [2,3].

We have for the first time applied these approaches, including the swedge method, to multilayer structures of interest in future magnetic data storage and logic technologies, or "spintronics", using higher energy x-rays in the HIKE experiment to excite the photoelectrons. One system studied is an insulator on top of a ferromagnet (MgO/Fe), a combination that is important in current devices for magnetic data retrieval known as tunnel junctions (cf. Fig. 1(a)). Fig. 1(b) shows clear oscillations of about 20% in the intensity of two Fe photoelectron peaks as the sample position is scanned in front of the beam, which effectively scans the SW through the Fe/MgO interface [2,3]. Via an analysis of these data using x-ray optical theoretical calculations, these data and other similar results obtained for photoelectron emitted from other elements will permit determining the thickness and chemical composition of the MgO overlayer, as well as the nature of the buried Fe/MgO interface. A wide variety of applications of this hard x-ray photoemission approach seems possible.

Another important dimension of photoemission is its use as the imaging mechanism in a photoelectron microscope (PEEM). Such devices are now able to observe features along the two surface dimensions of x and y in Fig. 1(a) with resolutions of about 20 nm, and current developments at BESSY (e.g. the SMART project) promise resolutions in the few nm regime. However, PEEMs cannot resolve the third depth-related dimension z in Fig 1(a). In order to add this important dimension to PEEM images, we have incorporated the swedge method into the BESSY "spin-polarized PEEM", which has the essential feature of being able to resolve photoelectron images according to energy. We have studied a multilayer test structure consisting of a narrow wedge of silver (Ag) that is capped with layers of cobalt (Co) and gold (Au), as shown in Fig. 2(a). In this case, the angle of x-ray incidence is fixed at the Bragg condition, and the radiation energy is scanned so as to move the SW through the Ag/Co interface. Plotting the Ag intensity in the images as a function of energy clearly shows the SW moving down the slope of the wedge, as summarized in Fig. 2(b). Fig. 3(a) further shows another view of the sample, and Fig. 3(b) illustrates the phase shift between the Ag 3d and C 1s intensities due to their different distances from the surface, as amplified in a video available elsewhere [3]. These results thus represent a first proof-of-principle that the swedge method can be used to provide depth (or z) resolution in PEEM images, with many possible applications in the future.

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**References:**

[1] Special journal issue dedicated to photoemission with hard x-rays: Nuclear Instruments and Methods A **547** (2005), edited by J. Zegenhagen and C. Kunz, plus Program and abstracts of recent international workshop on hard x-ray photoemission, HAXPES06, Spring8, Japan, available at: http://haxpes2006.spring8.or.jp/program.html.
[2] S.H. Yang et al., Synchrotron Radiation News 17 (no. 3), 24 (2004).
[3] Videos illustrating the swedge method and standing-wave spectromicroscopy are available at: http://www.physics.ucdavis.edu/fadleygroup/.

**Figure captions:**

Figure 1: (a) Illustration of photoemission from a multilayer sample and the standing wave/wedge ("swedge") method for studying buried layers and interfaces. A movie illustrating the "swedge" method is available at: http://www.physics.ucdavis.edu/fadleygroup/. (b) Oscillatory intensity modulation of the iron photoelectron intensities as the standing wave is scanned through the iron/magnesium oxide interface shown in (a). The sample was scanned under the x-ray beam (cf. Fig. 1(a)) and the hard x-ray excitation energy was 4,000 eV.

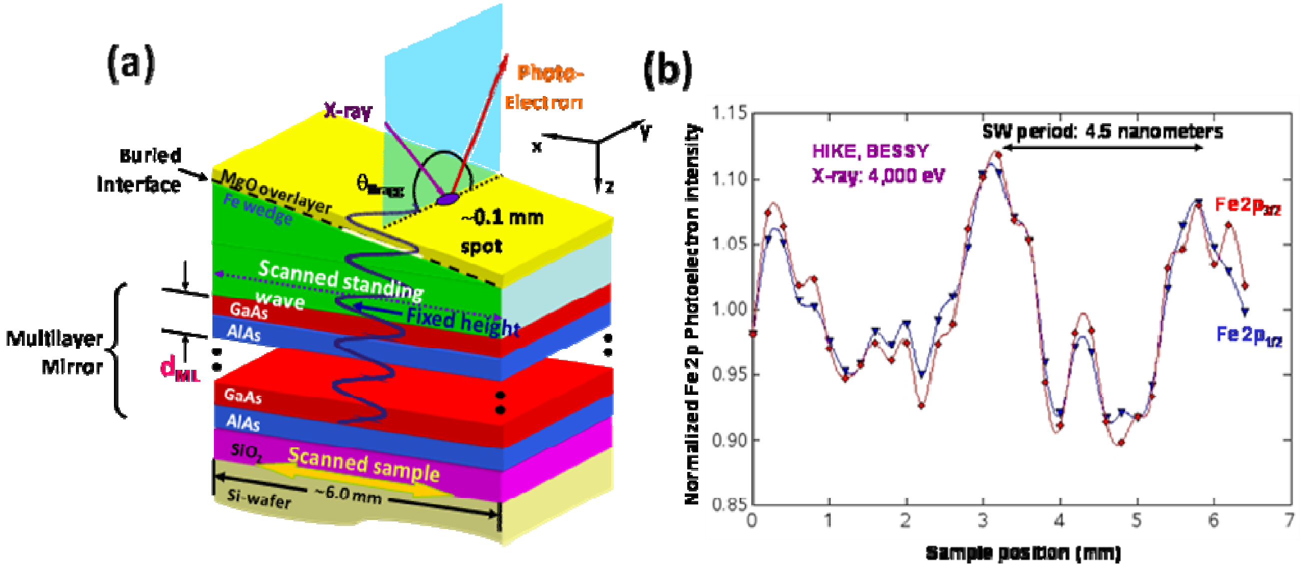

Figure 2: (a) Illustration of the use of the swedge method in a photoelectron microscope, for the case of a Ag wedge below Co and Au layers. Here, 1 micron = 1μm = 1,000 nanometers. (b) Summary of images based on silver photoelectron intensities obtained as the soft x-ray energy is scanned over the multilayer Bragg condition, and showing clearly that the SW maximum moves down the wedge. A movie illustrating this movement is available at: [http://www.physics.ucdavis.edu/fadleygroup/](http://www.physics.ucdavis.edu/fadleygroup/).

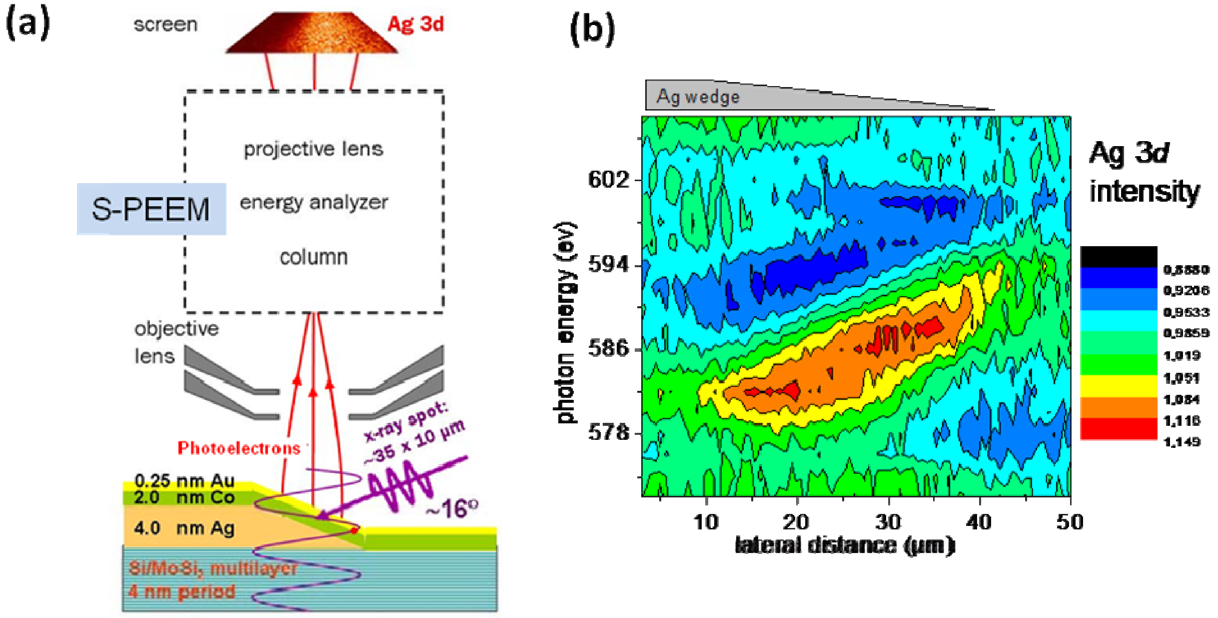

Figure 3: (a) Alternative view of the sample in Fig. 2(a). (b) Snapshots from a video showing the variation in both Ag 3d and C 1s intensity as the soft x-ray energy is scanned over the multilayer Bragg condition at an energy of 590 eV, from 574 eV to 602 eV. Note the phase shift between the two images, as the C is a thin contaminant layer on top of the Au, and so is about 2.00+0.25 = 2.25 nm or a little over ½ of the SW period of 4.00 nm above the Ag/Co interface. Video at: [http://www.physics.ucdavis.edu/fadleygroup/](http://www.physics.ucdavis.edu/fadleygroup/).