SYNCHROTRON THAILAND CENTRAL LAB

PHOTOEMISSION ELECTRON MICROSCOPY

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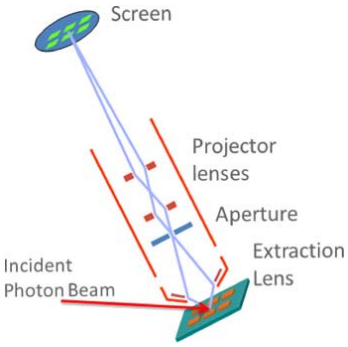
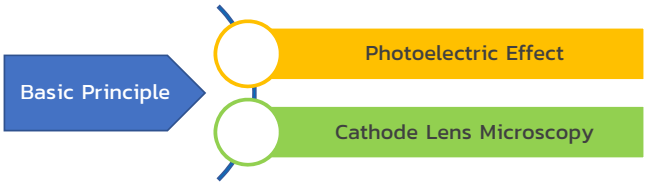
Photoemission Electron Microscopy (PEEM)

Introduction



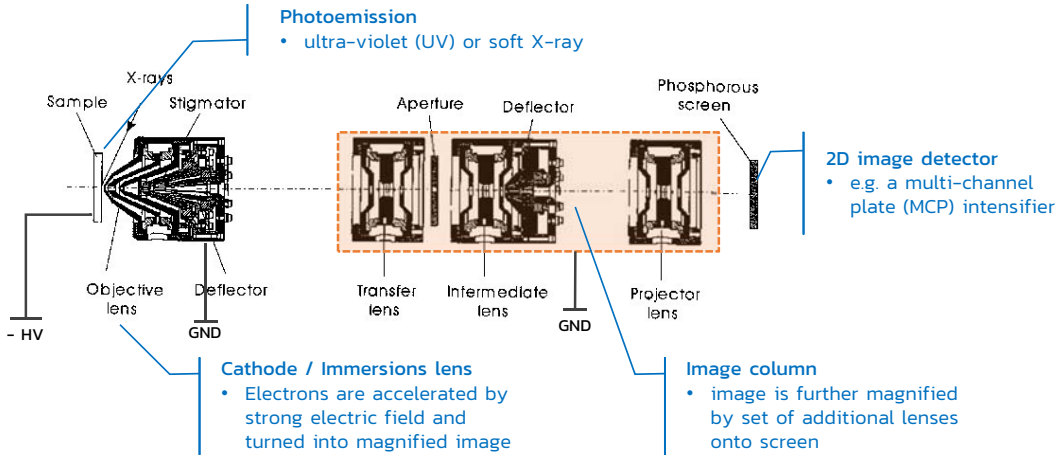
- PEEM is the full field imaging that utilizes emitted electrons from specimen absorbing photon energy to generate image of its surface



- Synchrotron radiation based PEEM (SR-PEEM) is spectro-microscopic technique with chemical, magnetic and electronic structure sensitivities, based on well known spectroscopic methods of
  - X-ray absorption spectroscopy (XAS)
  - Photoemission Spectroscopy (PES)

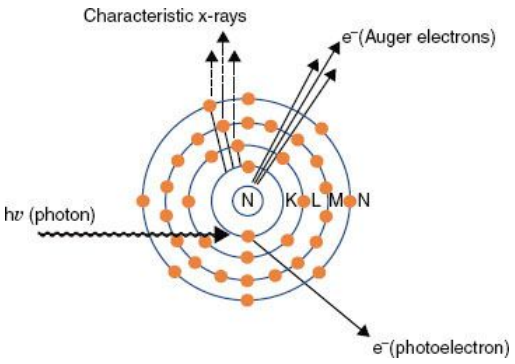
Photoemission Electron Microscopy

Operating Principle



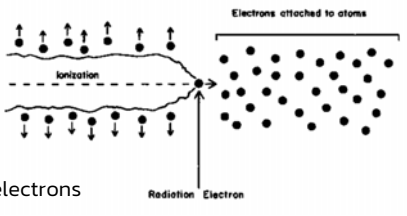
Photoelectric Effect

- In photoelectric effect, electrons are ejected from atom by which photon energy is completely absorbed upon exposure to electromagnetic radiation. (dominant for hv ≤ 50 keV)

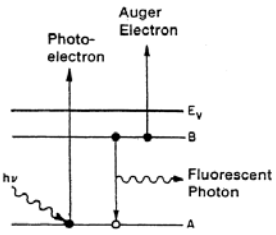


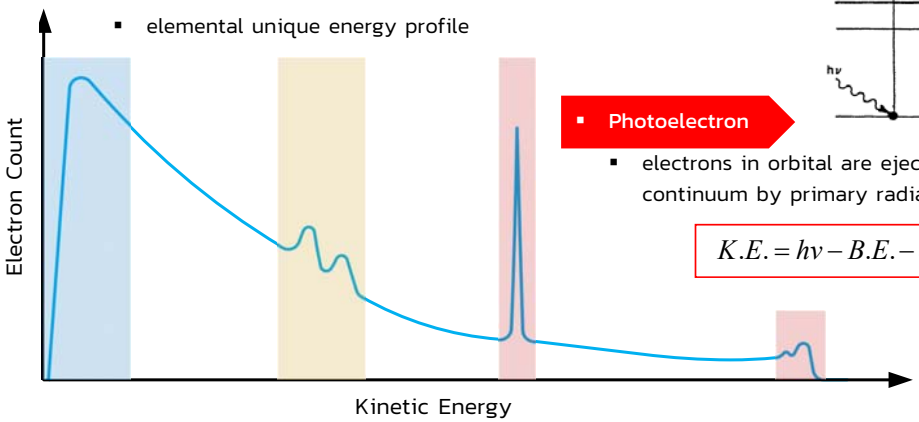
- **The intensity of emitted electrons is responsive to**
  - photon energy and flux
  - chemical, electronic and local structure
- **The energy of emitted electron depends on their origin which is**
  - Photoelectrons
  - Auger electrons
  - Secondary electron

Photoelectric Effect



- **Secondary electron**
  - generated by energetic electrons interact to other electrons
  - sensitive to electron transition & scattering of photoelectron wave
- **Auger electrons**
  - electrons in orbital are ejected by secondary radiation
  - elemental unique energy profile



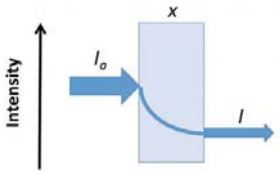


- **Photoelectron**
  - electrons in orbital are ejected to continuum by primary radiation

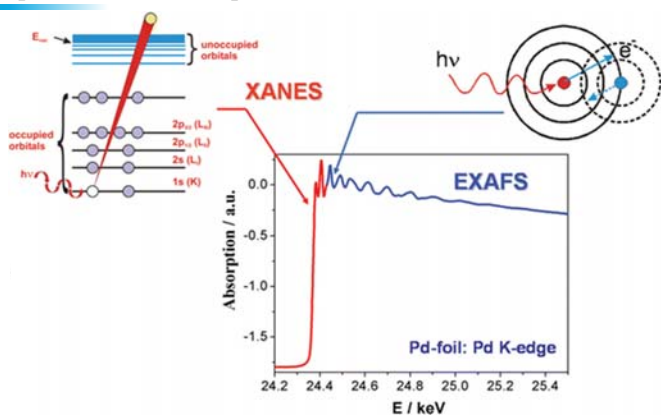
$$K.E. = h\nu - B.E. - \varphi$$

X-ray Absorption Spectroscopy (XAS)

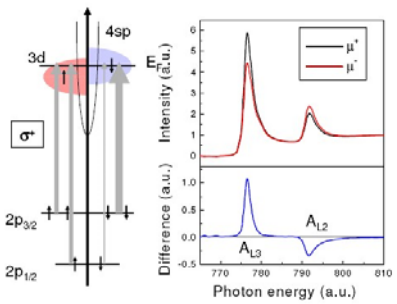
- an element specific characterization for electronic structure and local geometric of matter



$$I = I_0 e^{-\mu(E)\cdot x}$$

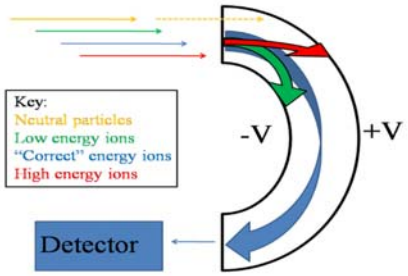


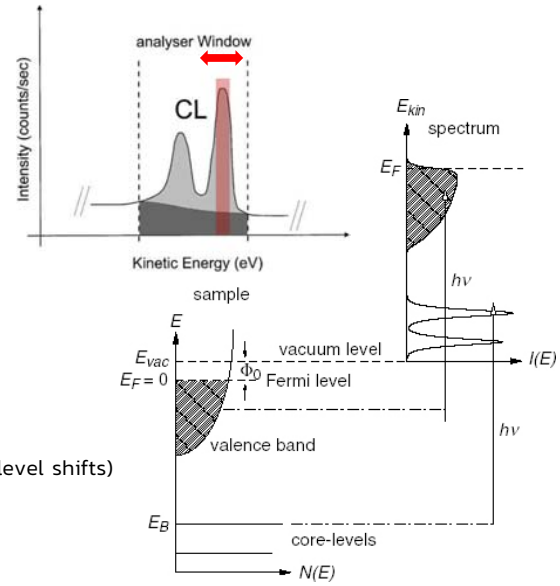
- The measurement of linear absorption coefficient as function of photon energy is sensitive to
  - Element and chemical state
  - Valence state, bond orientation, nearest-neighbour
  - Final state
  - Magnetic order



Photoemission Spectroscopy (PES)

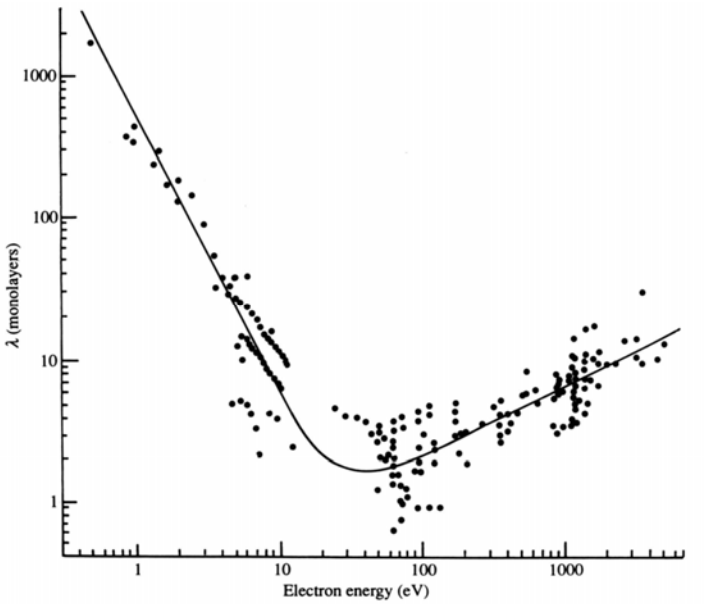
- In PES, it measures the energy distribution of the photoemitted electron from the specimen





- Features
  - highest surface sensitivity
  - Elemental and chemical sensitivity (core level shifts)
  - electronic structure sensitivity

Inelastic Mean Free Path



Electron Inelastic Mean Free Path ("universal curve")

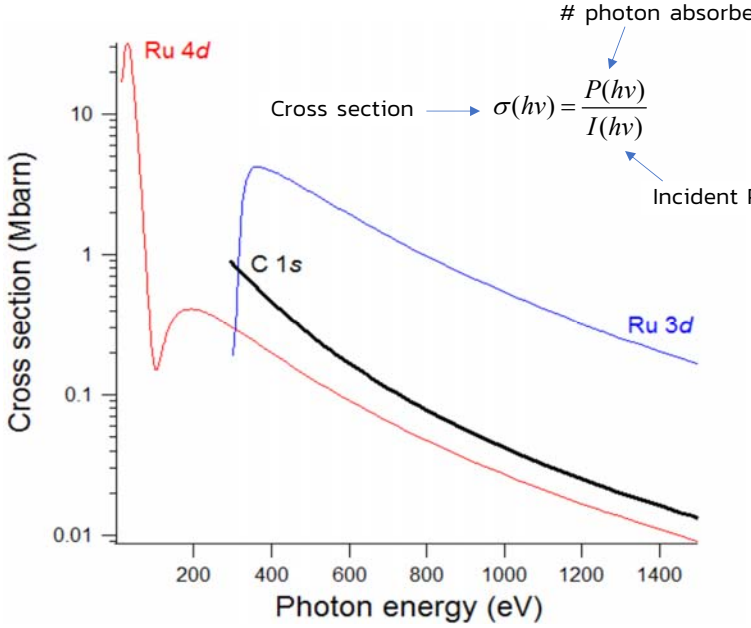
an index of how far an electron on average travels through matter before losing energy

Photoionization cross section

photon absorbed per unit time

Cross section $\sigma(h\nu) = \frac{P(h\nu)}{I(h\nu)}$

Incident Photon Flux



The probability per unit area, per unit time that a photon of a given energy can be absorbed by an atom to excite the photoelectrons.

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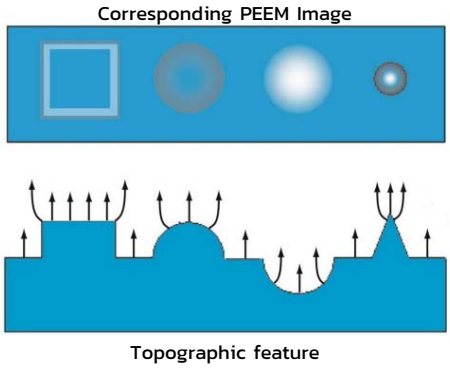
Photoemission Electron Microscopy (PEEM)

Contrast mechanism in PEEM

- Image contrast in PEEM arise from the variation in electron emission which is sensitive to surface topography, chemical state, magnetic order and electronic structure

1. Topographic contrast

- electron deflection due to roughness and structure surface



2. Work function contrast

Sub ML quantities of Cu on Si(100)

Pentacene Molecules on Si

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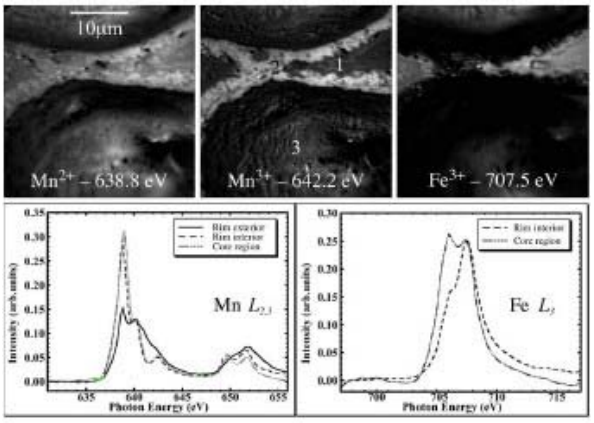
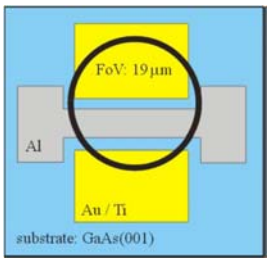
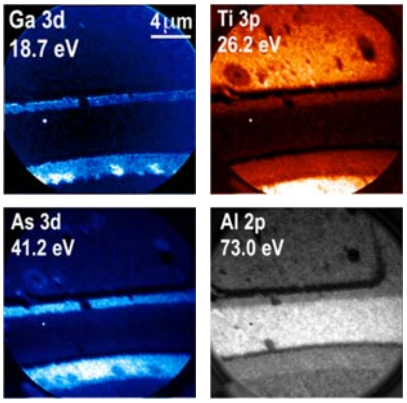
Photoemission Electron Microscopy (PEEM)

Contrast mechanism in PEEM

3. Chemical contrast







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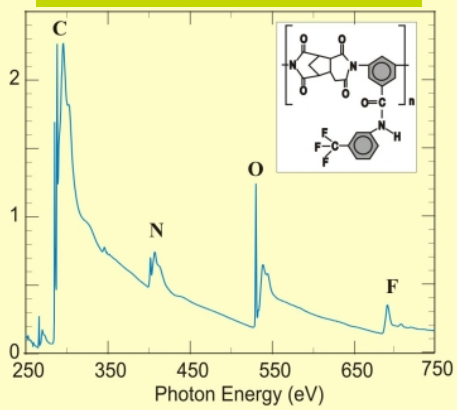
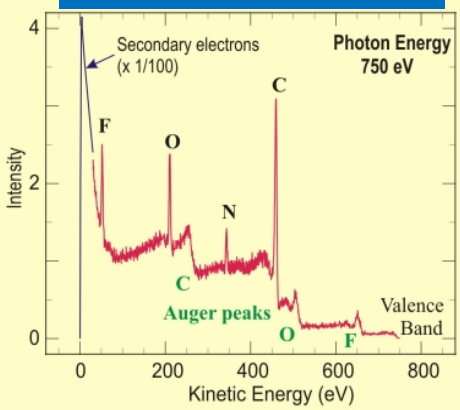
XAS and PES with SR-PEEM

X-ray Absorption Spectroscopy



Photoemission Spectroscopy



- XAS can be implemented by measuring intensity of secondary electron yield from the image as a function of photon energy
- PES requires energy analyser/filter to implement by these following methods
  i. measuring intensity of image as function of electron energy
  ii. Imaging on energy dispersion plane at exit of analyser

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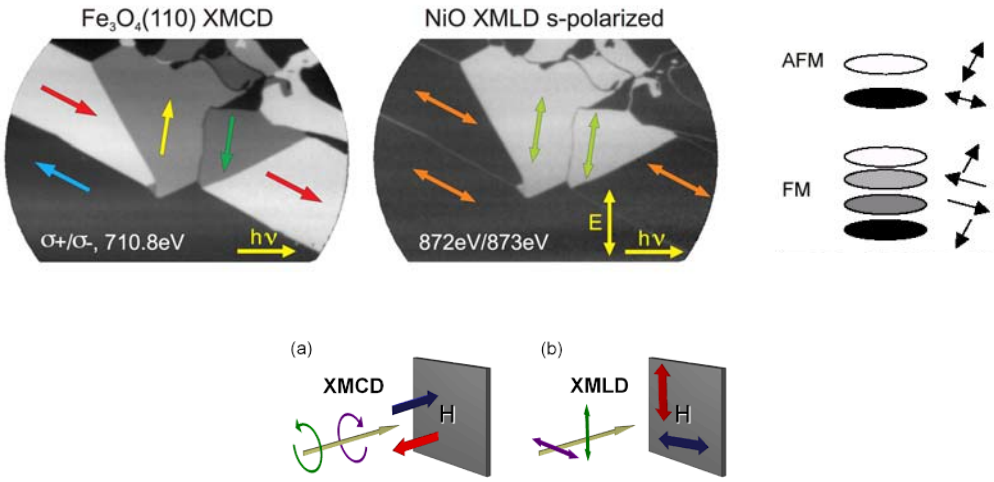
Photoemission Electron Microscopy (PEEM)

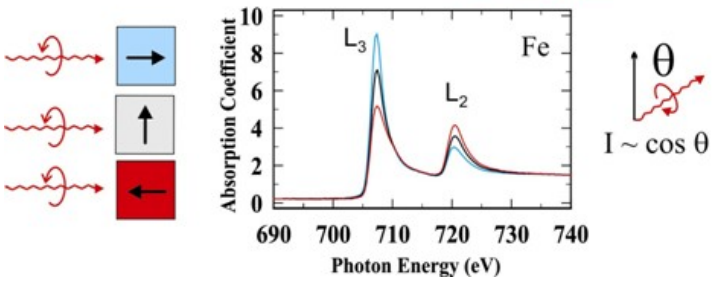
Contrast mechanism in PEEM

4. Magnetic contrast

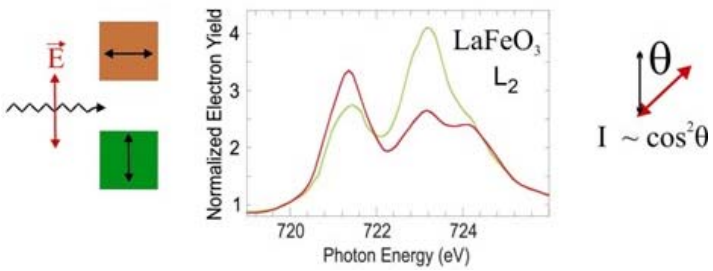


XMCD & XMLD

X-ray Magnetic Circular Dichroism (XMCD): Ferromagnetism

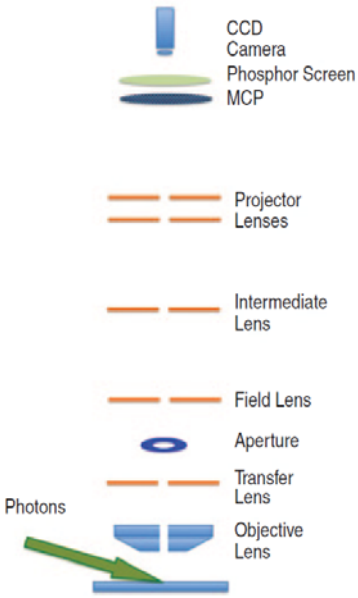


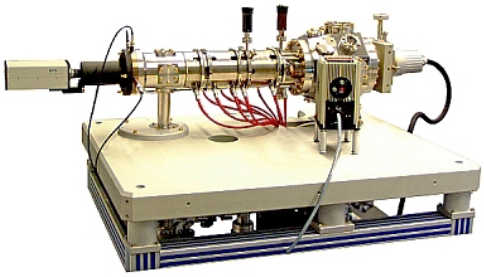
X-ray Magnetic Linear Dichroism (XMCD): Anti-ferromagnetism



PEEM Instrument

Standard PEEM

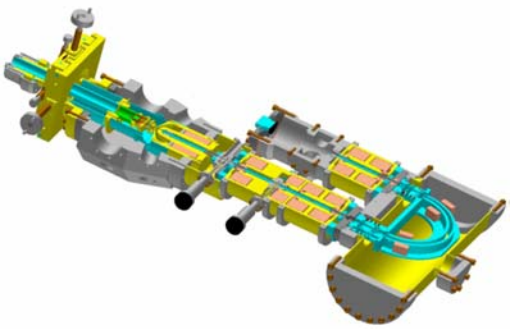


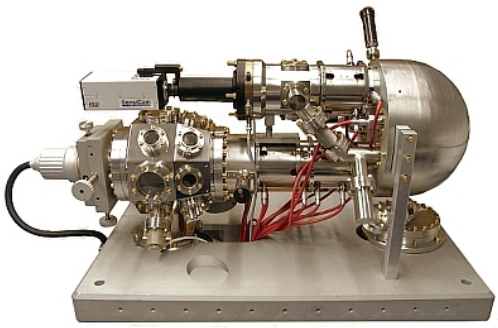


PEEM Instrument

PEEM with imaging energy analyzer

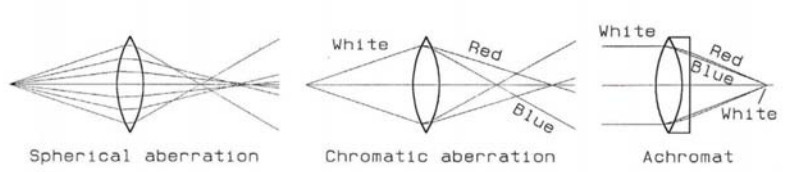
- Elmitec PEEM III

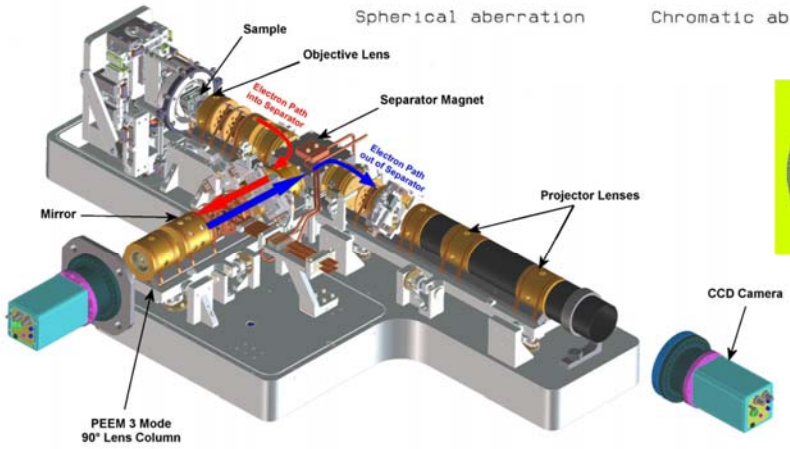


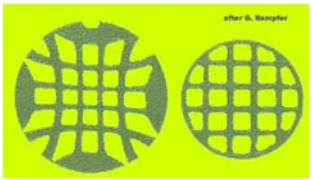


PEEM Instrument

PEEM with Aberration Correction

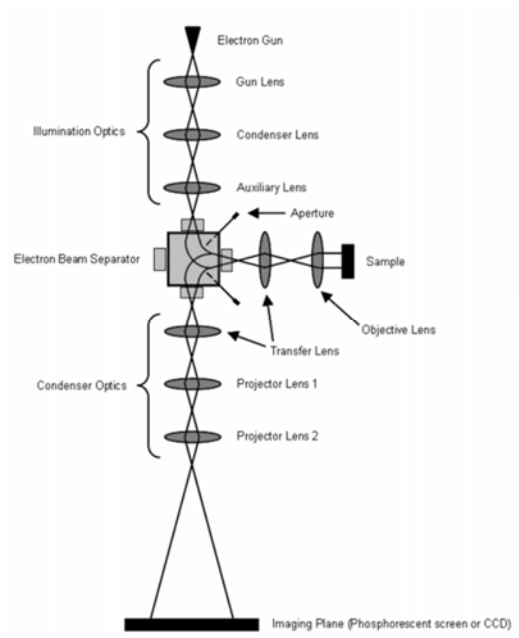


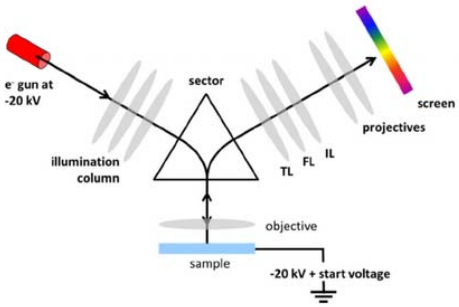


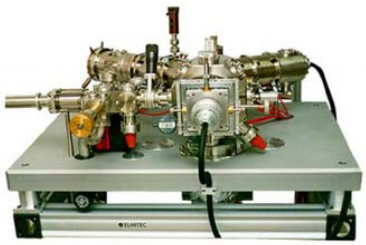


PEEM Instrument

Low Energy Electron Microscope

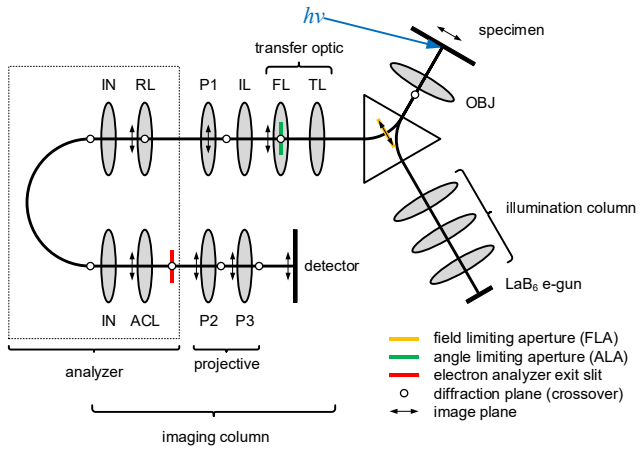


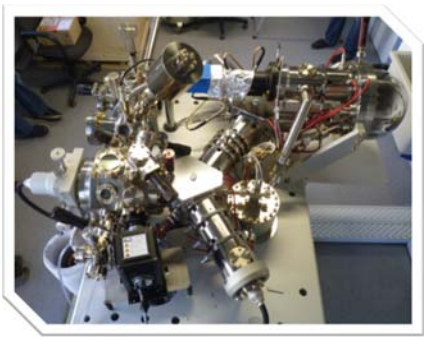




PEEM Instrument

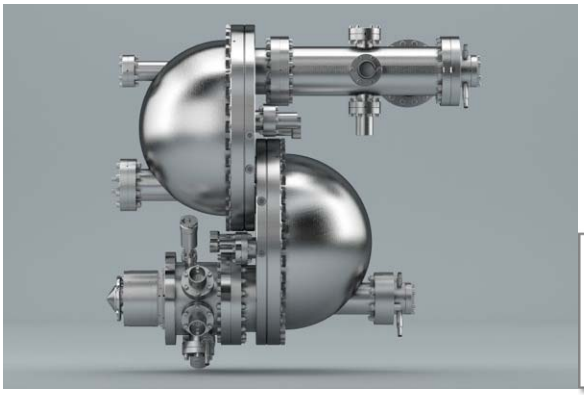
SPELEEM

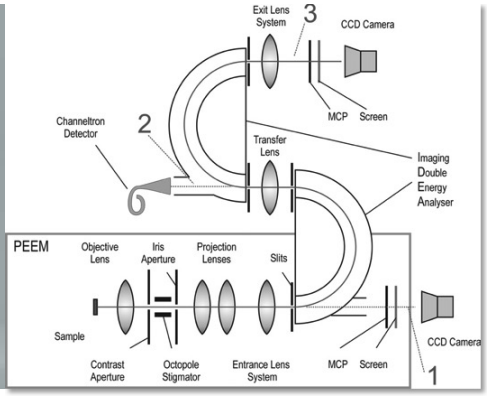




PEEM Instrument

NanoESCA

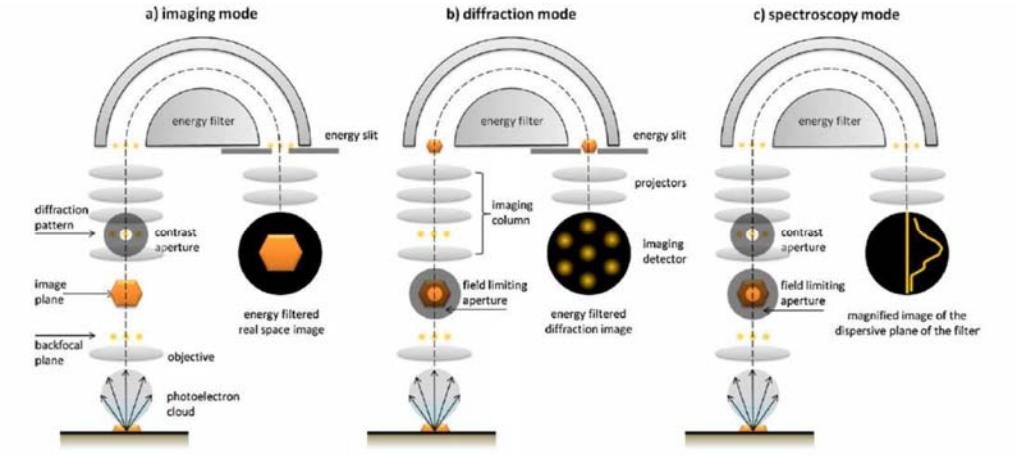




Photoemission Electron Microscopy (PEEM)

PEEM Operation Mode in SPELEEM

Spectroscopic Imaging | Microprobe diffraction | Microprobe-spectroscopy



Real space	Reciprocal space	Energy dispersion
(image plane)	*(diffraction plane)*	*(dispersive plane)*
X-PEEM, EF-PEEM	PED / μ-ARPES	PED / μ-ARPES

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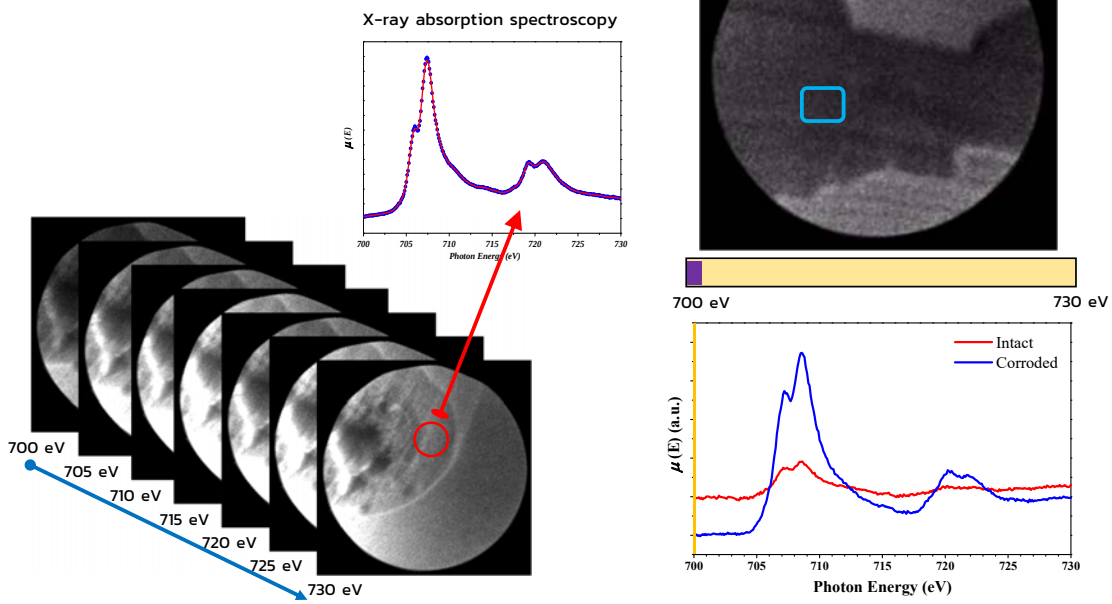
Application of PEEM

Spectroscopic Imaging



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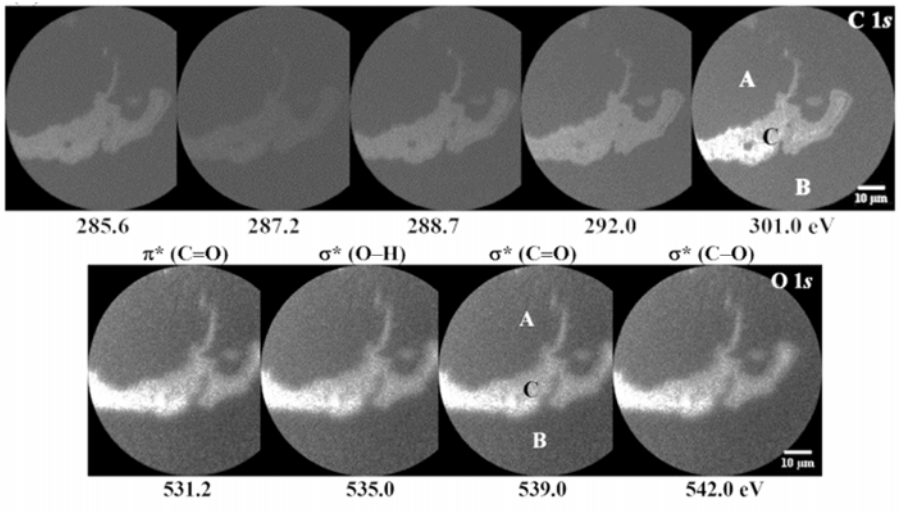
Application of PEEM

Spectroscopic Imaging

Investigation of pitting corrosion of diamond-like carbon films
using synchrotron based spectromicroscopy



Sarayut Tunmee, et.al, Journal of Applied Physics 120, 195303 (2016)

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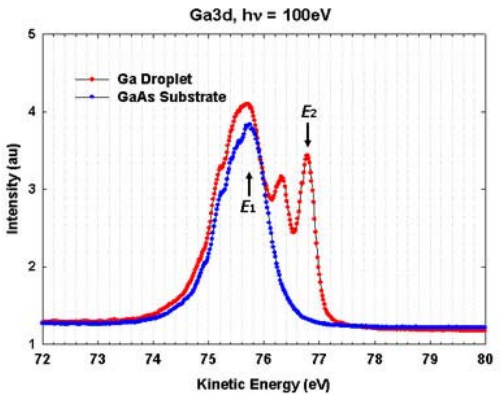
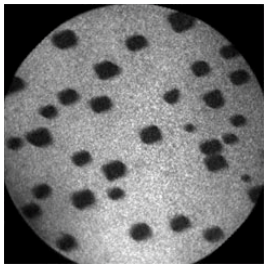
Application of PEEM

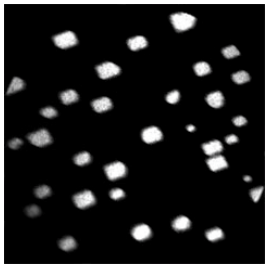
Energy Filter PEEM

- Photon Energy = 100eV
- FOV = 20μm
- Energy Slit = 25μm
- Contrast aperture = 30μm



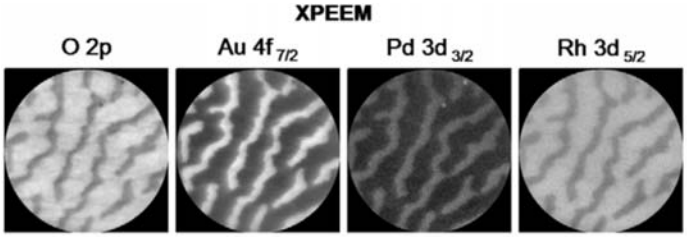


K.E = 75.6eV



K.E = 76.8eV

XPEEM



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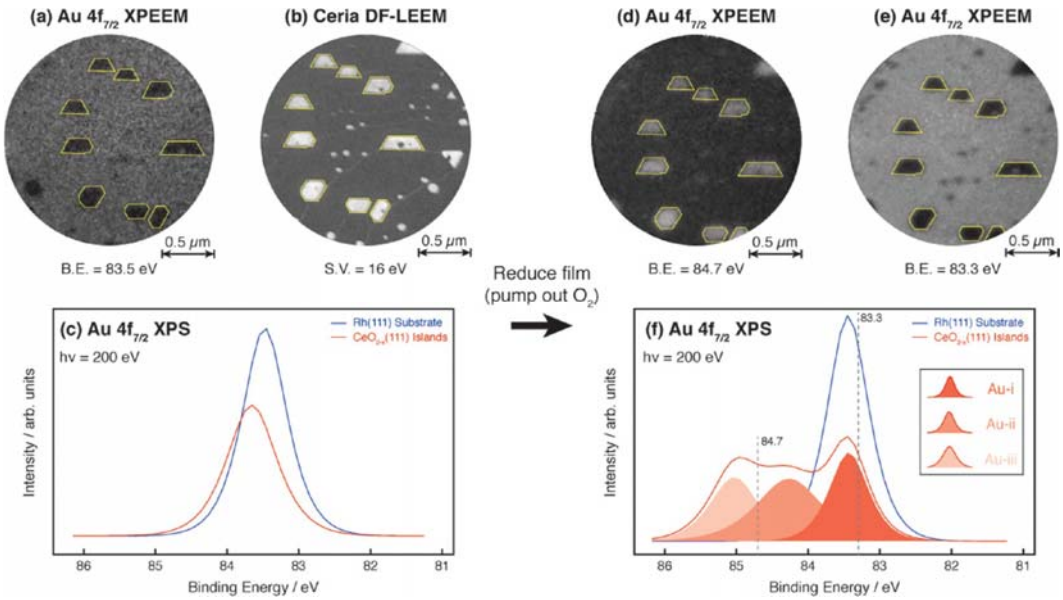
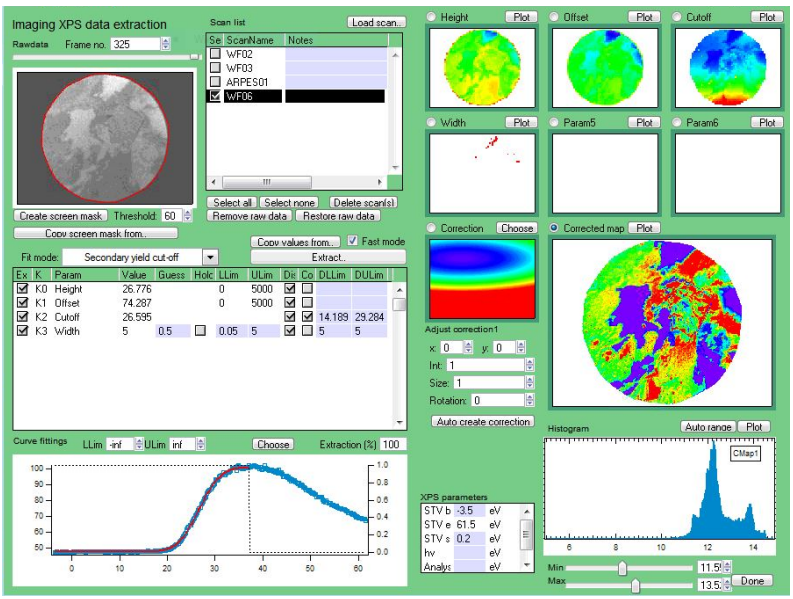
Application of PEEM

Energy Filter PEEM



Application of PEEM

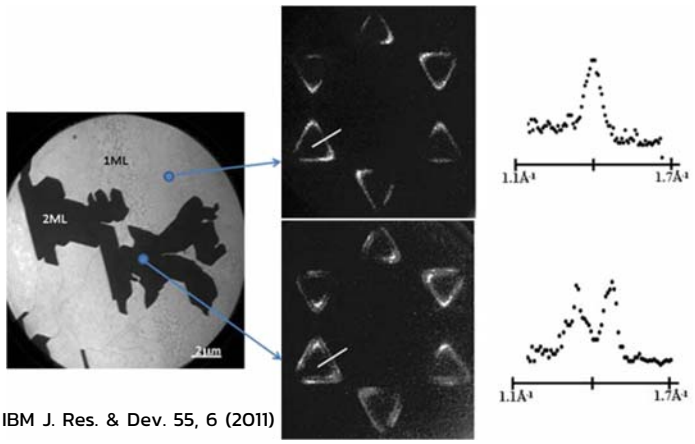
Work Function Mapping



Application of PEEM

Microprobe diffraction

1ML Graphene with 2ML islands grown on SiC (0001)



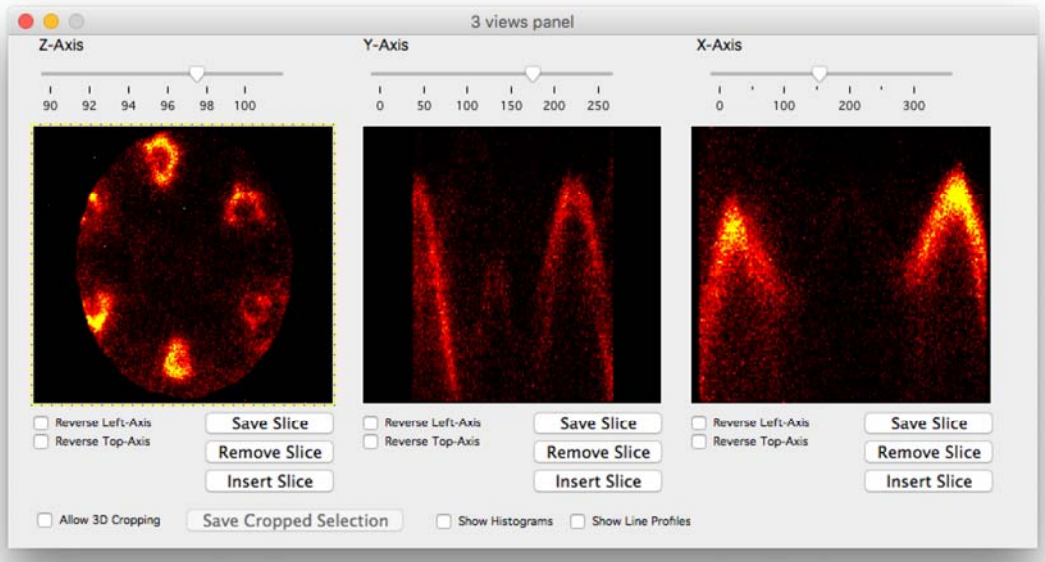
IBM J. Res. & Dev. 55, 6 (2011)

hv = 35eV, E_{bin} = 2.5eV.

The PED (μARPES) taken from 1 ML Grahpene and 2ML islands are shown on the right. High energy resolution 2-D (k_x,k_y) maps for 1-ML and 2-ML graphene taken at an electron binding energy of 2.5 eV below the Fermi level. 2π-bands are clearly seen from the two-ML island. The profile of π-bands also illustrates the resolution of PED in k-space.

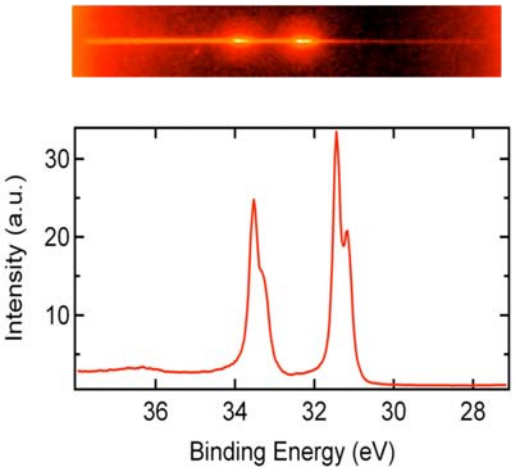
Application of PEEM

Microprobe diffraction

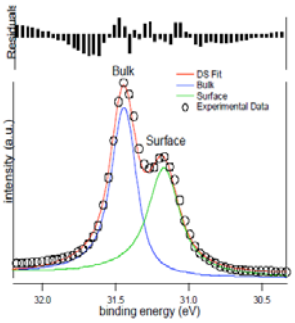


Application of PEEM

microprobe PES

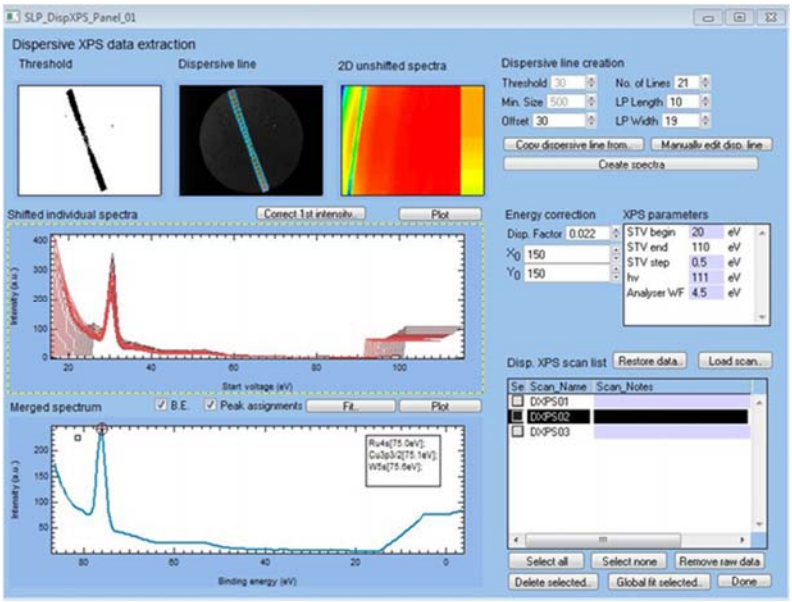


- W{110} clean surface
- W 4f core level
- Photon energy = 131 eV



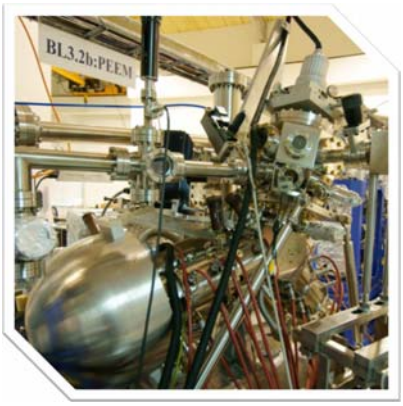
Application of PEEM

microprobe PES



BL3.2Ub: PEEM at SLRI

Photoemission Electron Microscopy (PEEM)



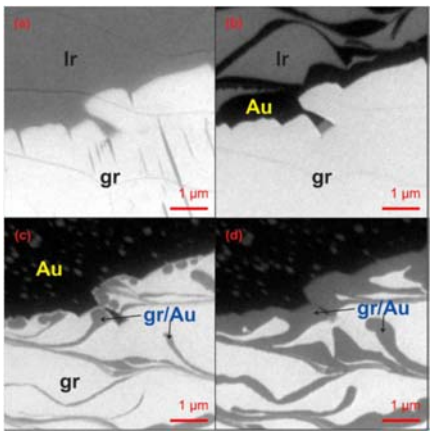
Technical information	
source	planar halbach-type undulator (U60) 41 periods. 0.5467 Tesla at gap 26.5mm
monochromator & energy range	varied line spacing plane grating 40-160eV and 220-1040eV
energy resolution & flux	$\Delta E/E = 10^{-5}$ at 100eV flux: 10^{10} photons/sec
beam size (HxV)	0.8 mm x 0.1 mm
end station	Elmitec SPELEEM
Technique	XAS, PES, APRES MEM, LEEM, LEED

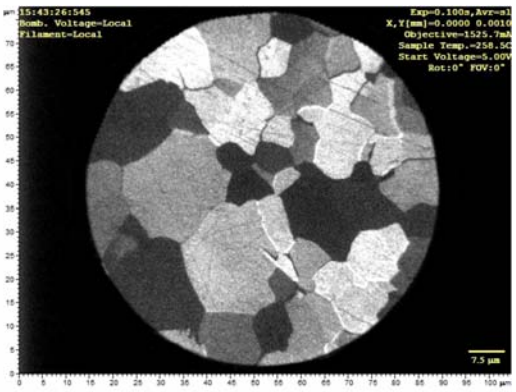
- Photon polarization of this beamline is horizontally linear – **therefore it is NOT possible for XMCD, XMLD, and magnetic contrast imaging**
- End station is also equipped with ion sputtering gun and residual gas analyser

Low Energy Electron Microscopy

Introduction

- LEEM is a cathode lens microscopy technique which probes surfaces and interfaces with low energy electrons, using the elastically backscattered beam for imaging.
- LEEM is particularly well suited to monitor dynamic processes, such as surface reconstructions, epitaxial growth, step dynamics, self-organization



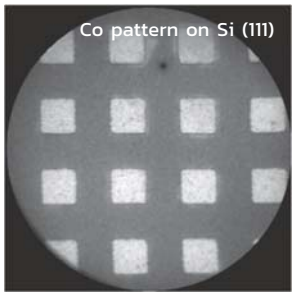


Low Energy Electron Microscopy

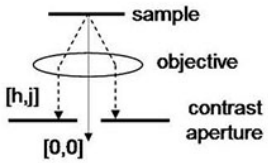
Contrast mechanism in LEEM

- Different contrast mechanisms are available for structure characterization

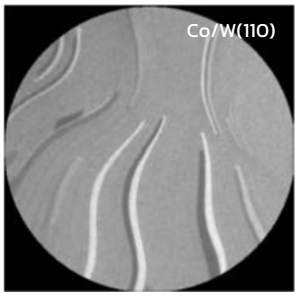
SURFACE STRUCTURE



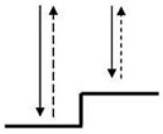
diffraction contrast



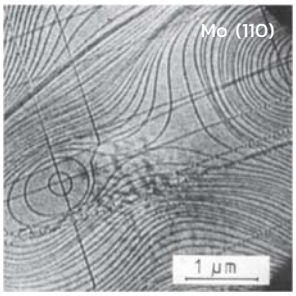
FILM THICKNESS



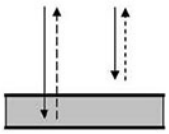
quantum size contrast



STEP MORPHOLOGY



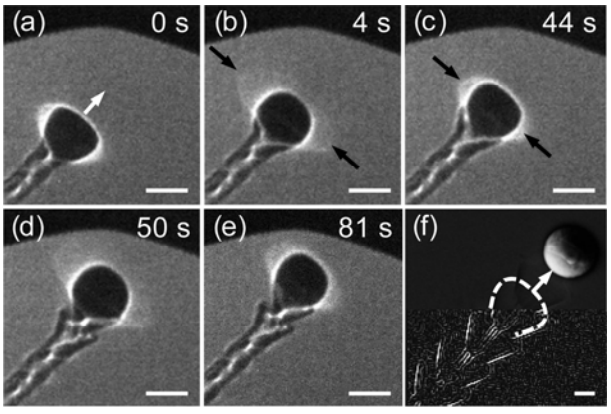
geometric phase contrast



LEEM Operation Mode

Mirror Electron Microscopy (MEM)

Self-Running Ga Droplets on GaAs (111)A



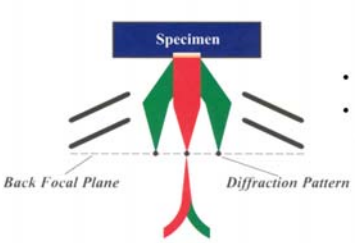
Snapshots from the MEM video showing a Ga droplet making two stick-slip cycles. The droplet appears as a dark region surrounded by bright caustic features (black arrows in b and c). (f) SEM image of a droplet with faceted trail (lower half digitally enhanced to hi-light the edges). White dash superimposed on the trail in f is the perimeter of the droplet in a.

The scale bars are 2 µm.

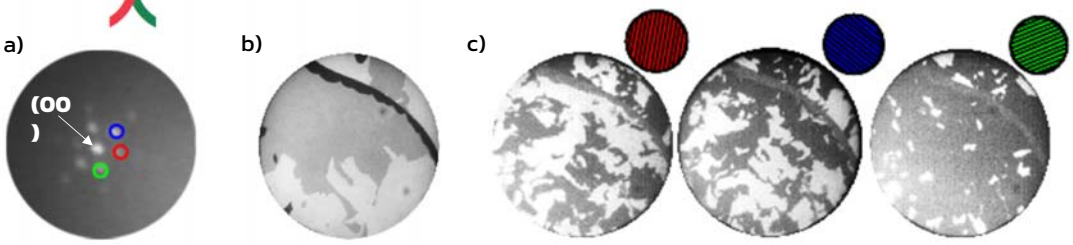
Kanjanachuchai, S. and Euaruksakul, C.
ACS Applied Materials & Interfaces 5 (2013): 7709-7713.

LEEM Operation Mode

LEEM – Bright Field and Dark Field



- The bright field imaging uses (00) or specular beam to form an image
- The dark field imaging does not but select a desired diffraction spot and use a contrast aperture to pass only those electrons, specially useful for identifying the spatial distributions of coexisting phases



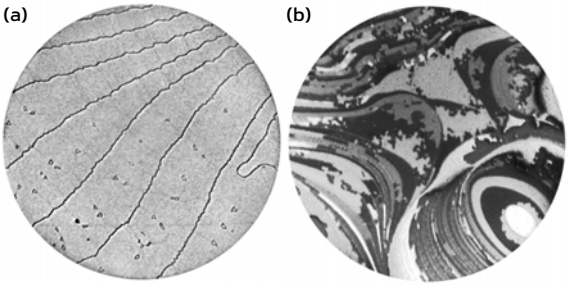
LEED BF LEEM DF LEEM

Microstructure of a 2 ML Cu film on Ru(0001) a) LEED pattern arising from the superposition of three rotational domains b) bright-field image showing the distribution of the two different layer stacking sequences (light and medium grey) c) LEEM dark-field images from three different diffraction spots

F.E. Gabaly, W. Ling, K. McCarty, J. de la Figuera, Science 308, 1303 (2005)

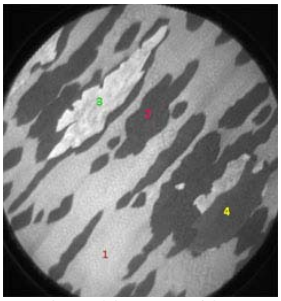
LEEM Operation Mode

LEEM – Phase Contrast

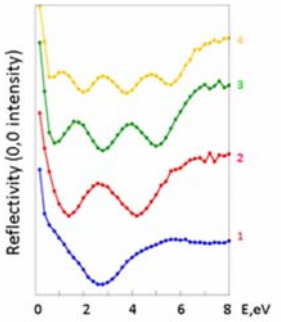


(a) LEEM Step phase contrast on the Si(111) (7x7) surface. The imaging energy is 42.5 eV. The field of view is 6 μm.

(b) LEEM quantum size phase contrast in a Cu film on a W(110) surface. The imaging energy is 8.4 eV. The image field of view is 6 μm.



FOV = 20μm, E = 1.6eV



Atomic layer of graphene

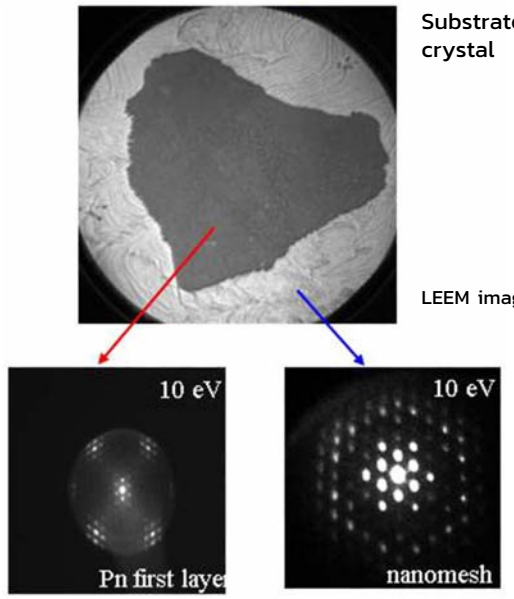
LEEM image shows a strong contrast due to graphene different thickness 1-4 monolayers. The electron reflective intensity change as function of electron energy and film thickness

C. Virojanadara, M. Syväjärvi,, R. Yakimova, L. I. Johansson, A. A. Zakharov, T. Balasubramanian, Phys. Rev. B 78, 245403 (2008)

LEEM Operation Mode

Low Energy Electron Diffraction (LEED)

Epitaxial grown pentacene on the h-BN nanomesh



Substrate: BN nanomesh grown on Rh(111) crystal

LEEM image: FOV=20μm, E = 3.4 eV

LEED pattern of pentacene 1st layer comparing to the substrate

Summary

- SR-PEEM or X-PEEM is widely used technique in synchrotron facilities for imaging a surface of materials with chemical, magnetic and electronic structure sensitivity.
- It is surface sensitive spectro-microscopy based on X-ray absorption (XAS) and photoemission spectroscopy (PES)
- UV and soft X-ray is usual source for X-PEEM. Hard x-ray is possible but photoionization cross section is much lower at high photon energy
- The sample for PEEM should be smooth and flat – to minimize topographic effect and to enhance lateral resolution.
- Switchable photon polarization make X-PEEM become more powerful – magnetic properties study