Abstracts
Poster Session 1

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Structure and magnetism in ultra-thin hcp Fe films on Re(0001)

Benito Santos¹, T. O. Menteš¹, N. Stojić², J. I. Cerda³, J. M. Puerta³, A. Locatelli¹

¹Sincrotrone Trieste S.C.p.A., Trieste 34149, Italy
²Abdus Salam International Center for Theoretical Physics, Trieste 34151, Italy
³Instituto de Ciencia de Materiales de Madrid, CSIC, Madrid 28049, Spain

Email: benito.santos@elettra.trieste.it

The differences in the magnetic properties between ultrathin films and bulk materials are mainly based on the reduced coordination of the atoms at the surface. One of the most surprising examples was reported by Kubetzka et al., who showed that even a prototypical ferromagnetic metal such as Fe becomes antiferromagnetic as a monolayer on W(001) [1]. Bulk Fe shows a bcc structure but by choosing an appropriate substrate it is possible to obtain ultra-thin Fe films with modified crystal symmetry. In particular, Fe on Re(0001) provides a model system for studying the magnetism in a hexagonal Fe layer. Past calculations showed that the layer may assume ferromagnetic, non-magnetic or antiferromagnetic order depending on the lattice parameter [2], and the transition between the different magnetic states depends on small changes in the crystal structure and/or the hybridization with the substrate [3]. In spite of the numerous theoretical calculations, there are only few experimental studies regarding magnetic layers on the Re(0001) surface. Here we present a structural and magnetic study of an Fe monolayer on Re(0001). The growth mode and morphology of Fe on Re(0001) up to 5 atomic layers (AL) were studied by LEEM and LEED, which show hcp sequence for one monolayer. The structure of the films was determined by means of LEED-IV analysis. The structural data obtained in the LEED-IV fits were used as input to the theoretical calculations in order to extract information on the magnetic state of the Fe films. We will also report XMCD and XMLD-PEEM measurements, which will be discussed in light of the DFT calculations.

Figure 1. (a) LEEM image acquired during the nucleation of 1 AL of Fe/Re(0001). The presence of triangular islands with two different orientations in the same terrace suggests stacking faults. (b) XMCD-PEEM image of a region with 2 and 3 AL Fe. Ferromagnetic domains can be observed in areas where the films are 3 AL thick. Field of view is 4 and 10 μm respectively.

References
Observation of Magnetic Domain Structure of 3% Si-Fe (110) during Heating/Cooling Process by XMCD-PEEM

M. Hashimoto¹, K. Iwata², M. Suzuki¹, M. Ueda¹, Y. Matuoka¹, M. Kotsugi³, T. Kinoshita³, Y. Watanabe³, K. Tanaka², T. Yasue¹, and T. Koshikawa¹

¹Fundamental Electronics Research Institute, Osaka Electro-Communication University, 18-8 Hatsu-cho, Neyagawa, Osaka 572-8530, Japan
²Advanced Technology Research Laboratories, Nippon Steel Corporation, 20-1 Shintomi, Futtsu, Chiba, 293-8511, Japan
³SPring-8/JASRI, 1-1-1 Kouto, Sayo, Hyogo 679-5198, Japan

Email: h-michi@isc.osakac.ac.jp

3% Si-Fe(110) [001] is well known soft magnetic material which is widely used in industry such as the dynamo, the transformer, the magnetic shield, etc. due to its superior magnetic characteristics. The iron loss in the soft magnetic material is classified into the hysteresis loss and the eddy current loss (classical and anomalous eddy current losses). In usual case, the anomalous eddy current loss reaches at about 50% among the total iron loss. It has been an important subject how anomalous eddy current loss is reduced, and great efforts have been devoted in order to lower the core loss so far, which includes the improvement of the orientation alignment, the refinement of the magnetic domains, and so on. The anomalous eddy current loss is strongly affected by the presence of the flux closing domain, which is called as lancet, so that it would be quite important to understand that the behavior of the magnetic domains including lancets under several environmental conditions.

In the present study, the magnetic domain structures of 3% Si-Fe(110) [001] were observed by X-ray magnetic circular dichroism photo emission electron microscopy (XMCD-PEEM) at the Fe L₃ absorption edge (hν = 707 eV) during the heating up to the Curie temperature and the cooling processes in order to obtain the knowledge of the thermal stability of the domain structure. The experiments were carried out at the soft X-ray beam line BL17SU in the SPring-8. A commercial spectroscopic photoemission and low energy electron microscope (SPELEEM) was used.

Fig. 1 shows the change of the magnetic domain structure during heating from room temperature to Curie temperature observed by XMCD-PEEM. Triangular lancets are observed with the magnetization direction opposite to the surrounding main domain. Fig. 1 (a) shows the XMCD-PEEM image at room temperature. As shown in Fig. 1 (b), at about 515 °C, the size of lancets becomes small. Some of lancets disappear in Fig. 1 (c), and they disappear mostly in Fig. 1 (d). By further heating at around 700 °C, a 180° domain wall vigorously fluctuates as shown in fig. 1 (e), and spontaneous magnetization disappears at Curie temperature. When the sample was cooled down from Curie temperature, the reversed process took place. Surprisingly sizes and positions of lancets are quite similar to those observed in the heating process. The movement of lancets to keep their uniform separation was also observed during thermal process. It is considered that the arrangement of lancets is determined by repulsion between lancets.

![Figure 1](image-url)

**Figure 1.** Change of the magnetic domain structures during the heating from room temperature to the Curie temperature by XMCD-PEEM taken at the Fe L₃ edge. The size of the images is 50 μm. The temperature is (a) RT, (b) 515 °C, (c) 535 °C, (d) 610 °C and (e) 725 °C.
Stabilization of Perpendicular Magnetization in Co/Ni Multilayer—Study with High Brightness and Highly Spin-Polarized LEEM—

Masahiko Suzuki¹, Tsuneo Yasue¹, Takanori Koshikawa¹, Ernst Bauer²

¹Fundamental Electronics Research Institute, Osaka Electro-Communication University, 18-8 Hatsu-cho, Neyagawa, Osaka 572-8530, Japan
²Department of Physics and Astronomy, Arizona State University, Tempe, Arizona 85287-1504, USA

Email: m-suzuki@isc.osakac.ac.jp

Current induced domain wall motion [1] is a key phenomenon to realize novel spintronic devices such as a race-track memory [2] and a domain wall motion magneto-resistive random access memory (DW-motion MRAM) [3]. It has been indicated that domain walls in nanowires with perpendicular magnetic anisotropy can move with lower current density than those with in-plane magnetic anisotropy [4, 5]. Multilayer consisting of pairs of a Co and Ni layer is known to exhibit perpendicular magnetic anisotropy and is expected as a material for the devices with low operation current [6, 7]. However, process of stabilizing the perpendicular magnetization in the multilayer has not been shown in detail. In the present study, we investigated magnetization behavior during growth of the Co/Ni multilayer with high brightness and highly spin-polarized LEEM [8-10].

Figure 1 shows magnetic domain images of a multilayer consisting of pairs of 2 ML of Ni and 1 ML of Co on W(110). Magnetic contrast emerged with in-plane magnetization during Co deposition of the first Co/Ni pair (Fig. 1 a). The in-plane magnetic domains became hardly observable and perpendicular magnetic domains became clearly observable upon Ni deposition (Fig. 1 b). The perpendicular magnetic domains broke up and the in-plane magnetic component appeared again upon the following Co deposition (Fig. 1 c). It is indicated that the Ni and Co deposition enhance perpendicular and in-plane magnetic anisotropy, respectively. In the following growth, the in-plane magnetic contrast after Co depositions became weaker with number of Co/Ni pairs and only the perpendicular magnetic domains were observable above four Co/Ni pairs (Figs. 1 d-i). It is shown very clearly that the perpendicular magnetization is stabilized with number of Co/Ni pairs as the perpendicular magnetic anisotropy prevails against the in-plane one.

Figure 1. SPLEEM images with perpendicular (⊥) and in-plane [1 1 0] (∥) magnetization of a multilayer consisting of pairs of 2 ML of Ni and 1 ML of Co on W(110). A LEEM image obtained in the same area with the magnetic images is shown in the left column. Field of view = 6 μm.

Development of Perpendicular Magnetic Anisotropy by Au Overlayer on Co/Ni Magnetic Film

M. Suzuki$^1$, T. Yasue$^1$, E. Bauer$^2$ and T. Koshikawa$^1$

$^1$Fundamental Electronics Research Institute, Osaka Electro-Communication University, 18-8 Hatsu-cho, Neyagawa, Osaka 572-8530, Japan
$^2$Department of Physics and Astronomy, Arizona State University, Tempe, AZ 85287-1504, USA

Email: yasue@isc.osak.ac.jp

Magnetic thin films have been extensively studied because of their potential on the application to the spintronic devices. Understanding of the magnetic properties of the magnetic thin film is basically of importance, and also it is required to control them in order to achieve the highly sophisticated function. It is known that non-magnetic overlayer can modify the magnetic anisotropy of the magnetic thin films [1]. In the present study, we have observed the spin reorientation process during the deposition of Au overlayer on CoNi$_2$/W(110) with high brightness and highly spin polarized low energy electron microscopy (SPLEEM) [2].

Figure 1(a) shows out-of-plane (top row) and in-plane (middle row) components of the magnetic domain structure and relevant LEEM image (bottom row) of CoNi$_2$ on W(110). The CoNi$_2$ film exhibits the uniaxial in-plane anisotropy along [1 -1 0] direction. As Au deposition, the in-plane magnetic anisotropy becomes weak and almost vanishes at around a half ML of Au (fig. 1(c)). Then the out-of-plane component starts to develop after 0.5 ML, and the strong perpendicular magnetic anisotropy is established at 1 ML of Au. The domain structure observed here is completely different from that before Au deposition. In the corresponding LEEM images, the behavior of the step contrast well correlates with the change of the magnetic anisotropy. And the intensity of LEEM image decreases with Au coverage up to around 0.5 ML and recovers after that. It would be suggested that the spin reorientation process seen in fig. 1 is relevant to the growth process of Au layer on top of CoNi$_2$ film.

References

Figure 1. Out-of-plane and in-plane SPLEEM images (top and middle rows) and LEEM image (bottom row) during Au deposition on CoNi$_2$/W(110). The coverage of Au is (a) 0, (b) 0.25, (c) 0.5, (d) 0.75 and (e) 1 ML.
Spin-dependent inelastic mean free path from quantum size oscillations in reflectivity of slow electrons

Ryszard Zdyb\textsuperscript{1}, Ernst Bauer\textsuperscript{2}

\textsuperscript{1}Institute of Physics, Maria Curie-Sklodowska University, 20-031 Lublin, Poland
\textsuperscript{2}Department of Physics, Arizona State University, Tempe, Arizona, 85287-1504

Email: zdybr@hektor.umcs.lublin.pl

The inelastic mean free path (IMFP) of electrons can be obtained by a variety of experiments among which the most common are the overlayer method and calculations based on optical data [1, 2]. The results can be fitted to the so called universal curve and agree with this curve above about 50 eV. At lower energies the IMFP depends considerably on the electronic structure, which can cause large deviations from the universal curve. Also the experimental methods used in the past pose problems for electron energies below this energy [1, 3]. In our paper we present another approach to the determination of the IMFP at low energies. The approach is based on quantum size oscillations in the reflectivity of electrons impinging on nanostructures with well-defined thickness [4]. The oscillations can be modeled as reflectivity oscillations in a Fabry-Perot interferometer consisting of an absorbing medium. The absorbing medium is modeled with a complex refractive index whose imaginary part is associated with the absorption process and thus with the inelastic mean free path. The absorbing medium is characterized by the experimentally determined spin-dependent band structure [4] fitted with a two band model. The only remaining parameter is the inelastic mean free path which can be directly calculated from the experimental data. The resulting IMFP values for spin-up electrons are clearly larger than those for spin-down electrons with agreement with theoretical predictions [6].

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References
Quantum Size Effect in Fe films on the Cu-covered W(110) Surface

Q. Wu and M.S. Altman

Department of Physics, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong

Email: wqxaa@ust.hk

The quantum size effect (QSE) in electron reflectivity from Fe films on a W(110) surface pre-covered with 1 and 2 ML Cu films has been investigated using spin polarized low energy electron microscopy (SPLEEM). SPLEEM image intensity vs. energy, I(V), curves at fixed thickness exhibit spin-dependent quantum size oscillations, which increase in number with thickness in accordance with expectations [1]. Analysis of these oscillations using the phase accumulation model [2-4] demonstrates that the spin-dependent unoccupied band structure of the Fe film is consistent with bulk band structure in the ΓN direction. This modeling and comparison with previously published results for Fe films grown directly on W(110) [2] also reveal two surprising features of the QSE in these systems. Firstly, we discovered that quantum size intensity oscillations in Fe(N ML)/W(110), Fe(N ML)/Cu(1 ML)/W(110), Fe(N-1 ML)/Cu(2 ML)/W(110), where N = integer, are similar (Fig. 1). This suggests that the first Cu layer in contact with W(110) extends the substrate interface that imposes the quantum well confinement in subsequent film layers, i.e. in a pure covering Fe film in Fe/Cu(1ML)/W(110) and in an additional Cu layer covered by Fe in Fe/Cu(2ML)/W(110). We also determined that the interface scattering phase of electrons that reflect from the buried interface must be zero, in order to model the quantum size intensity oscillations for Fe/Cu/W(110) and Fe/W(110). This discovery is particularly startling because it contrasts with the behavior for Ag films on W(110), where the interface scattering phase plays a substantial role in defining the quantum interference conditions in electron reflectivity [4].

Acknowledgement

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References


Figure 1. (a) SPLEEM image of magnetic domains in Fe(7ML)/Cu(2ML)/W(110) at E = 3.9 eV. (b) Spin-dependent I(V) curves for Fe(5ML)/Cu(1ML)/W(110). (c) The spin-up I(V) curves for Fe(5ML)/Cu(1ML)/W(110) and Fe(4ML)/Cu(2ML)/W(110) after subtracting the bulk I(V) characteristics exhibit nearly identical QSE intensity oscillations.
Development of novel compact spin-polarized electron gun

T. Koshikawa¹, T. Yasue¹, M. Suzuki¹, K. Tsuno¹, S. Goto², X. Jin³ and Y. Takeda⁴

¹Osaka Electro-Communication Univ., 18-8 Hatsu-cho, Neyagawa 572-8530
²San-yu Electric Corp., 1-22-6 Hyakunin-cho, Shinjuku, Tokyo 167-0073
³School of Engineering, Nagoya Univ., Furo-cho, Chigusa, Nagoya 468-8602
⁴Synchrotron Light center, 250-3 Yamaguchi-cho, Seto 489-0965

Email: kosikawa@isc.osakac.ac.jp

We have already developed a novel high brightness and high spin-polarized low energy electron microscope (SPLEEM) and applied it to clarify the magnetic property of [CoNix]y/W(110) and Au/CoNi2/W(110) during growth of ultra thin films [1-3]. Such thin film multi-layers are important for current driven domain wall motion devices [4]. Our developed SPLEEM can make us the dynamic observation of the magnetic domain images possible. However the size of the spin-polarized electron gun is large and we have started to develop a new compact spin-polarized electron gun with new idea. It is necessary two devices to operate 3 dimensional spin direction. One is a spin manipulator which changes the out of plain spin direction and another one is a spin rotator which can change the in plain spin direction. We have proposed a multi-pole Wien filter which can make 3 dimensional spin operation with one device possible. Fig.1 shows a drawing of the developing 3D multi-pole spin manipulator which has 8 poles.

![Figure 1. 3D eight-pole spin manipulator and uniformity of magnetic and electric field](image)

References
Low energy electron microscopy (LEEM) and transmission electron microscopy (TEM) with spin-polarized electron beam have been used for magnetization-sensitive imaging. In order to investigate the change of the magnetic domain by a high time-resolution, the application of a pulse spin-polarized electron beam is necessary. In our previous study, we achieved a high spin-polarization (90%) of electron beam from a GaAs/GaAsP superlattice photocathode [1]. In this study, we report the generation of picosecond electron bunch from the GaAs/GaAsP strained superlattice photocathode.

Figure 1 shows the GaAs/GaAsP superlattice photocathode structure. Following the growth of a 2-μm GaAs0.67P0.33 buffer layer, 12 pairs of the GaAs(3.6-nm)/GaAs0.67P0.33(3.6-nm) superlattice layers were grown on the GaAs substrate. For generation of pulse electron beams, the mode locked Ti-Sa laser was used. The pulse repetition frequency was 81.25 MHz (1/16 of 1.3 GHz). The pulse widths of the laser were about 2–3 ps. The measurements were carried out under the surface-side irradiation arrangement of the pump laser light and the emission current was about 3 nA.

Figure 2 shows the emission current pulse shape for the GaAs/GaAsP superlattice photocathode. t_{90}, in which 90% of pulse charge is contained, is 10.34 ps. The pulse shape shows a typical asymmetry due to the retarded response of the electrons arriving back to the surface by diffusion process. Using a diffusion model [2], the diffusion constant and the transport time of the superlattice structure will be discussed.

Acknowledgement
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References
Magnetic Imaging with 10 nm Spatial Resolution Using Laser-Excited Photoemission Electron Microscopy

Toshiyuki Taniuchi\textsuperscript{1,2}, Shinnosuke Abe\textsuperscript{1}, Yoshinori Kotani\textsuperscript{3}, Takeshi Seki\textsuperscript{4}, Masato Kotsugi\textsuperscript{3}, Koki Takanashi\textsuperscript{4}, Shik Shin\textsuperscript{1,2}

\textsuperscript{1}The Institute for Solid State Physics, The University of Tokyo, Kashiwa 277-8581, Japan
\textsuperscript{2}CREST-JST, Honcho, Kawaguchi 332-0012, Japan
\textsuperscript{3}Japan Synchrotron Radiation Research Institute, Kouto, Sayo, Hyogo 679-5198, Japan
\textsuperscript{4}Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan

Email: taniuchi@issp.u-tokyo.ac.jp

We report the laser-excited photoemission electron microscope (PEEM) system to achieve the spatial resolution better than 10 nm in magnetic imaging. Since the magnetic circular dichroism near the Fermi level was observed [1], the laser-excited PEEM is a good candidate for the high spatial resolution magnetic imaging, which can overcome the resolution limit due to the space charge effect in the conventional pulsed sources. In this work we have developed the measurement system with combination of the continuous wave (CW) laser and the aberration-corrected PEEM instrument. The photon flux of the laser is more than 10,000 times of that of the synchrotron radiation. This allows us to minimize the influence of the vibrations and drifts by acquiring images in a much shorter time. In order to demonstrate the potential of this technique, we show the experimental result on FePt thin films (Fig. 1).

Another feature of the use of the CW laser is that it can be switched rapidly between the linear and right/left circular polarizations. This indicates that this method will be a useful tool to investigate the system with the coexistence of the ferro- and antiferro-magnetic domains, for example.

![Figure 1. Magnetic domains of the FePt thin films observed by laser excited PEEM.](image)

Reference
Imaging Spin Filter for Electrons

D. Kutnyakhov1, P. Lushchyk1, M. Kolbe1, K. Medjanik1, S.A. Nepijko1, H.J. Elmers1, C. Tusche2, A. Krasyuk2, J. Kirschner2, F. Giebels3, H. Gollisch3, R. Feder3, G. Schönhense1

1Johannes Gutenberg-Universität, Institut für Physik, D-55099 Mainz, Germany
2Max Planck-Institut für Mikrostrukturphysik, D-06120 Halle, Germany
3Universität Duisburg-Essen, Theoretische Festkörperphysik, D-47057 Duisburg, Germany

Email: schoenhense@uni-mainz.de

As Stern-Gerlach type spin filters do not work with electrons, spin analysis of electron beams is accomplished by spin dependent scattering processes based on spin-orbit or exchange interaction [1]. Existing polarimeters are inherently single-channel devices characterized by a low figure of merit (FoM) of typically $10^{-4}$ to $10^{-3}$. This single-channel approach is not compatible with parallel imaging microscopes and also not with modern electron spectrometers that acquire a certain energy and angular interval simultaneously. Comparing a common spin-resolving electron spectrometer with a hemispherical analyzer of the present generation (detecting $10^4$ data points simultaneously) we are facing a difference in detection efficiency of 7-8 orders of magnitude!

Here we present a novel method that can transport a full image by making use of k-parallel conservation in low-energy electron diffraction (Fig. 1). For high-Z materials (we show data for W(001) and Ir(001)) spin-filtered images are obtained at certain diffraction energies and angles, see right panel. Different application cases will be discussed: When the two lateral coordinates correspond to spatial coordinates (x,y) on the sample we obtain high-contrast spin-filtered images, e.g. of ferromagnetic domains [2]. Exploiting the energy- and angle-coordinates (E,$\theta$) behind an electron spectrometer (Fig.1 left) we arrive at multichannel spin polarimetry [3]. Finally, imaging the transversal components of the momentum vector ($k_x,k_y$) constitutes the new method of spin-filtered momentum microscopy [4]. In the column of a PEEM or momentum microscopy 3800 image points were resolved [2]. The multichannel approach yields 4 orders of magnitude improvement of spin detection efficiency [3]. This is a large advantage for the study of reactive surfaces, for weak signals e.g. in the hard X-ray range (Spin-HAXPES) or in single-shot experiments.

![Figure 1](image)

**Figure 1.** Left: Scheme of the 2D spin filter; in acquisition of spin-filtered spectra about 1000 data points (here energy and emission angle) can be taken simultaneously. Right: Measured spin asymmetry for an Ir(001) surface in comparison with a relativistic layer-KKR SPLEED calculation.

Acknowledgement

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References

High Resolution TOF Photoemission Electron Microscope -
Spectrometer (PEEM-S)

G. Lebedev

Lawrence Berkeley National Laboratory, One Cyclotron Rd., Berkeley, CA, 94720, USA

Email: gvlebedev@lbl.gov

The Time-of-Flight approach in photoemission electron spectroscopy implemented in TOF ARPES-Spin [1] and TOF ARPES [2] was used in design of TOF PEEMS with spatial resolution 2-3 nm in PEEM mode and less than 0.2 degree angle resolution in ARPES mode. Calculated energy resolution of analyzer is in submilivolt range and is mapped to spatial or reciprocal space (or a combination) of emitted photoelectrons, depending on the mode of operations. This makes the analysis effectively three dimensional, leaving two dimensions for real or reciprocal space and a third for electrons energy spectrum converted from time of flight.

The electron optical system (EOS) of the analyzer consist of 4 electrostatic lenses, two variable apertures, two deflectors, a stigmator and aberration corrector, consisting of stigmatic non axial symmetrical focusing elements for correction of the third order spherical aberration. Linear magnification of EOS is in range of M = 2000-10000.

We plan incorporate delay line detector with timing accuracy better than 130 ps FWHM and spatial resolution less than 35 \( \mu m \) [3]. Detector can operate at ~0.4MHz count rates for a specified range of incoming electron energies.

Times to energy conversion algorithm is expressed as a series of polynomial approximations in time-energy domain. Criteria for EOS optimization of TOF-EEA with maximum energy resolution and sensitivity and required image quality were formulated.

References
Development of a new electrostatic OMEGA filter for SMART-II

Francesca Genuzio, Giuseppe Rombolà, Helder Marchetto, Thomas Schmidt, Hans-Joachim Freund

Fritz-Haber-Institut der Max-Planck-Gesellschaft, Faradayweg 4-6, 14195 Berlin, Germany

Email: fgenuzio@fhi-berlin.mpg.de

The SMART (Spectro-Microscope with Aberration correction for many Relevant Techniques) [1] combines electron spectroscopy with electron microscopy at high lateral and energy resolution to obtain spatially resolved information about the morphology, chemical distribution, work function and structural properties on nanometer scale. The basic instrument is a Low Energy Electron Microscope (LEEM) and Photo-Emission Electron Microscope (PEEM) equipped with an imaging energy analyzer and an aberration corrector, compensating simultaneously for both, the spherical and the chromatic aberrations. This leads to an outstanding lateral resolution of 2.6 nm [2] which is twice as good as for an uncompensated LEEM/PEEM. Currently we are setting up a new instrument, called SMART-II. The aim of the new instrument is a routine operation with easy handling at a high lateral resolution better than 2 nm in LEEM and 5 nm in PEEM. The principle optical design is identical to that of the SMART-I, but the magnetic $\Omega$-filter will be replaced by an electrostatic analogous instrument which allows to float the analyzer potential on the sample potential, leading to much higher electronic stability and therefore improved lateral and energy resolution.

The four sectors of the new $\Omega$-filter are double focusing 80° deflectors, the shape of which has been optimized to be toroidal instead of the “classical” spherical shape – in order to avoid astigmatic imaging. Furthermore, the distance and relative position between the sectors have been determined. The residual geometric and chromatic aberrations up to the third order could be simulated for the entire system. This is important for the design of the multipole correctors to compensate for the leading aberrations and to estimate the final energy resolution (better than 0.1 eV) and lateral resolution. Furthermore, the adaptive optics at the entrance and the exit of the filter have been developed and optimized. The retarding and acceleration lens systems enable (i) the correct transfer of the surface image plane and the back focal plane into specific planes of the filter, (ii) retarding of the electron beam from 20,000 eV down to the analyzer pass energy of 2,000 eV and the following acceleration back to 20,000 eV and (iii) adjusting the proper beam size and angular spread in front of the analyzer to reduce the effect of the unavoidable aberrations.

References
Correction of the leading chromatic and spherical aberrations has been successfully realized for different electron microscopies including Transmission Electron Microscopy (TEM), Photo Electron Emission Microscopy (PEEM) and Low Energy Electron Microscopy (LEEM). For all these methods the intrinsic electron optical behavior is expressed in the Contrast Transfer Function (CTF) [1], which provides a wave-optical treatment of the effects of the various aberration coefficients on image formation. The ultimate resolution in aberration-corrected LEEM is predicted to be about 0.5 nm if the lowest order chromatic aberrations, \( C_1 \), and the third order spherical aberrations, \( C_3 \), are zero [1]. The question arises how precisely \( C_1 \) and \( C_3 \) must be controlled to achieve this ultimate resolution? Or, what is the resolution if the instrument is set so that only e.g. 90% of \( C_1 \) and \( C_3 \) are corrected? Using detailed image simulations, we find that resolution scales with \( C_1^{1/2} \) and \( C_3^{1/4} \). Thus, in the vicinity of the fully corrected state the resolution is highly sensitive to the residual values of \( C_1 \) and \( C_3 \) (see Fig. 1a). Precise adjustment of the corrector, therefore, is crucial to achieve ultimate resolution.

Negative \( C_3 \) imaging uses a slightly negative value of \( C_3 \) in combination with a small positive defocus \( C_1 \) to partially compensate for the next higher order spherical aberration, \( C_5 \), to improve the resolution of \( C_3 \)-corrected microscopes even further. Figures 1b and 1c show the LEEM point resolution (i.e. the spatial frequency at which the CTF first passes through zero) for weak phase objects and amplitude/strong phase objects, respectively, as a function of \( C_1 \), and \( C_3 \). A narrow band of highest resolution is located near the center. Resolution drops abruptly at the lower boundary of this band (see white dashed lines in Fig. 1b and 1c). Setting the operation point of the instrument just above this edge leads to the highest resolution. However, small fluctuations and drift away from the optimum set point can cause a significant degradation in resolution. We present a set of optimum negative \( C_3 \) imaging conditions (see white solid lines in Fig. 1b and 1c) that assure a most even contrast transfer, yet provide the microscope operator with a certain ‘instability budget’, i.e. the opportunity to trade resolution for stability over a significant range of parameters.

**Figure 1.** (a) Resolution of an amplitude object vs. the normalized value of \( C_3 \), for different settings of \( C_1 \) (uncorrected = 100%, fully corrected = 0%) in LEEM. The green dotted line shows the \( C_3^{1/4} \) prediction. Point resolution (nm\(^{-1}\)) vs \( C_1 \) and \( C_3 \) for weak phase objects (b) and amplitude/strong phase objects (c) in LEEM with a starting electron energy of 10 eV. The optimum negative \( C_3 \) imaging conditions are indicated by the solid white lines.

**Reference**

Independent chromatic and spherical aberration correction in PEEM using a hyperbolic triode mirror and an electrostatic lens

J. Fitzgerald, R. C. Word and R. Könenkamp

Physics Department, Portland State University, 1719 SW 10th Avenue, Portland, OR 97201, USA

Email: rkoe@pdx.edu

Several aberration-corrected LEEM/PEEM instruments are now in operation worldwide and efforts for their performance optimization are currently underway. An important issue for correctors based on electrostatic mirrors is the independent correction of spherical and chromatic aberration coefficients over a sufficient practical range. We present an analysis of an electrostatic triode mirror with one grounded and two controlled electrodes, combined with an electrostatic einzellens to allow for symmetric incident and outgoing beam paths. We show that this combination can correct spherical and chromatic aberration simultaneously and independently. Chromatic aberration can be compensated over a relative range of -40% to +100%, and spherical aberration over +/-100% range. We compare our analytic results with a numerical simulation and show that the two descriptions agree to within 5% in the relevant operating regime.

**Figure 1:** Interdependence of spherical and chromatic aberration in diode and triode mirrors of size $L$ (a)

Diode mirror: For a fixed mirror focal length, $z_0$, the aberration coefficients $C_S$ and $C_C$ are intimately coupled. (b) Adding another electrode to the mirror and allowing for concerted control with an electrostatic lens opens the line-graph in (a) to a surface allowing $C_S$ and $C_C$ to be varied independently.

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**Reference**

Differentiate between Fourier Optics and Contrast Transfer Function Approaches of LEEM Imaging

A. B. Pang$^{1,2}$, M. S. Altman$^2$, E. Bauer$^3$

$^1$School of Physics and Electronic Information, Huaibei Normal University, Huaibei, Anhui, 235000, PR China

$^2$Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, PR China

$^3$Department of Physics, Arizona State University, Tempe, Arizona 85287-1504, USA

Email: pangangbo@gmail.com

Both the Fourier optics approach and the Contrast Transfer Function method have been successfully developed to describe the image formation, investigate the contrast mechanism and optimize the resolution in LEEM theoretically [1, 2]. Here, we start with reviewing these two methods in respect of the fundamental ideas that build up the theories. The formulas in both methods incorporate the primary issues that affect the image formation, such as the inherent spherical aberration, the energy spread, the diffraction error from the aperture angle, and the source extension. Through the stepwise comparison between the two methods, we found that the substantial difference can be attributed to how we apprehend the nature of the electron source, i.e. the source with finite size and energy spread is coherent or not. For the line source that emits electrons from different positions rather than a single point, the superposition of all electron waves can be considered in two ways. One way is to add up the electron wave functions from each position first, and then compute the wave intensity with the resulted wave function. That means the wave is coherent in space. Another way is to compute the intensity of each wave first, and then add up all the intensities to obtain the final wave intensity. In this case, the wave is called spatially incoherent. For the energy spread of the electron beam, the superposition of electron waves is due to the waves propagating in succession but with different energy. Thus the problem can be handled similarly, and the wave is called temporal coherent or incoherent accordingly. The Fourier optics approach adopted the second way for the treatment of the source extension and energy spread, that is, to integrate the wave intensities originating from all the points or moments. While the CTF method used the first way, that is, to integrate the wave functions corresponding to different points or different moments. Whereas the above discrepancy leads to the diverse appearance of these two models, the simulated results do not diverge apparently with ordinary imaging parameters. Computed results indicated that significant discrepancy only arises at some extreme imaging conditions, such as the huge defocus.

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References
Introduction to A Flange-on Type Low Energy Electron Microscope (ELMITEC LEEM-IV)

G. H. Zhang¹, J. L. Sun¹, Y. L. Jin¹, K. Zang¹, F. Z. Guo¹²

¹Dalian Institute of Chemical Physics, Chinese Academy of Science, 457 Zhongshan Road, Dalian 116023, China
²Dalian Jiaotong University, 794 Huanghe Road, Dalian 116023, China

Email: zhanggh@dicp.ac.cn

Traditional LEEM/PEEM (low energy/photoemission electron microscope) is expensive and complicated to operate. In this work, we introduce a flange-on type LEEM/PEEM (Elmitec LEEM-IV). The 10º deflection angle of the electron beam splitter makes the electron illuminating lens and imaging lens compact enough to be integrated in one 10 inch flange. The flange-on system is mounting flexible and can be added to customized chambers. The simple construction also makes the lens easy to align for different modes. A most important feature of this type LEEM/PEEM is the grounded sample which makes external field application possible. Besides lateral resolution and typical modes test, surface plasmon enhanced photoemission with femtosecond laser as light source are also reported.

Figure 1. (a) A cross-section view of LEEM-IV mounted on a chamber. (b) PEEM image of an elongated lead island illuminated with 400 nm femtosecond laser.
Aberration Corrected PEEM at Shanghai Synchrotron Radiation Facility

F. Z. Guo\textsuperscript{1,2}, G.H. Zhang\textsuperscript{2}, J. L. Sun\textsuperscript{2}, K. Zang\textsuperscript{2}, Y. L. Jin\textsuperscript{2} and H. Ding\textsuperscript{3}

\textsuperscript{1}Dalian Jiaotong University, 794 Huanghe Road, Dalian 116023, China
\textsuperscript{2}Dalian Institute of Chemical Physics, Chinese Academy of Science, 457 Zhongshan Road, Dalian 116023, China
\textsuperscript{3}Institute of Physics, Chinese Academy of Science, 8 Nanshan Street, Zhongguancun, Beijing 100190, China

Email: guofz@hotmail.co.jp

An up-right designed ACPEEM (Aberration Corrected PhotoEmission Electron Microscope) will be installed at a super high energy resolution soft X-ray beamline in Shanghai Synchrotron Radiation Facility (SSRF). The soft X-ray energy ranges from 20eV to 2000eV, the polarizations can be changed to linear or circular. The electrostatic mirror will correct the spherical and chromatic aberration, and will guarantee quite high transmission at even high kinetic energy. The X-ACPEEM image lateral resolution is expected to be lower than 10 nm, while the energy resolution is below 0.15eV. Nano-XPS, Nano-ARPES and surface/interface magnetic domain structures are the main researches to be studied.
NanoESCA beamline at Elettra

C. M. Schneider¹,², C. Wiemann¹, M. Patt¹, V. Feyer¹,³

¹Peter Grünberg Institute (PGI-6) and JARA-FIT, Research Center Jülich, D-52425 Jülich, Germany
²Fakultät f. Physik and Center for Nanointegration Duisburg-Essen (CENIDE), Universität Duisburg-Essen, D-47048 Duisburg, Germany
³Sincrotrone Trieste, NanoESCA beamline, in Area Science Park, 34149 Basovizza, Trieste, Italy

Email: v.feyer@fz-juelich.de

A novel electrostatic PEEM (PhotoEmission Electron Microscope) named NanoESCA (FOCUS GmbH/Omicron) has been installed and commissioned on the second branch of the Nanospectroscopy beamline at Elettra synchrotron radiation facility [1]. The NanoESCA beamline is managed by an international consortium led by Prof. Dr. Claus Michael Schneider (Forschungszentrum Jülich). From January 2012 NanoESCA beamline is opened to Elettra general users.

The main focus of this instrument is the analysis of chemical and electronic states as well as magnetic characterization in complex and nanostructured material systems requiring electron spectroscopy. The NanoESCA is a unique instrument that combines a parallel imaging photoelectron emission microscope with an appropriate energy filter in the Imaging Double hemispherical Energy Analyser (IDEA) scheme [2]. The microscope places particular emphasis on spectroscopic aspects and enables laterally resolved photoelectron spectroscopy from the VUV to the soft x-ray regime. Additionally, a different mode of operation can be used which images the angular distribution of electrons by projecting the back focal plane. This reciprocal space spectromicroscopy in the valence band region (k-space PEEM or k-PEEM) is typically performed over selected areas of ~ 10 μm diameter as defined by the setting of an iris aperture.

The NanoESCA end-station [3] consists of a load-lock for fast sample introduction, a preparation chamber, a sample storage chamber, and an analyzer chamber (see Fig. 1). The preparation chamber is equipped with a manipulator heating stage (up to 1200 °C), LEED, an Auger analyzer, an ion sputtering gun, a mass spectrometer, a metal e-beam evaporator, a gas-inlet system and a number of optional ports for user owned sample preparation accessories. The liquid helium cooled sample manipulator of the analyzer chamber with five degrees of freedom is currently under test.

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References
Investigation wear-resistant thin film by X-ray Photoelectron Emission Microscopy

Pat Photongkam\textsuperscript{1}, Natthaphong Konkhunthot\textsuperscript{2}, Sarayut Tunmee\textsuperscript{1}, Chanan Euaruksakul\textsuperscript{1} and Pornwasa Wongpanya\textsuperscript{2}

\textsuperscript{1}Synchroton Light Research Institute, Muang District, Nakhon-Ratchasima, Thailand 30000
\textsuperscript{2}School of Metallurgical Engineering, Suranaree University of Technology, Muang District, Nakhon-Ratchasima, Thailand 30000

Email: pat@slri.or.th

The Elmitec LEEM/PEEM with energy analyzer installed at a VUV/soft X-ray undulator beamline of Siam Photon Laboratory has opened for general users from March 2011. By using synchrotron radiation together, it provided spectroscopic and sub-micron imaging obtaining information about the surface chemical composition and microstructure of matters. The instrument has been used by local researchers and industries in various areas, e.g. organic and inorganic thin film, biological tissue, droplet surface dynamics, and metallurgy. For metallurgy research, AISI H13 hot work tool steel is widely used for hot working of industries, especially in Thailand due to its toughness, wear and abrasion resistance. It is however, an application under exposure to lubricant and high temperature may result in corrosion and degradation of this material. Chromium nitride (CrN) coating shows enhanced hardness and good wear and corrosion resistance, as well as reduced adhesion to the molten or semisolid meta [1]. Diamond like carbon (DLC) coating also provide low friction coefficient and high chemical inertness [2]. In order to evaluate coating efficiency, XPEEM for µ-XAS is suitable to investigate specific area on coated surface. In this work, we present study of corrosion resistant CrN coated steel using XPEEM and preliminary work on DLC coated steel.

References

HAXPEEM: Bulk-Sensitive Photoemission Electron Microscopy

M. Escher¹, N.B. Weber¹, M. Merkel¹, C. Wiemann², M. Patt² and C.M. Schneider²

¹Focus GmbH, D-65510 Hünstetten, Germany
²Peter Grünberg Institute (PGI-6) and JARA-FIT, Research Centre Jülich, D-52425 Jülich, Germany

Email: m.escher@focus-gmbh.com

Hard x-ray photoemission spectroscopy (HAXPES) is already a well proven technique for bulk sensitive photoemission [1] due to the larger information depth of the high energetic electrons. To extend this technique for laterally structured samples, the NanoESCA [2], up to now used for imaging XPS, k-space imaging or workfunction mapping, has been upgraded to be used for hard x-ray photoemission electron microscopy (HAXPEEM) with kinetic energy up to 10keV [3].

For the high kinetic energy the extraction voltage has been raised to 24 keV to enable an easy sample biasing scheme. Image stacks or spectra can be acquired continuously from threshold photoemission towards 10keV. A simple model predicts the change of magnification with kinetic energy, that is confirmed by simulations. During an energy scan the focusing of the objective lens is maintained automatically using look-up tables and focusing parameters obtained using threshold imaging.

First results were obtained during a beamtime at PETRA III [3]. Figure 1(a) shows a checkerboard-patterned Au/Si sample imaged on the Au4f⁷/₂ core level electrons with a kinetic energy of 6.43keV. The image proofs the sub-micron resolution even at very high energy and for long acquisition time. Bulk sensitivity is demonstrated at the Si2p peak. Whereas the spectrum taken at hv=4.9keV (Fig. 1(b)) shows predominantly the elemental silicon signal and a shifted oxide peak, consistent with a native oxide layer of 10Å, the spectrum at hv=400eV acquired with the same sample and instrument at Elettra [4] is dominated by a mixture of different oxidation states of silicon, probably resulting from the non-prepared microstructured surface.

Figure 1. (a) Image of the Au/Si sample using Au4f⁷/₂ electrons at 6.43keV. The image acquisition time was 2 h. (b) Si 2p spectra for hard (hv=4.9keV, taken at PETRAIII, beamline P09 and soft x-ray excitation (hv=400eV, taken at the Elettra Nanospectroscopy-beamline).

References
Observation of the Side of the materials by PEEM-possibility for 3D PEEM

Kotaro Miyazaki\textsuperscript{1}, Iwai Takashige\textsuperscript{2}, Katsushige Tsuno\textsuperscript{1}, Kiyotaka Asakura\textsuperscript{1}

\textsuperscript{1}Catalysis Research Center, Hokkaido University, N21, W10, Kita-ku, Sapporo, Hokkaido, 001-0021, Japan

\textsuperscript{2}Suga co. Ltd, Oiwake, Hokuto-Shi, Hokkaido, 049-0101, Japan

Email: k-miyazaki@cat.hokudai.ac.jp

Introduction
We have developed a new type of PEEM with a tetrarode objective lens, the design of which allows us to install the diffraction aperture at the exact focal point immediately after the object lens.

Thus we can select the electron emitted toward a certain direction exactly. Since the metallic sample, the electron emitted largely in the perpendicular direction, contrast changes with the position of the aperture according to the inclination angle of the surface to the optical axis. It means the 3 dimensional observation will be possible by putting the aperture at the different two positions to detect the inclination angle. In this paper we successfully observe the right and left slopes just by changing the selection of electron by the aperture.

Experiment
We observed the gold mesh with the line width of 27 micrometers, and a square hole with 35 μm with a 62 μm pitch as shown in Figure.1. Fig.1 shows this grid having a flat top with slopes toward a hole by those both sides.

The aperture could be translated gradually till the aperture gave the brightest image of flat top. Then the aperture is shifted to the left hand side as shown in Figure.2 to select electron coming from the slope.

Result and Conclusion
When the aperture was shifted gradually from center to left, the PEEM images were changed as shown in Fig.3. When the aperture was put at the center, we could obtain the flat top picture. When the aperture was shifted to the left, we may have the bright slope picture. By moving the aperture, reversely to the right, we could observe the right side slope brightly. These results indicated that the 3 dimensional picture can be obtained by PEEM by selecting the certain directions.

Figure 1. SEM image of gold mesh sample

Figure 2. selection of focal point by aperture

Figure 3. When the aperture is made to slide to the left gradually, the PEEM image changes from the left to right.
Imaging of Free-standing Foils by Scanning Low Energy Electron Microscope (SLEEM)

Ilona Müllerová, Eliška Mikmeková

Institute of Scientific Instruments ASCR, v.v.i., Královořadská 147, 612 64 Brno, Czech Republic

Email: ilona@isibrno.cz

The cathode lens (CL) principle with negatively biased sample was used in the scanning electron microscope similarly as it is done in LEEM [1]. The anode of the CL is directly formed by the detector of reflected electrons, while another detector at the ground potential positioned below the specimen collects transmitted electrons [2]. Signal of transmitted electrons for graphene flakes was measured as a function of the landing energy and two maxima were observed. One of them exhibits normalized signal even larger than 100% at the electron energy 500 eV and then at the energy 5 eV, see Fig.1. This is explained by the increase of the secondary electron emission at these energies. The images formed by reflected and transmitted signals for graphene (Fig. 2a), for 3 nm thick foils of amorphous carbon and for free standing scandium foils are shown in Fig.2b and Fig. 2c, respectively. The increase of the transmitted signal from the amorphous carbon film is well visible in Fig.2b at 500 eV, too. Similar results were obtained for all tested materials.

Figure 1. Signal of transmitted electrons for graphene flakes measured in the most transparent areas. Signal is normalized to primary beam intensity (left) or to intensity at local maximum at 5 eV (right).

Figure 2. Graphene flakes (a); 3 nm thick foil of carbon (b); and scandium (c) imaged by SLEEM. Upper row: signal of reflected electrons, bottom row: signal of transmitted electrons. Incident electron energy is indicated.

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References

Polycrystalline Materials: Segregation and Diffusion of Impurities and Recrystallisation of Iron and Iron Nickel Alloys

Benjamin Borkenhagen\(^1\), Gerhard Lilienkamp\(^1\) and Winfried Daum\(^1\)

\(^1\)Institute of Energy Research and Physical Technologies, Clausthal University of Technologies, Leibnizstraße 4, 38678 Clausthal-Zellerfeld, Germany

Email: b.borkenhagen@pe.tu-clausthal.de

Surface properties of applied materials are frequently related to microstructural properties such as texture, grain boundaries and stacking faults in polycrystals. LEEM and \(\mu\)LEED enable us to characterize the surfaces of crystallites and their grain boundaries. In this contribution we report on our LEEM studies of segregation and diffusion processes at the surface of polycrystalline Fe and FeNi samples as well as of recrystallisations of entire crystallites.

During thermal treatment of the polycrystals, we observed formation of islands which consisted of bulk impurities segregated to the surfaces of the crystallites. Depending on temperature and surface orientation of the crystallites, different shapes of these islands were observed. At elevated temperatures Ostwald ripening of the impurity islands occurred. Increasing the temperature even more caused dissolution of these islands via diffusion into the bulk of the polycrystal. Linear and \(t^{1/2}\) time dependencies for the impurity concentrations were observed on different grains, pointing to different bulk concentration profiles.

We studied recrystallisations and their effects on surface topography in real time. By measuring triple point speeds and geometries of the grain boundaries the rate limiting step of the recrystallisation – grain boundary mobility or triple point mobility – was determined. Prior to the recrystallisations we noticed impurity segregation processes in the vicinity of the involved grain boundaries. The surface topography of the recrystallized grains exhibits residuals of previous grains and grain boundaries (fig. 1b).

![Figure 1. LEEM images of FeNi and Fe surfaces, respectively. (a) Stepped surface of a FeNi crystallite with segregated triangular or trapezoidal impurity islands. (b) Three Fe crystallites during a recrystallisation. Actual grain boundaries are marked with dashed lines, arrows indicate directions of the grain boundaries and their triple point. The former locations of the grain boundaries are memorized as surface grooves after recrystallisation.](image)
Scanning Low Energy Electron Microscopy of Polycrystalline Metals

Zuzana Pokorná¹, Šárka Mikmeková¹, Luděk Frank¹

¹Institute of Scientific Instruments of the ASCR v.v.i., Královopolská 147, 61264 Brno, Czech Republic

Email: zuzana.pokorna@isibrno.cz

Scanning Low Energy Electron Microscopy (SLEEM) is a technique which allows observing samples in a scanning regime using electrons of arbitrarily low incident energy [1]. This technique uses the Cathode Lens, preserving the good lateral resolution of SEM even to the energies of units of electronvolts. Due to the electrostatic field between the negatively biased sample and the grounded detector of Back-Scattered Electrons, signal electrons from a wide range of angles are drawn to the detector.

This work was concerned with the observation of various polycrystalline and single crystal metals, such as aluminium, copper and various types of steels. It was shown that in the incident electron energy between 0 and 45 eV, the intensity of the reflected electron signal from these samples uniquely corresponds to the crystallographic orientation of the sample (Fig. 1a). In a polycrystalline sample, this results in the differently oriented grains exhibiting different apparent brightness which changes with the incident electron energy [2]. This allows making areas with different orientation readily visible with a very good lateral resolution, and allows to estimate their orientation. It was also shown that in metal samples with a high internal stress, the intensity of the reflected electron signal at low incident energies is varied, as shown in Fig. 1b.

Figure 1a (left) illustrates the electron reflectivity spectra in the energy range between 0 and 45 eV for three different orientations of aluminium single crystals. Highly varied brightness of the grains in Fig. 1b (right) (taken at 500 eV) is due to high stresses in the sample. The material is X210Cr12 steel heated to a semi-solid state at 1265 C and then deformed 2:1 at 800 C prior to cooling in LN2.

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