When Organics Meet Ferromagnets

-- insights from X-ray spectromicroscopy --

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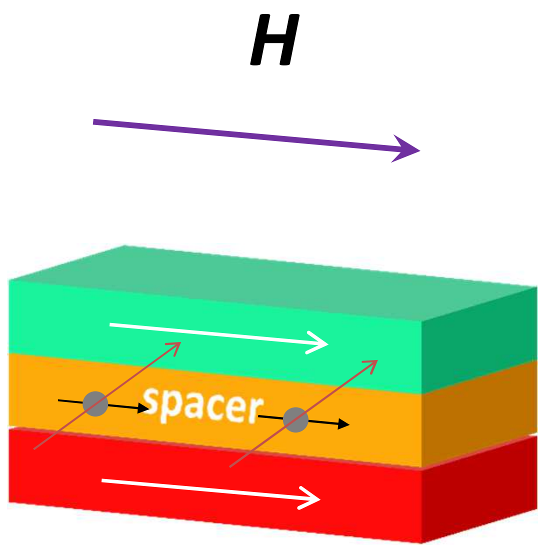
Plan of presentation

- Why organic-ferromagnet hybrid structure?
- Why study interface?
- Synchrotron-based X-ray spectromicroscopy
- Experimental results
- Insights learned
- Soft X-ray Nanoscopy Project for TPS at NSRRC

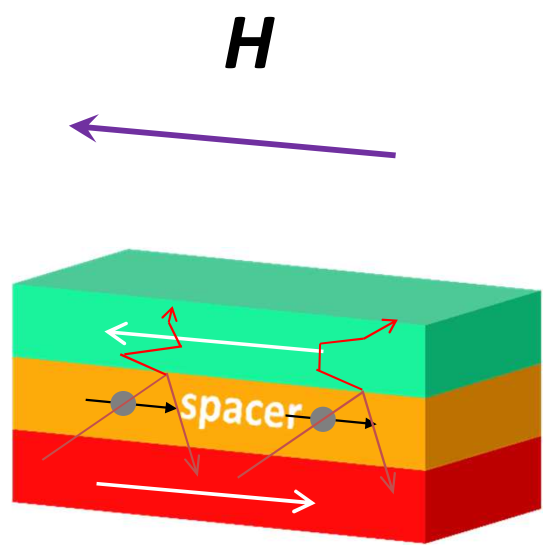

IBM
Blue Gene/P

- Artificial structures for TWO distinct states

organic spin valve ?

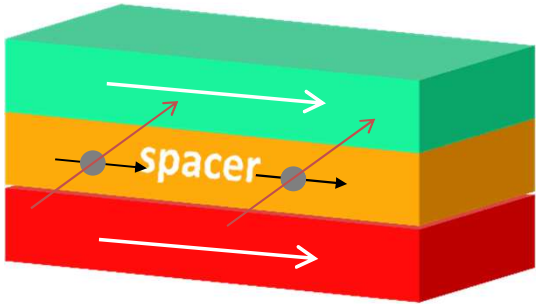


Low resistance
(parallel)



High resistance
(anti-parallel)

Why a non-magnetic spacer



Roles of the spacer (metal, semiconductor, insulator)

-- switch magnetizations independently

(thick spacer is preferred)

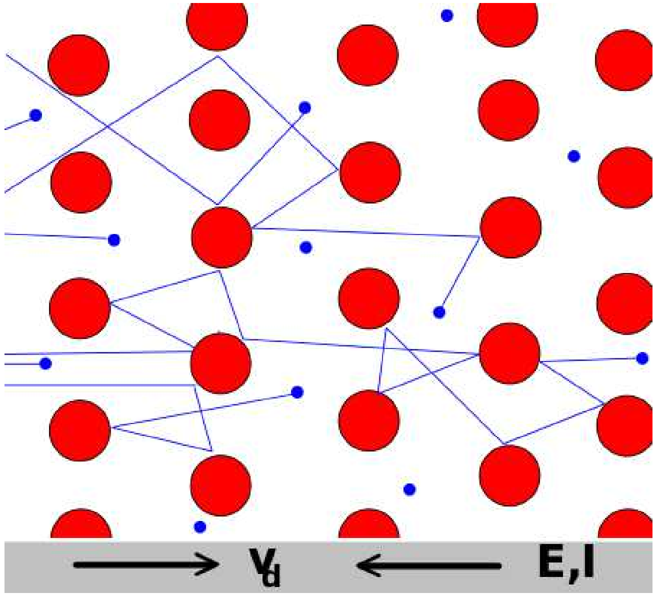
Trade off

-- lost a certain percentage of spin coherence (why?)

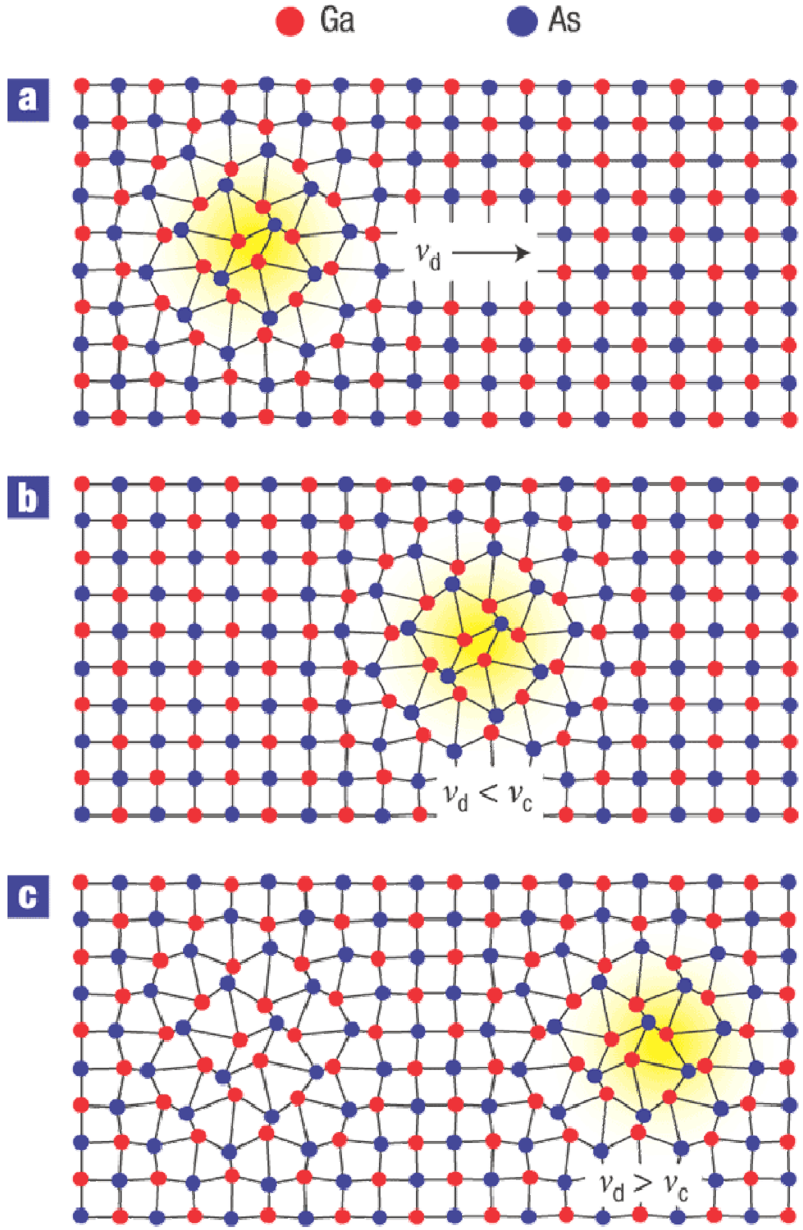
(thin spacer is better)

Metals vs dielectric materials

Charge



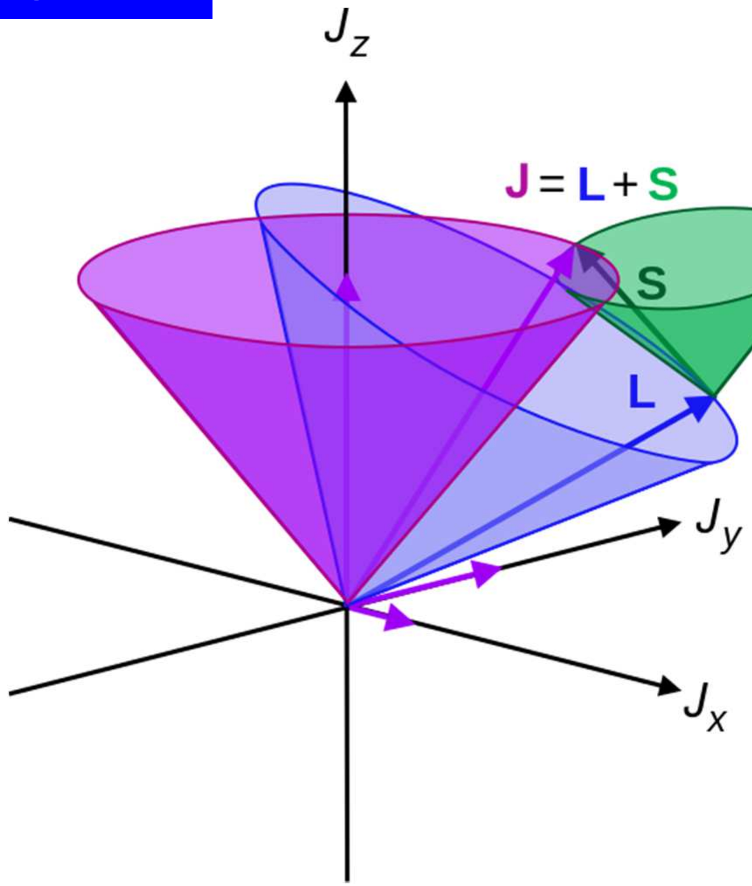
Metal
Free electron
(Drude model)



Semiconductor, polaron

Spin-orbit interaction

Spin



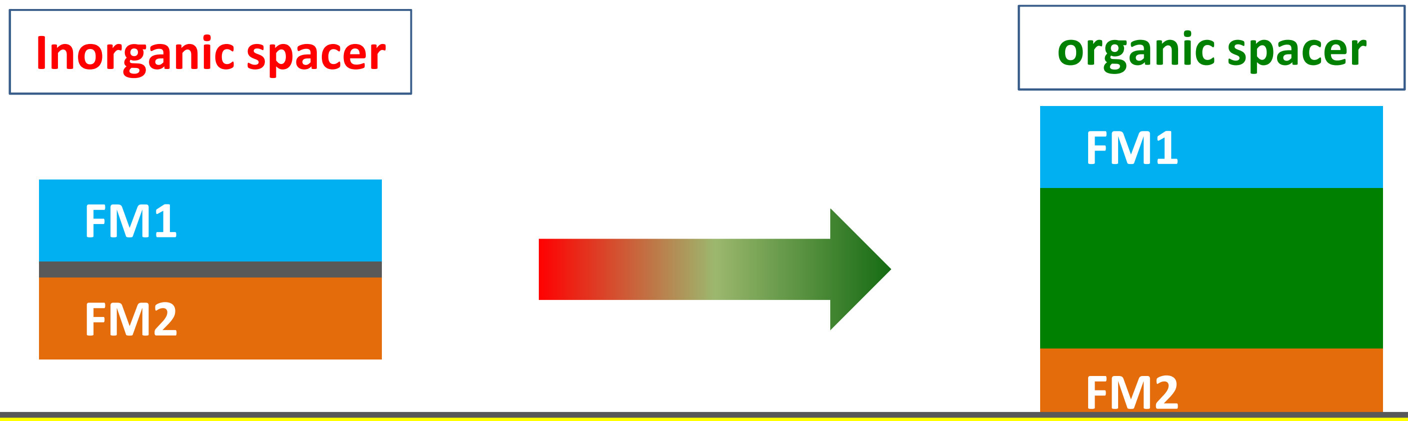
$$H_{SO} = \zeta_{SO} L \cdot S \propto Z^4$$

Copper	(Cu),	Z = 29
Gold	(Au),	Z = 79
Silicon	(Si),	Z = 13
Gallium	(Ga),	Z = 31
Arsenic	(As),	Z = 33
Carbon	**(C),**	**Z = 6**

- Energy of SOI : $10^{-1} – 10^{-3}$ eV
- Give relatively **small** impact to the shape of band structure
- Show its **greatest** impact on electrons close to Fermi level

❐ Scenarios faced:

- applications: *ride with the advances of organic electronics*
- physical properties: *extended spin coherence life time*
- fabrication: *less demanded process, reduced cost*



Puzzle:

What happens when FM electrodes meet organics?

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Interface is one of the key players

Control of charge and spin degree of freedom

↓

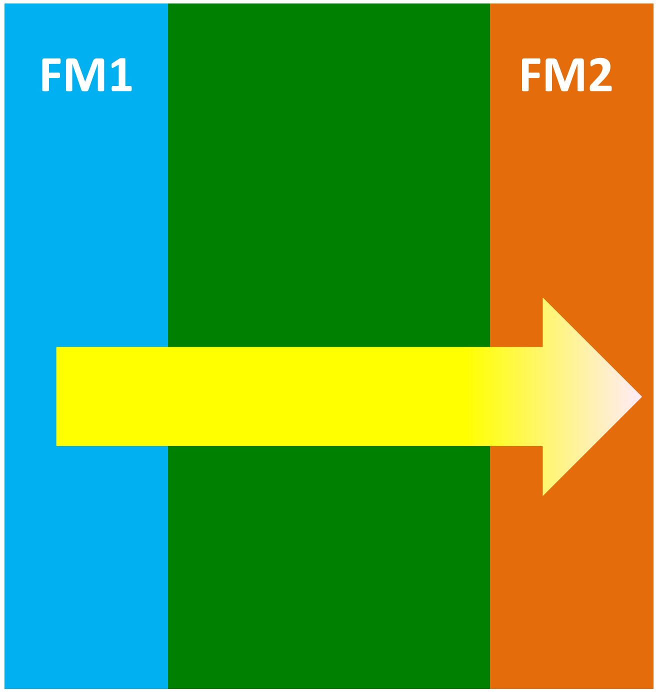
Layered structure (spin valve)

↓

★ **Materials**
- ✓ provide spin-polarized carriers
- ✓ preserve spin coherence

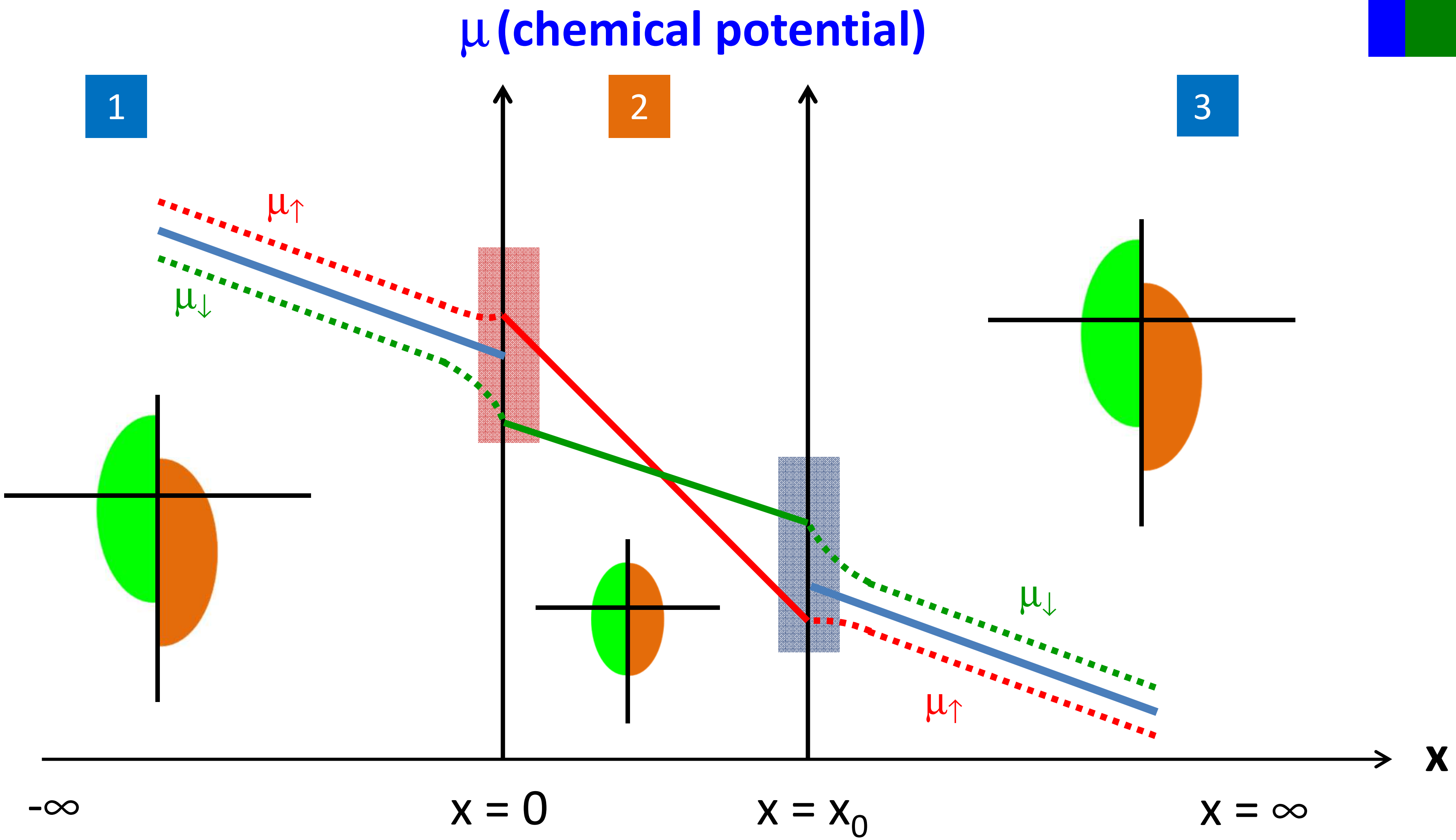
★ **Interface**
- ✓ effective spin injection/detection
- ✓ spin-dependent boundary resistance

Trilayers



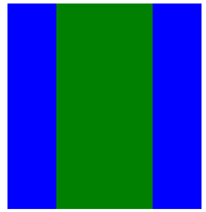
Take magnetization into account (in delocalized e⁻ picture; shifted bands)

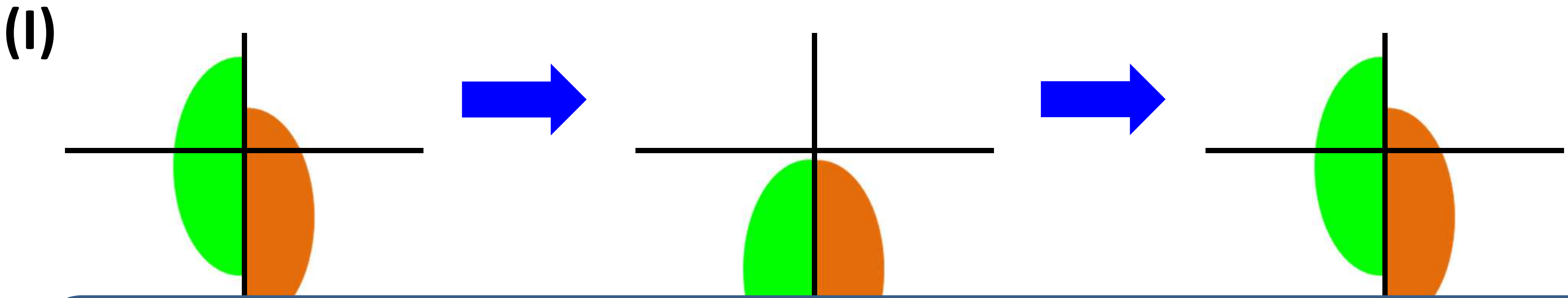
- Diffusive transport with M_1 // M_2



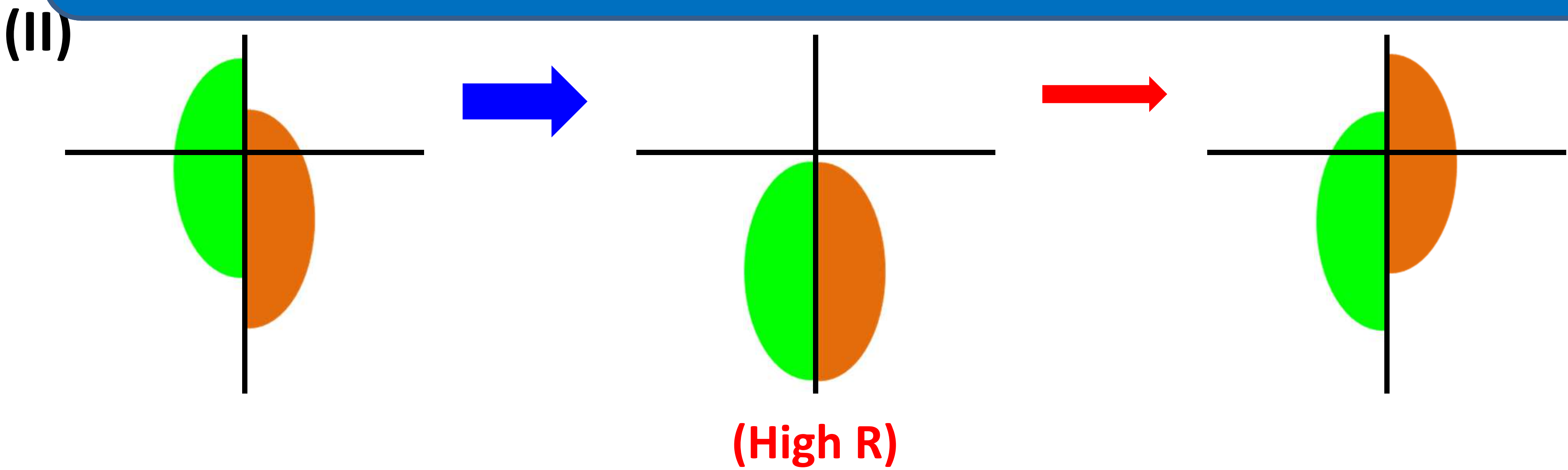
- assuming infinite spin coherence length in organic layer

Tunneling (in delocalized e⁻ picture; shifted bands)



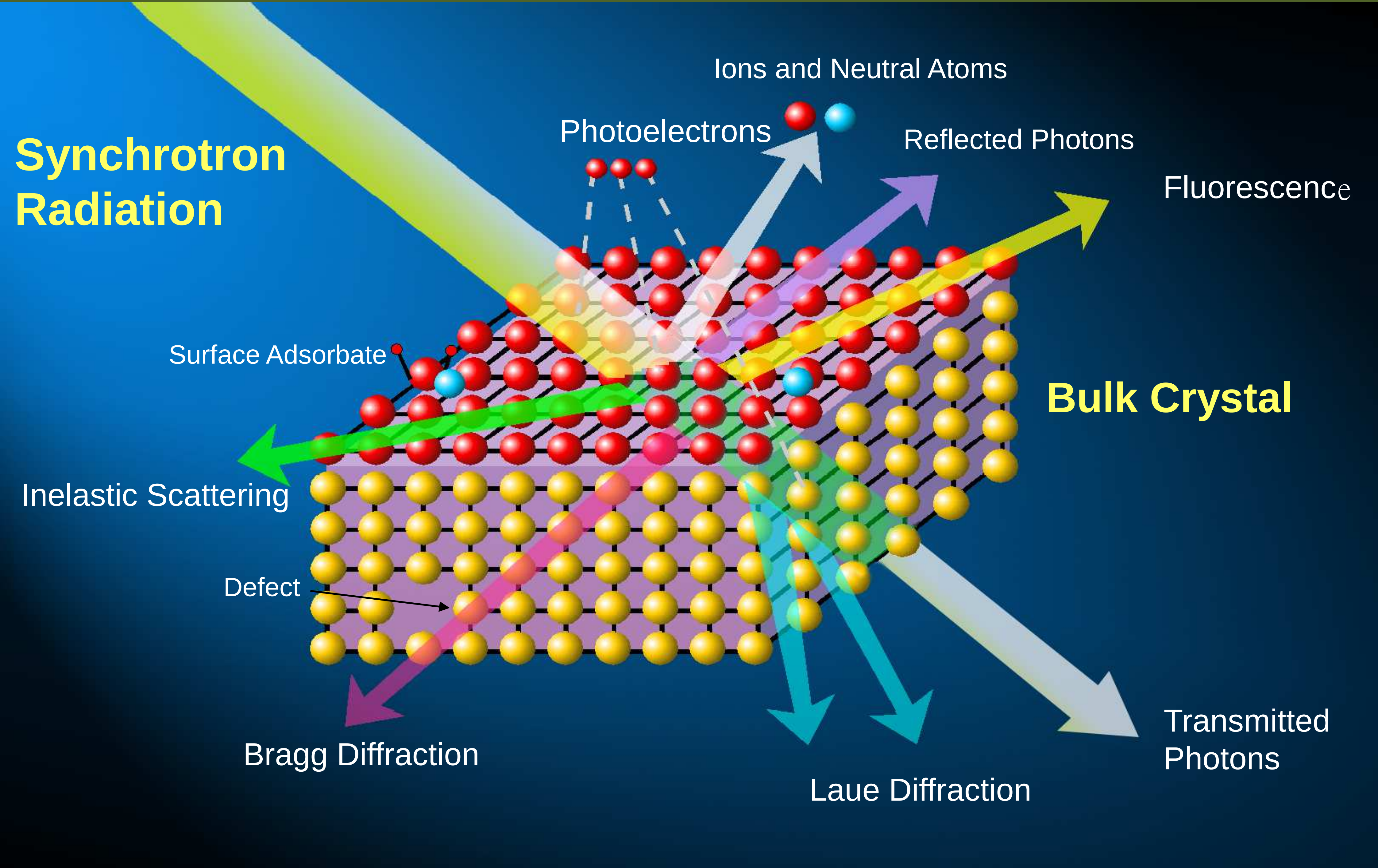


Regardless of the injection process, polarization of conduction electrons at interfacial regions matters.



How to explore a buried interface

Photon-matter interactions



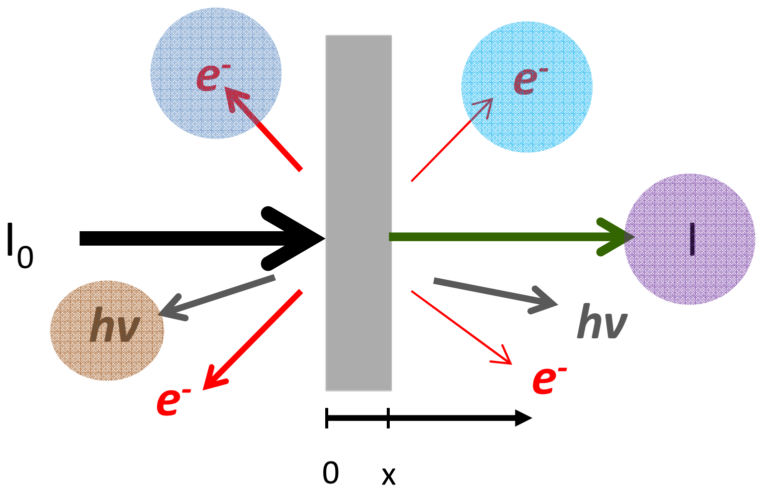
SR: penetration & element-specific

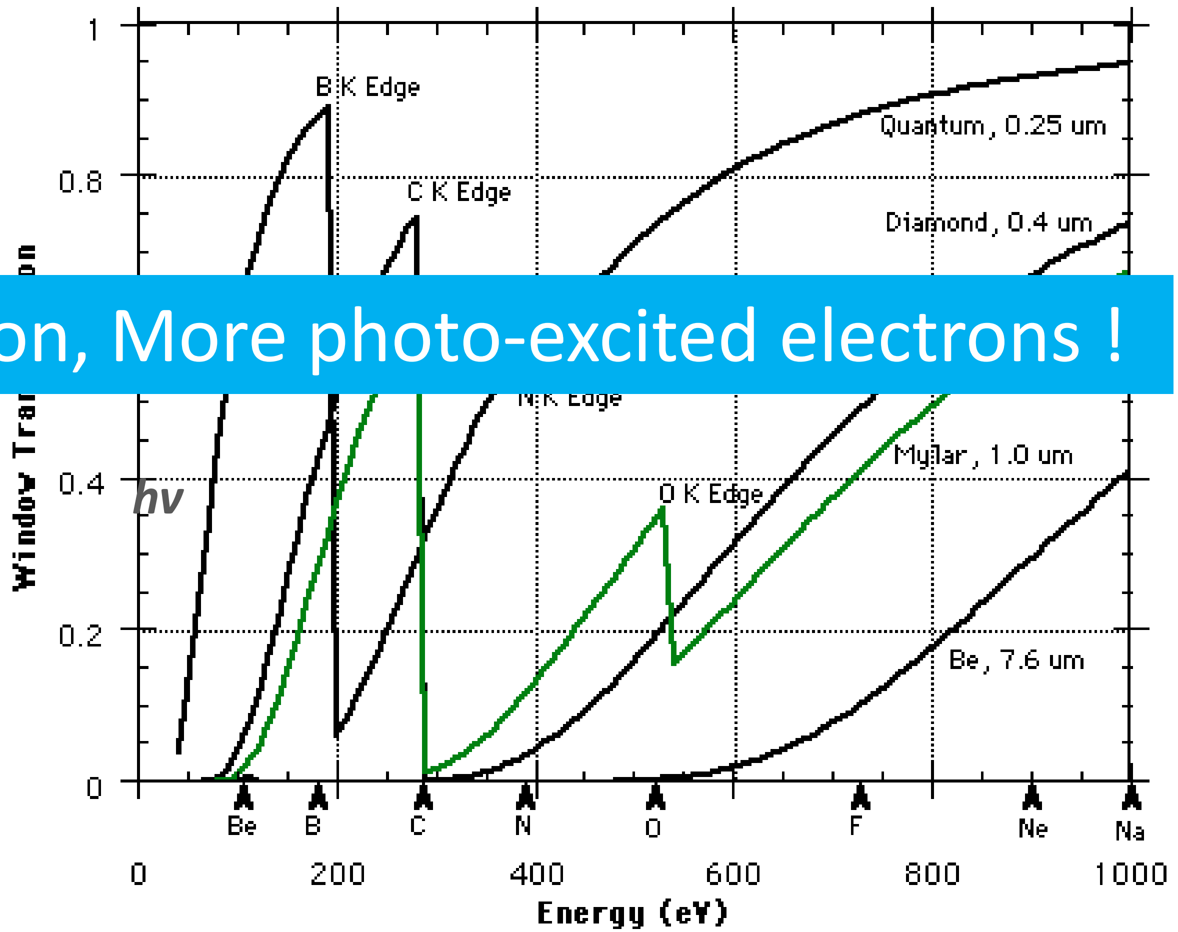
- ***Empirical expression;***

$$I = I_0 \exp(-\alpha x);$$

α = linear attenuation coefficient
x = material (lens) thickness

Stronger photon absorption, More photo-excited electrons !





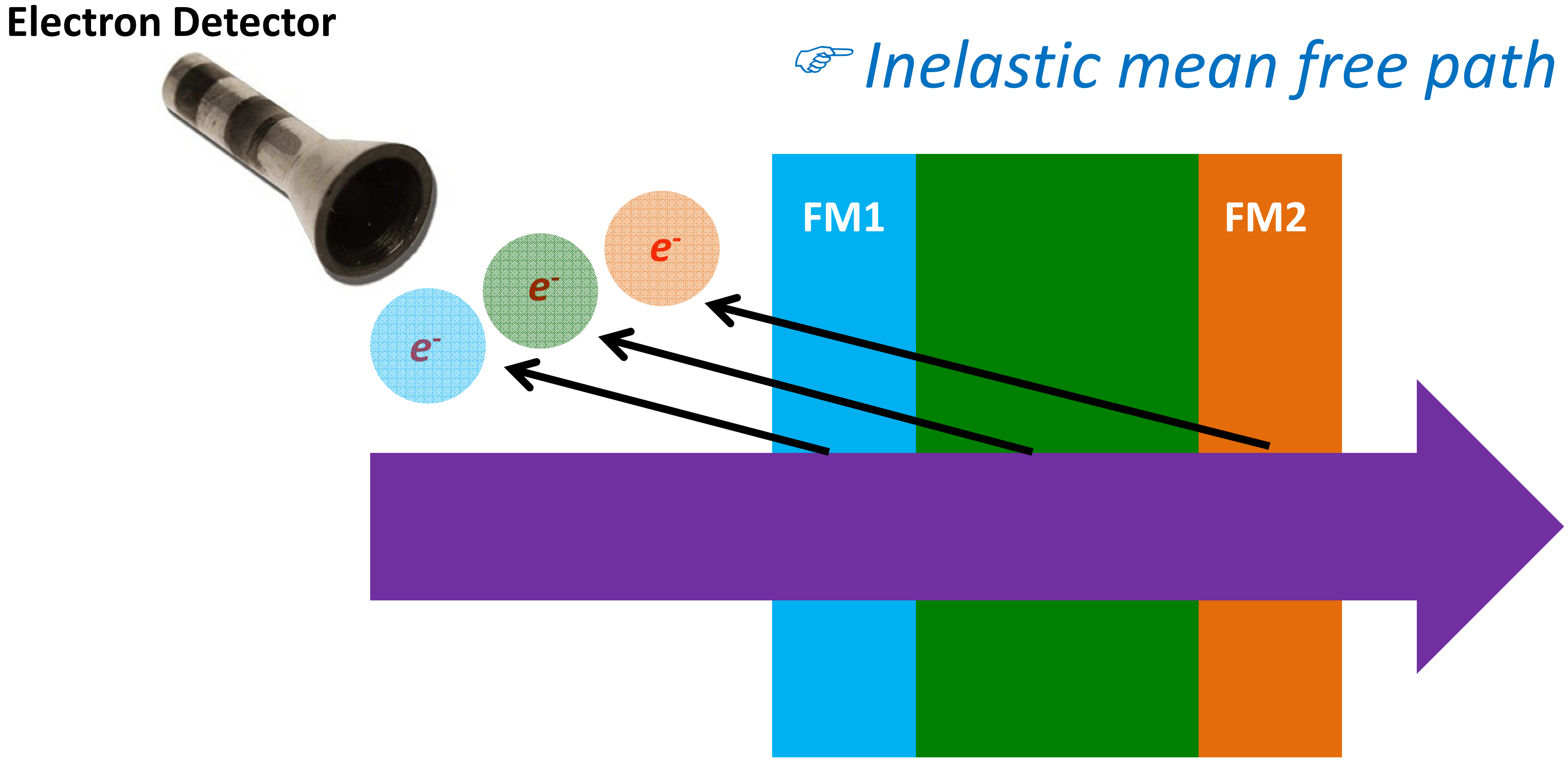
Q: physical origin?

http://www.cstl.nist.gov/div837/Division/outputs/DTSA/chapters/Appendix.html

Layer-resolved detection

☞ *Photon penetration depth*

☞ *Inelastic mean free path (electron)*



➢ *By tuning the photon energy, one can selectively amplify the signals (and thus resolve layers with different compositions)*

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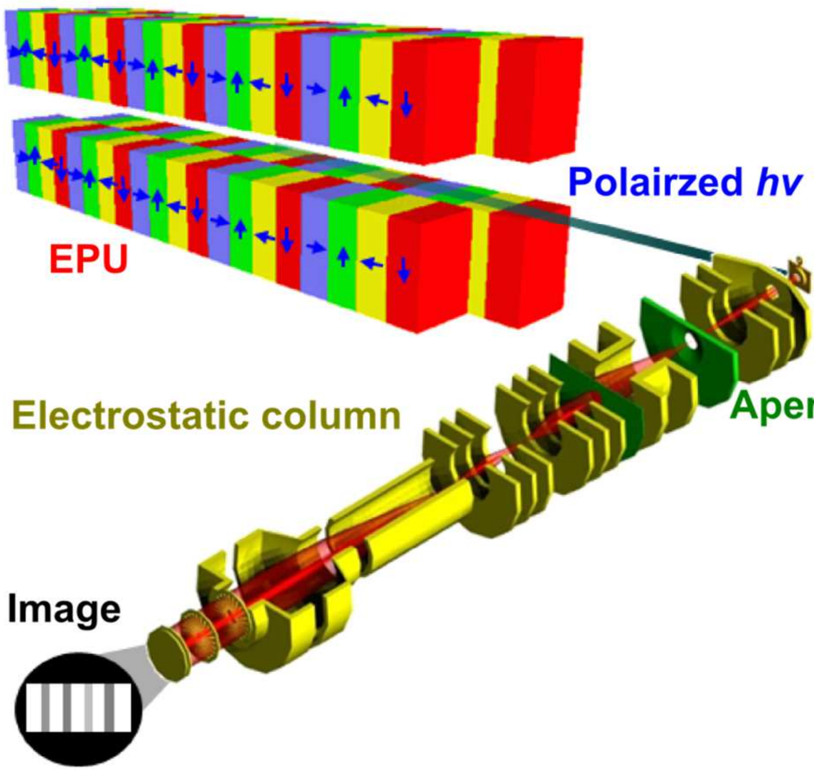
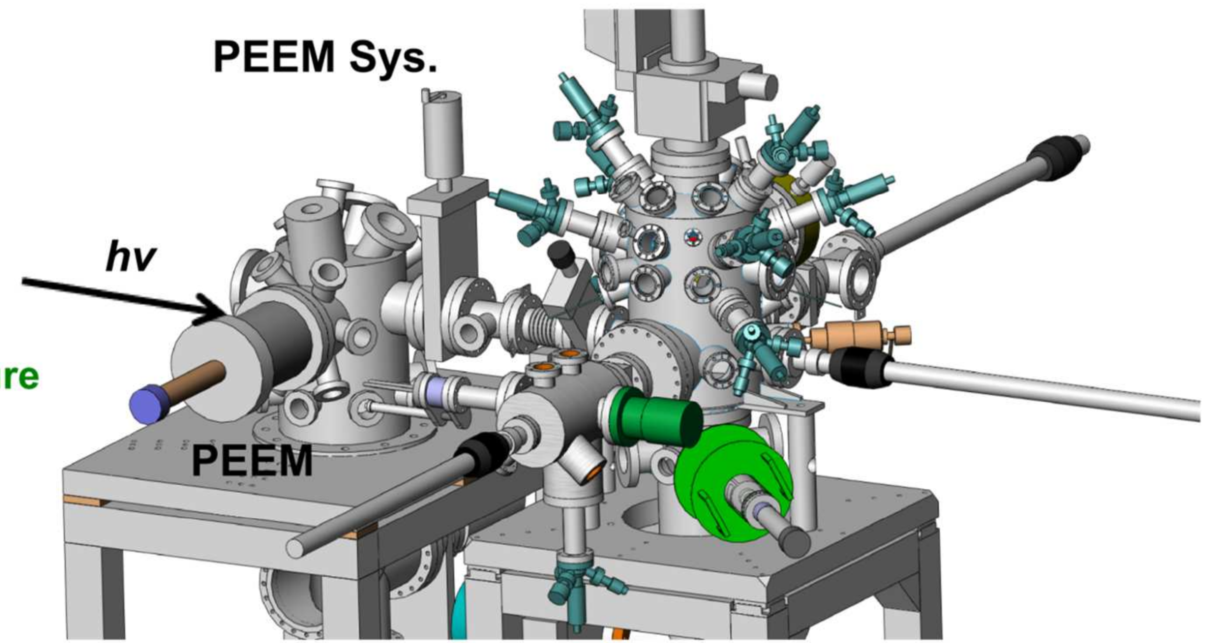
SR-based spectromicroscope (BL05B2)

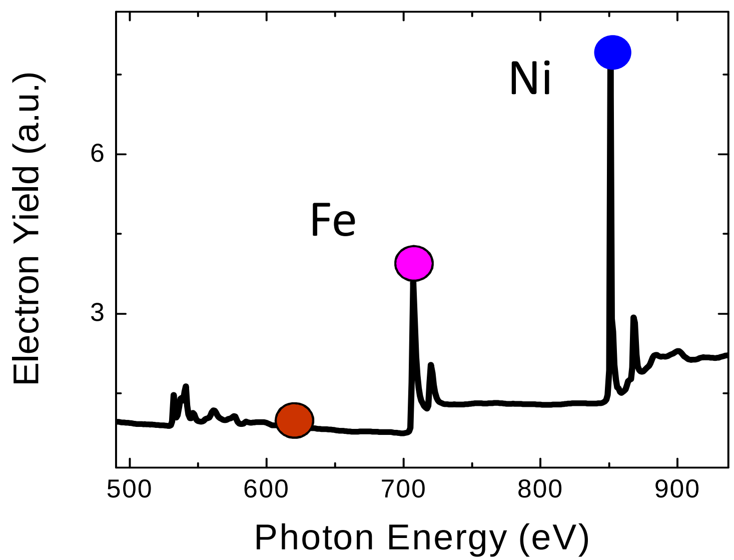
■ Photoemission electron microscope

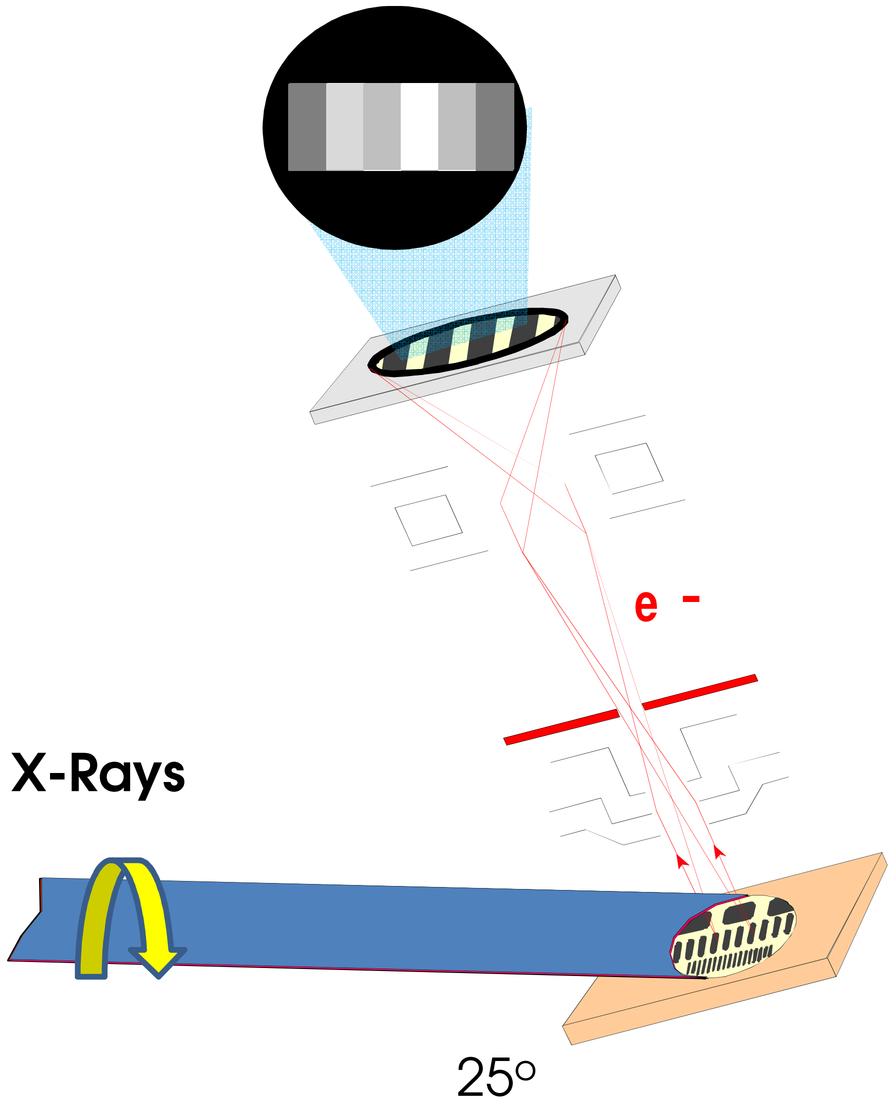




- ☑ Synchrotron ➔ accessing the buried interface with element-specificity
- ☑ Polarized photon ➔ magnetization detection (through XMCD effect)
- ☑ Ultra-high vacuum ➔ better interface control (consistency, one thing at a time)
- ☑ Microscopy ➔ Inhomogeneity (of chemicals, magnetism, etc.)

The way XPEEM works

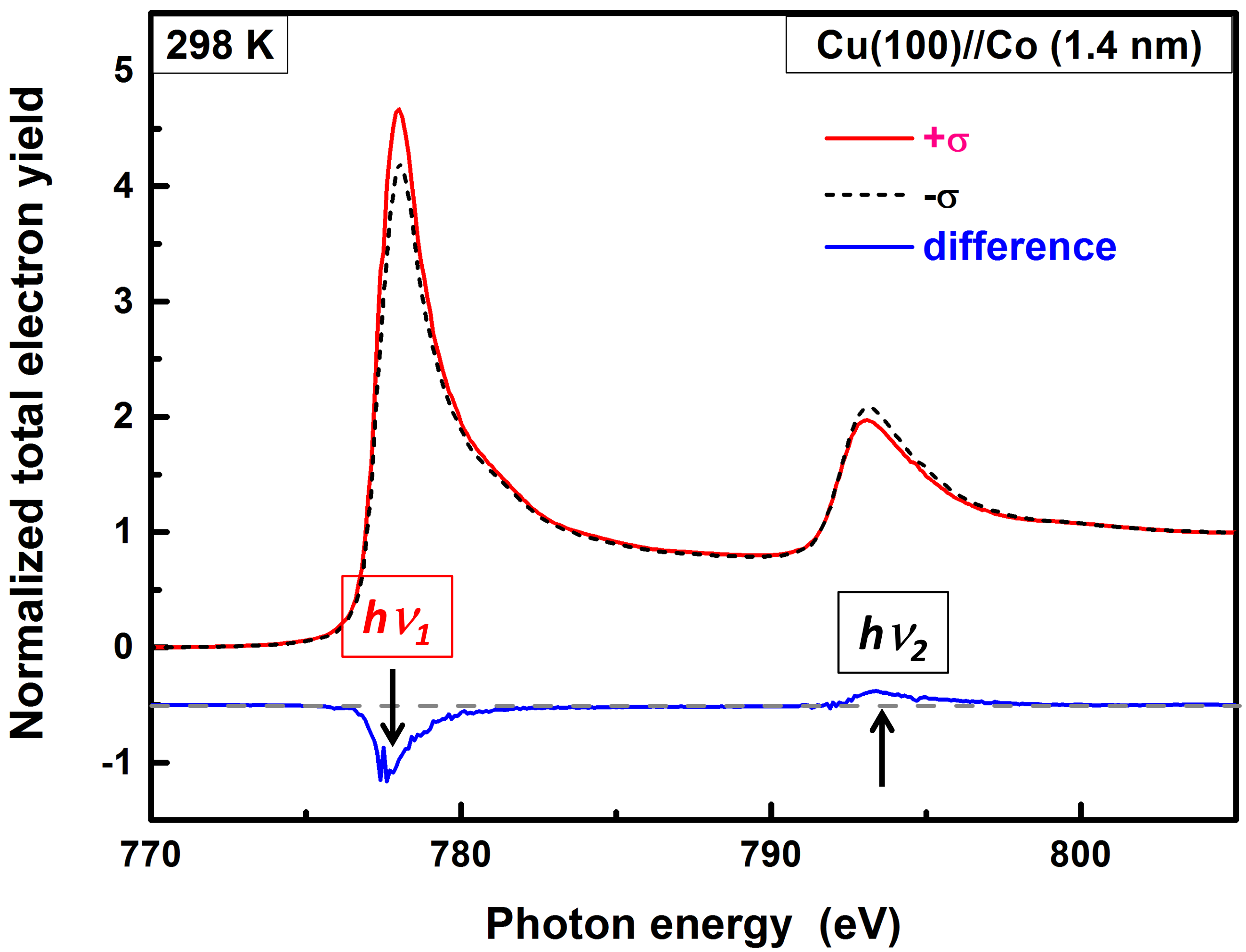




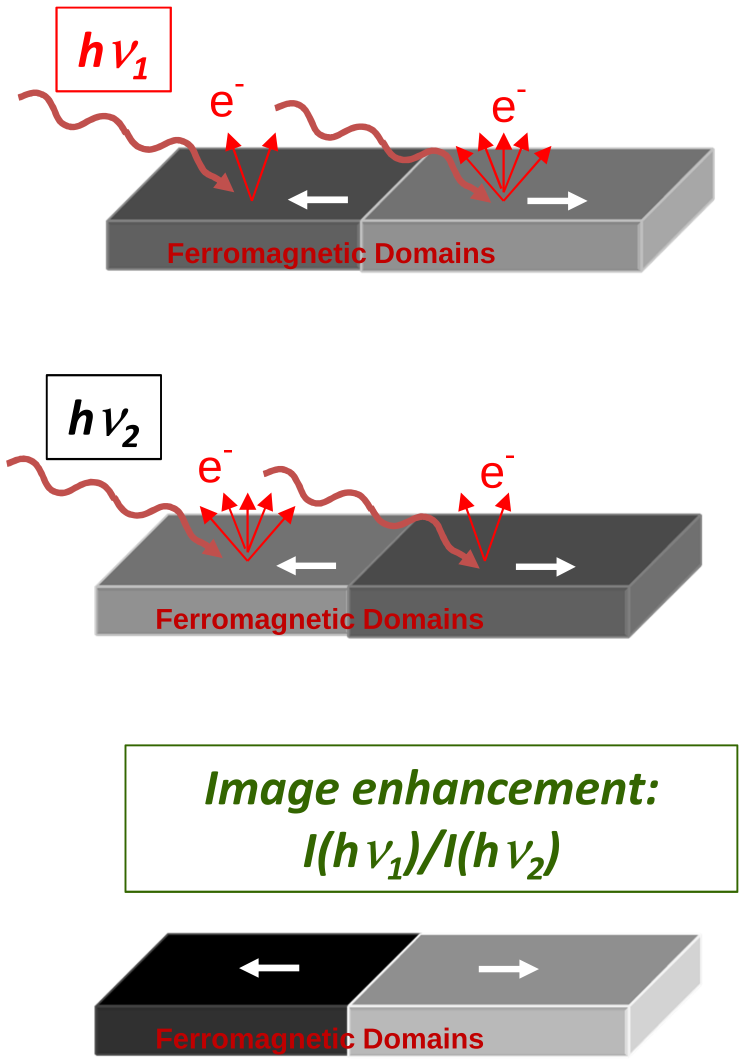
Full field electrostatic microscope :

- **Accelerating field → Topography**
- **Photoelectric effect → Work function**
- **X-ray energy → Chemistry**
- **X-ray polarization → Magnetism**

❒ X-ray Magnetic Circular Dichroism (XMCD)



❒ XMCD-based images



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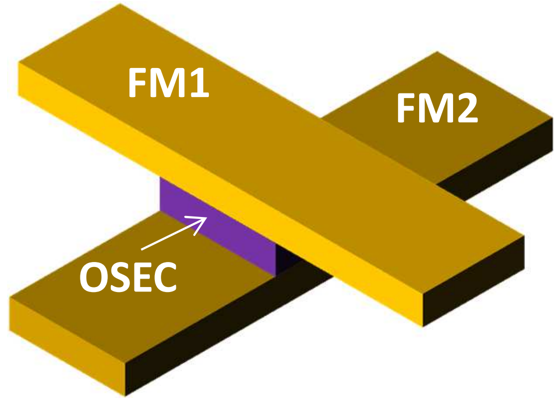
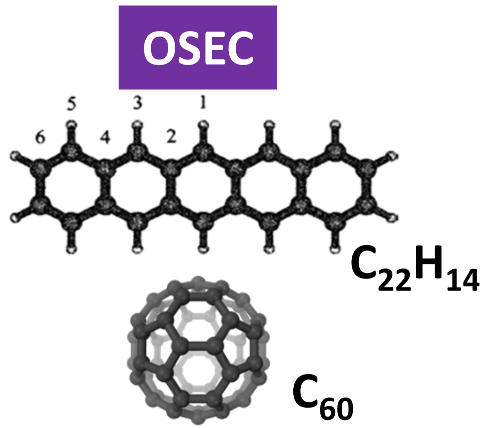
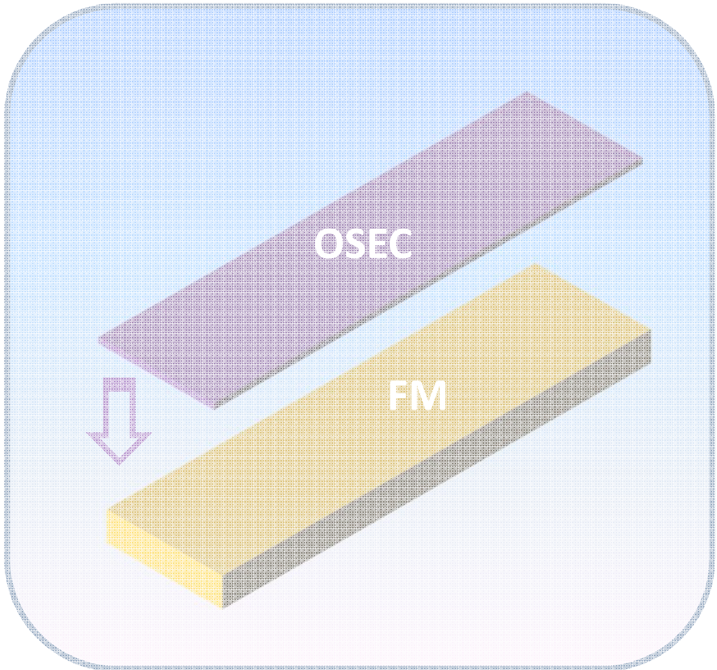
Experimental structures

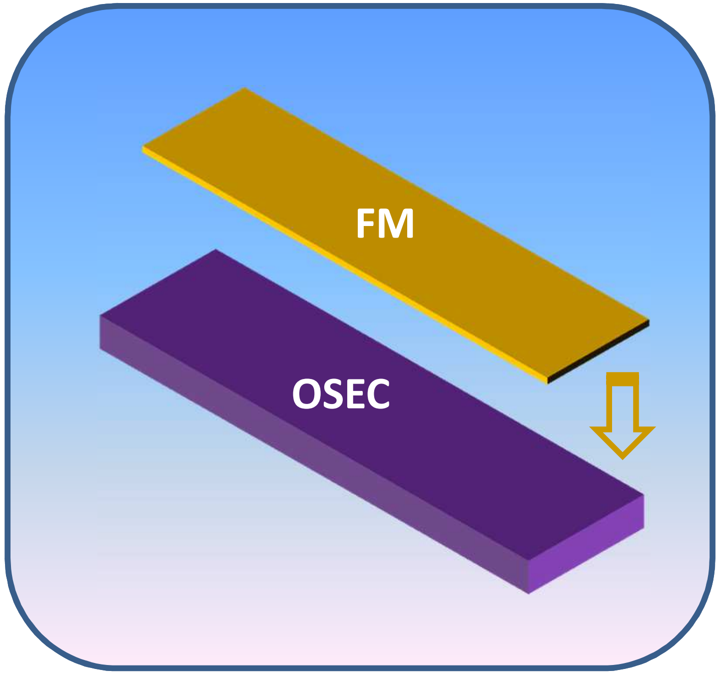
FM/OSEC/FM



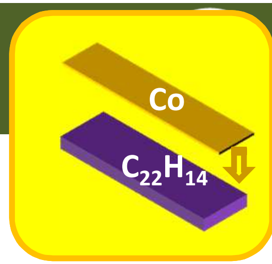




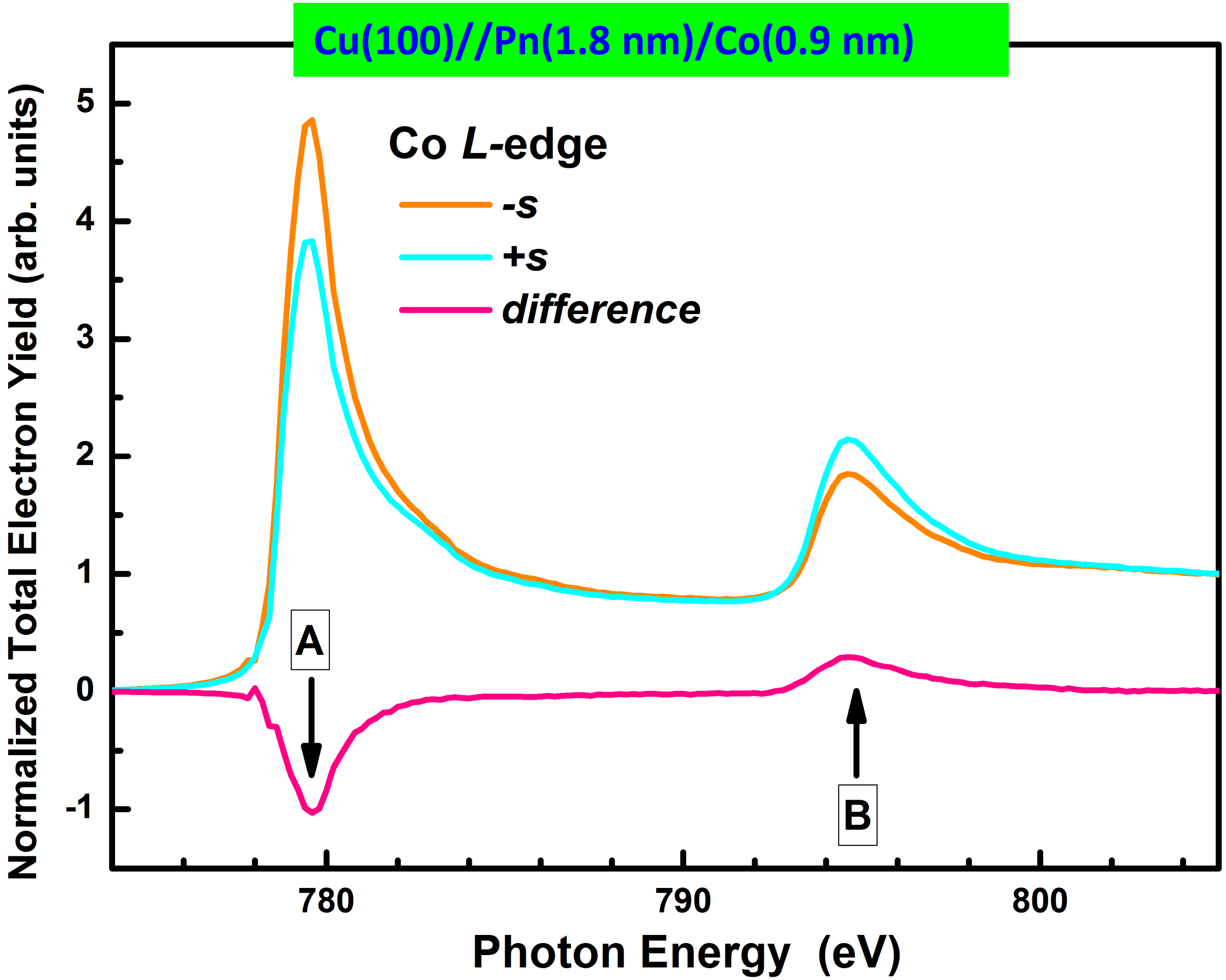
UHV



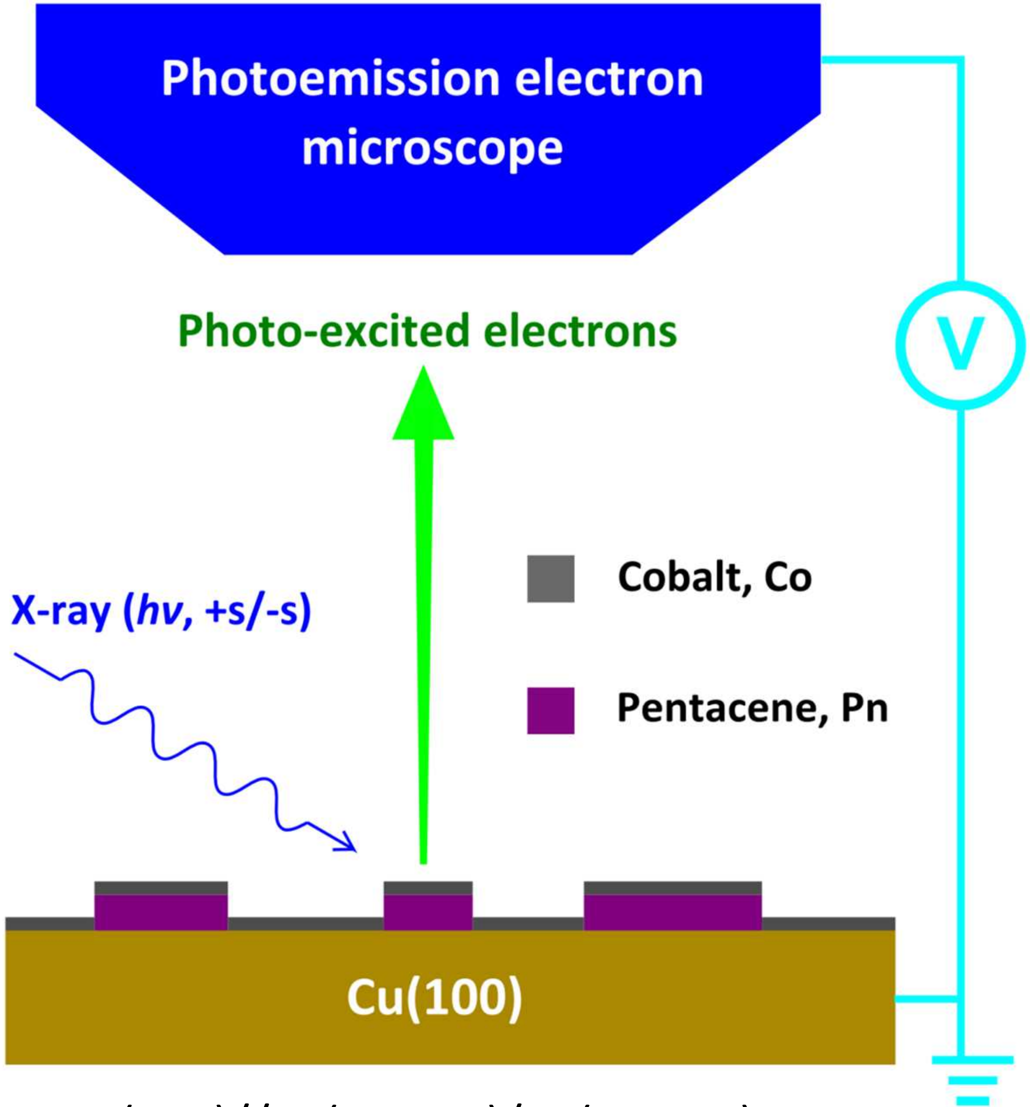
Co electrode retains its FM order



❐ X-ray absorption spectroscopy (near-edge) / XMCD

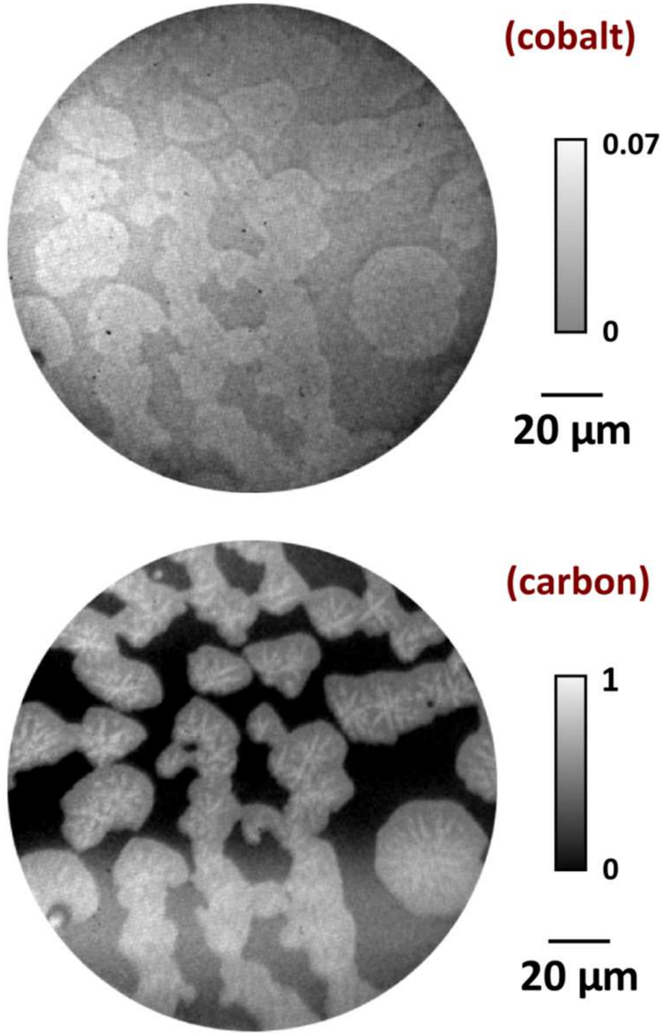


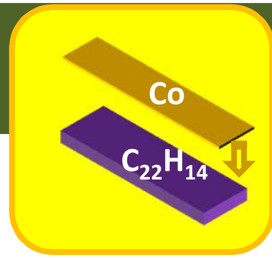
Electrode can maintain its individual (magnetic) properties in OSV structures



Cu(100)//Pn(1.8 nm)/Co(0.9 nm)

Field enhanced element contrast

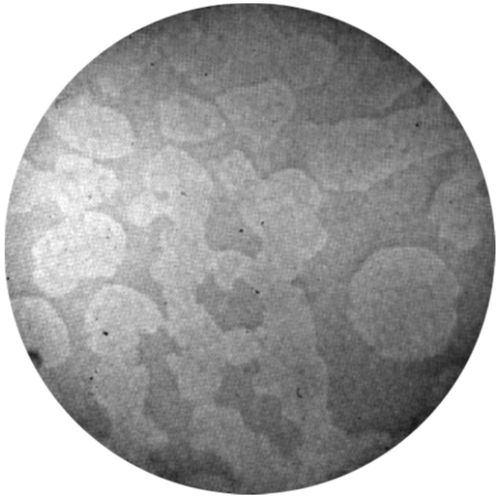




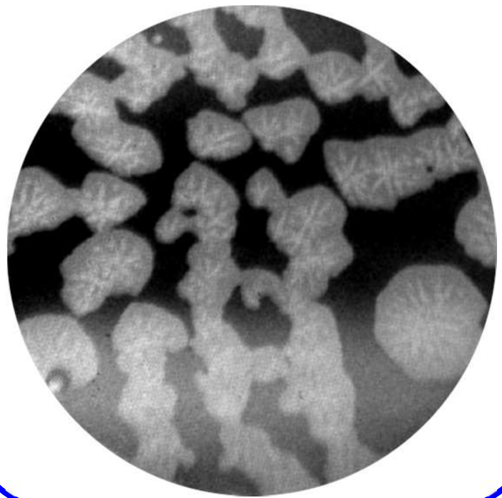
(Element contrast)

(Magnetic contrast)

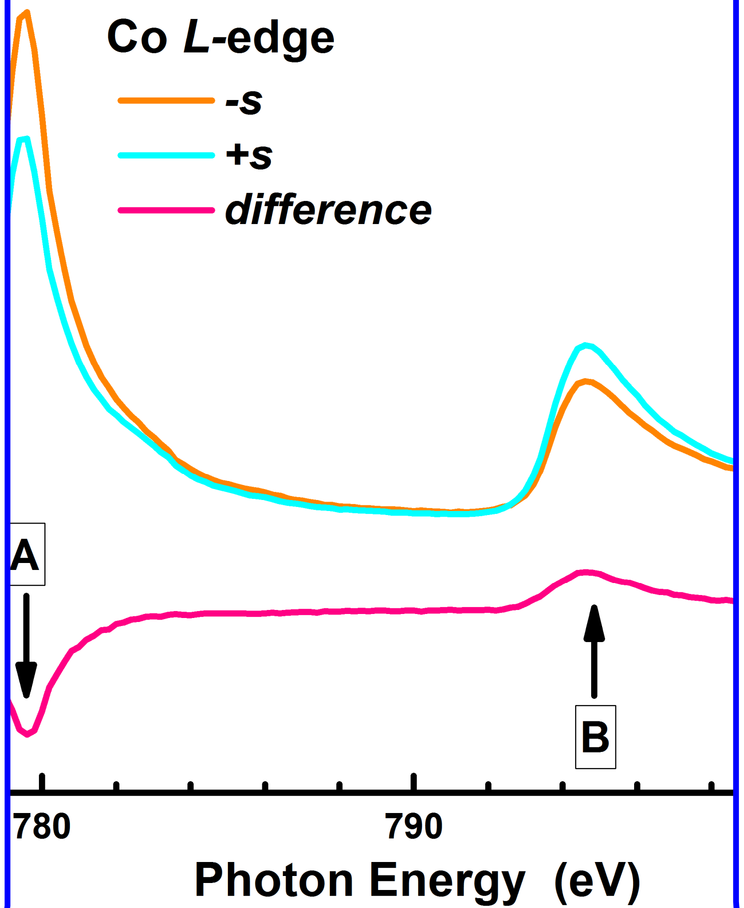
Co



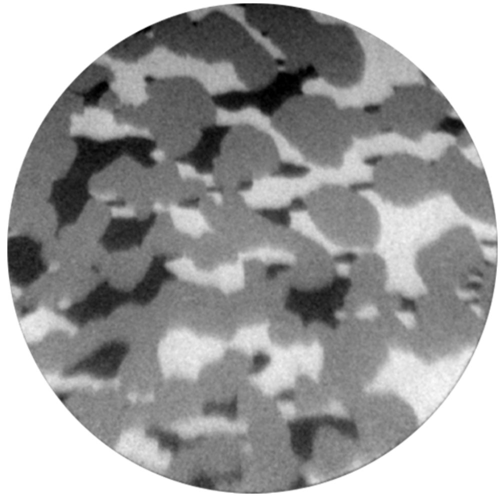
C



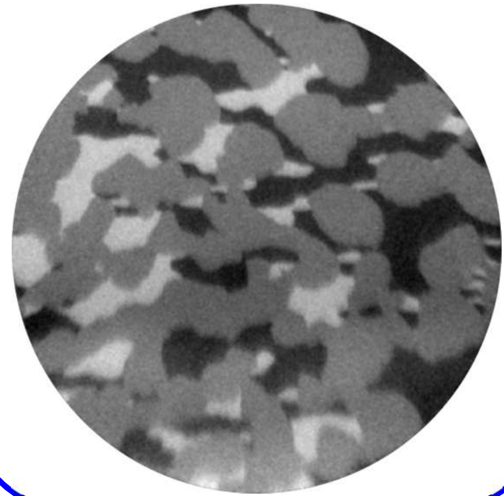
Cu(100)//Pn(1.8 nm)/Co(0.9 nm)



-s



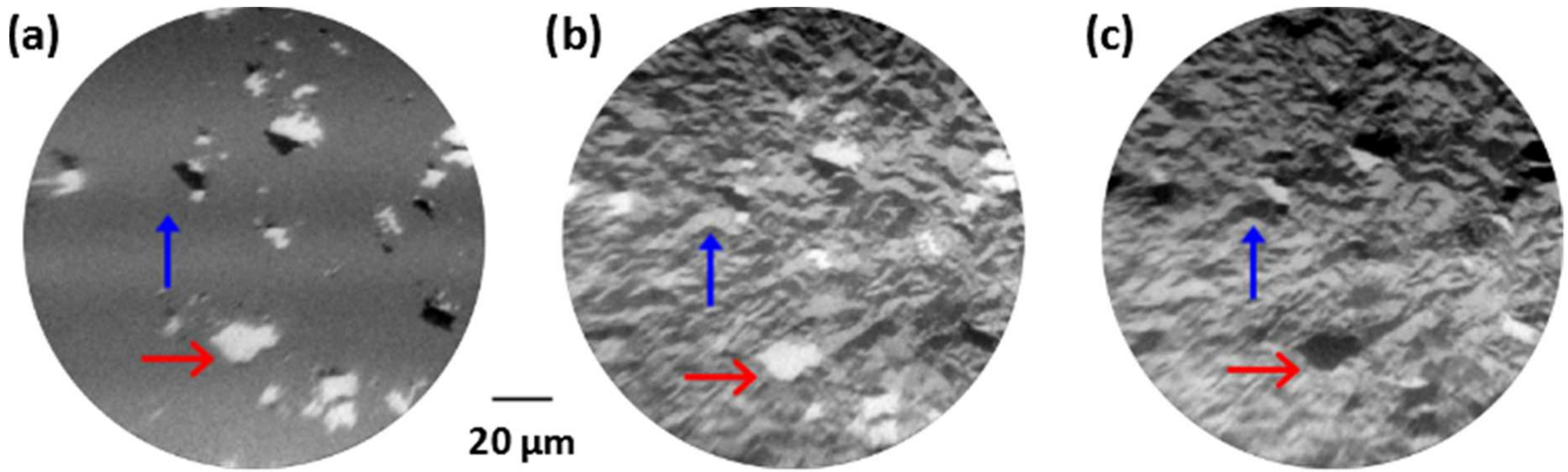
+s



Element-specific image in magnetic contrast

Cu(100)//Pn(3.6 nm)/Co(1.6 nm)

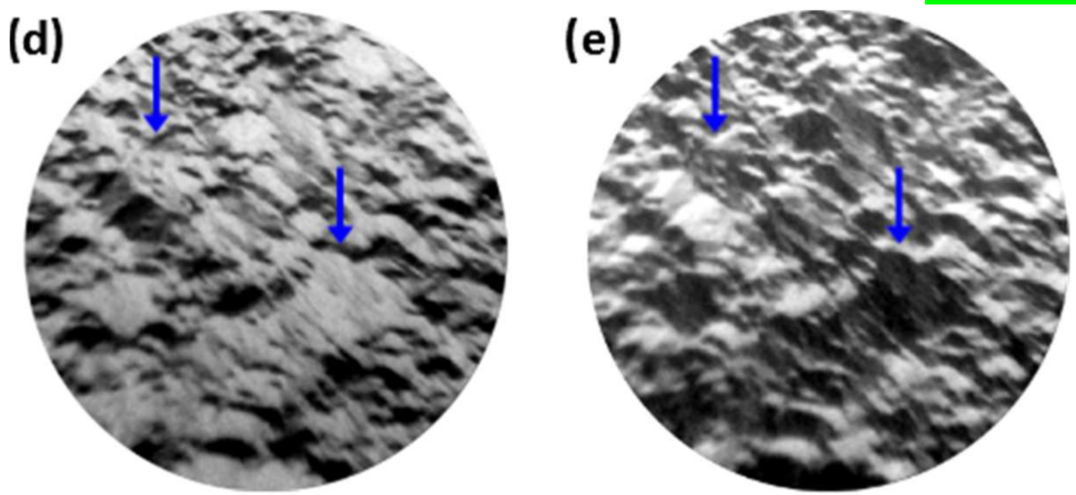
T



297 K / (-s)　*198 K / (-s)*　*198 K / (+s)*

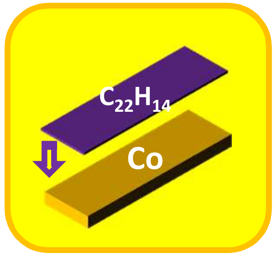
Cu(100)//Pn(7.2 nm)/Co(3.4 nm)

θ

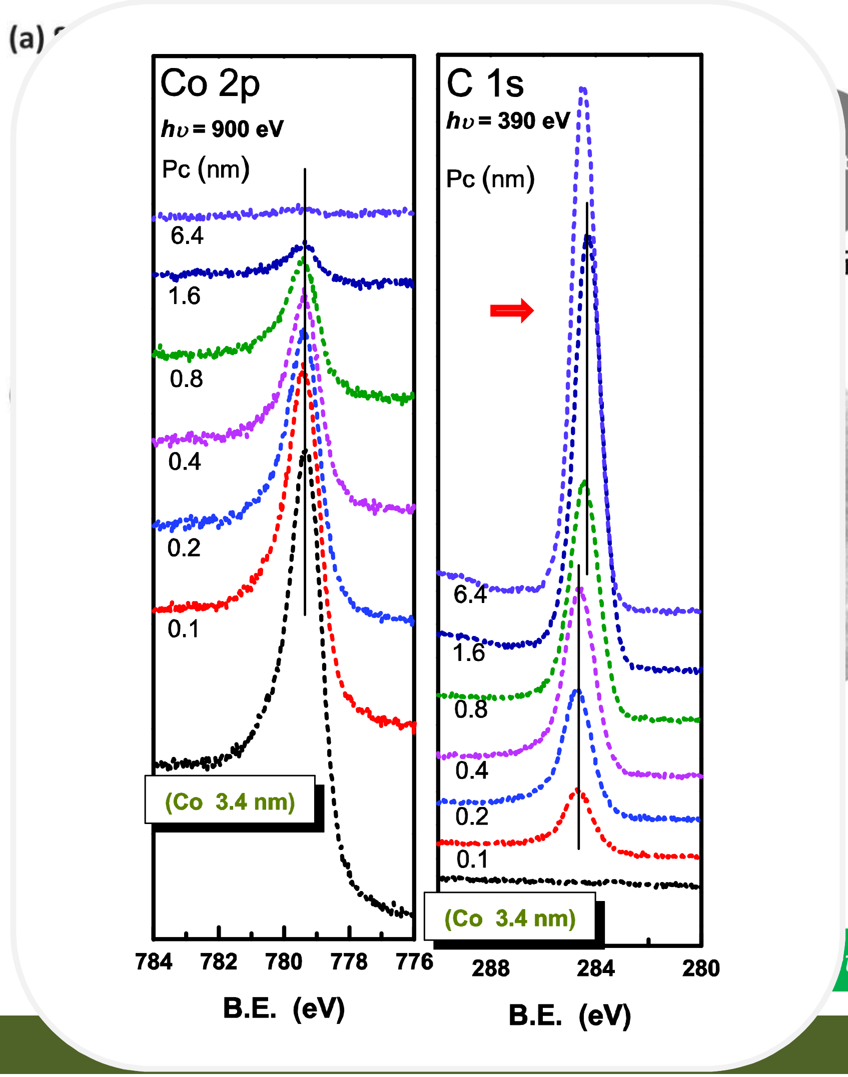


297 K / (-s)　*297 K / (+s)*

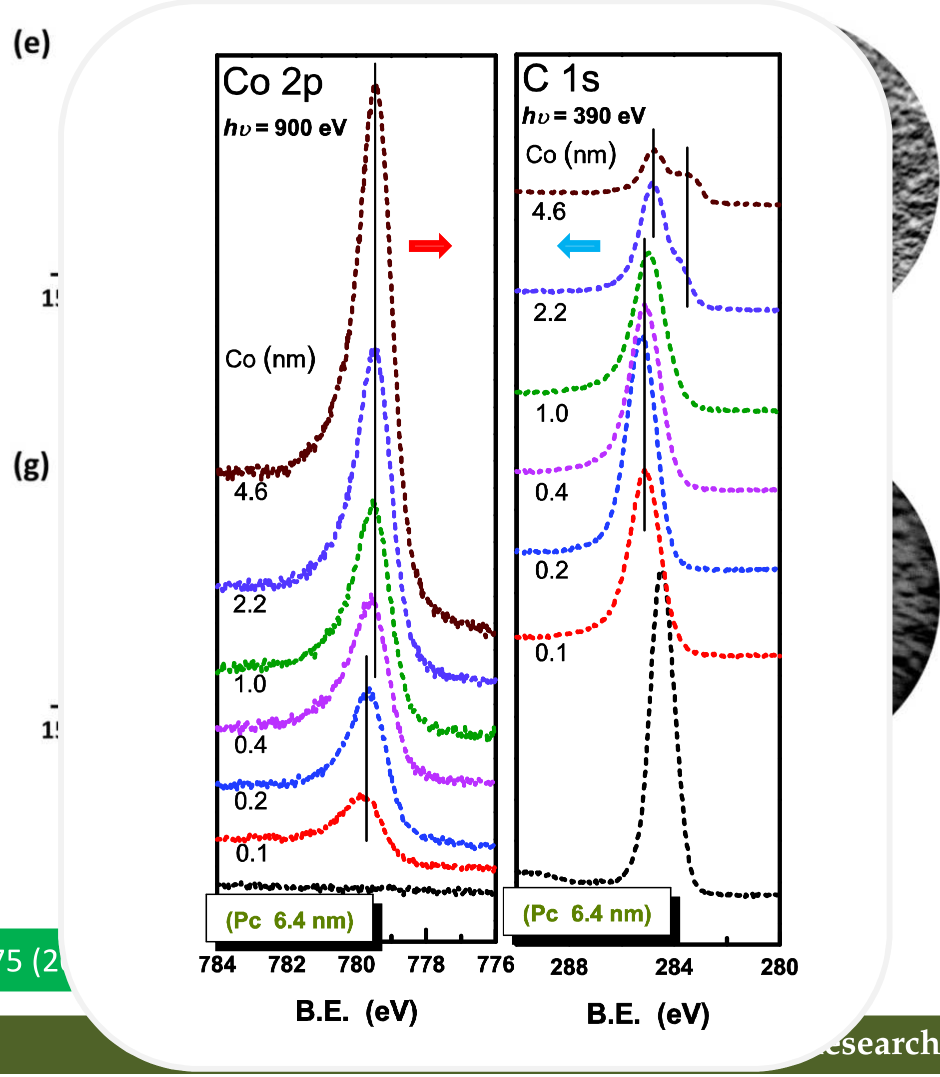
Order of deposition matters



Phys. Rev. Lett. **104**, 177204 (2010)



2 nm)



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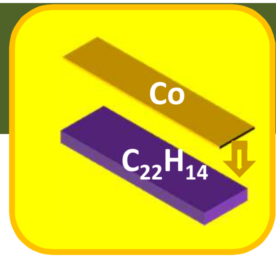
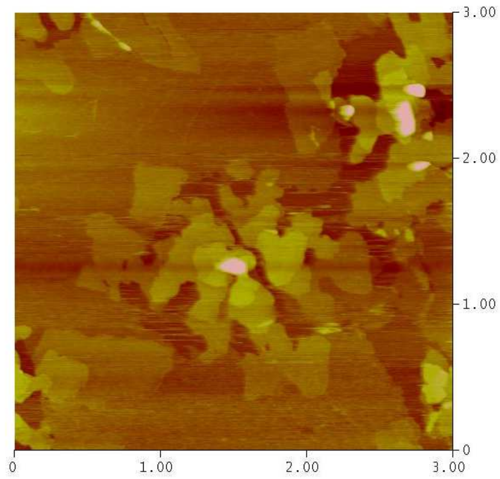
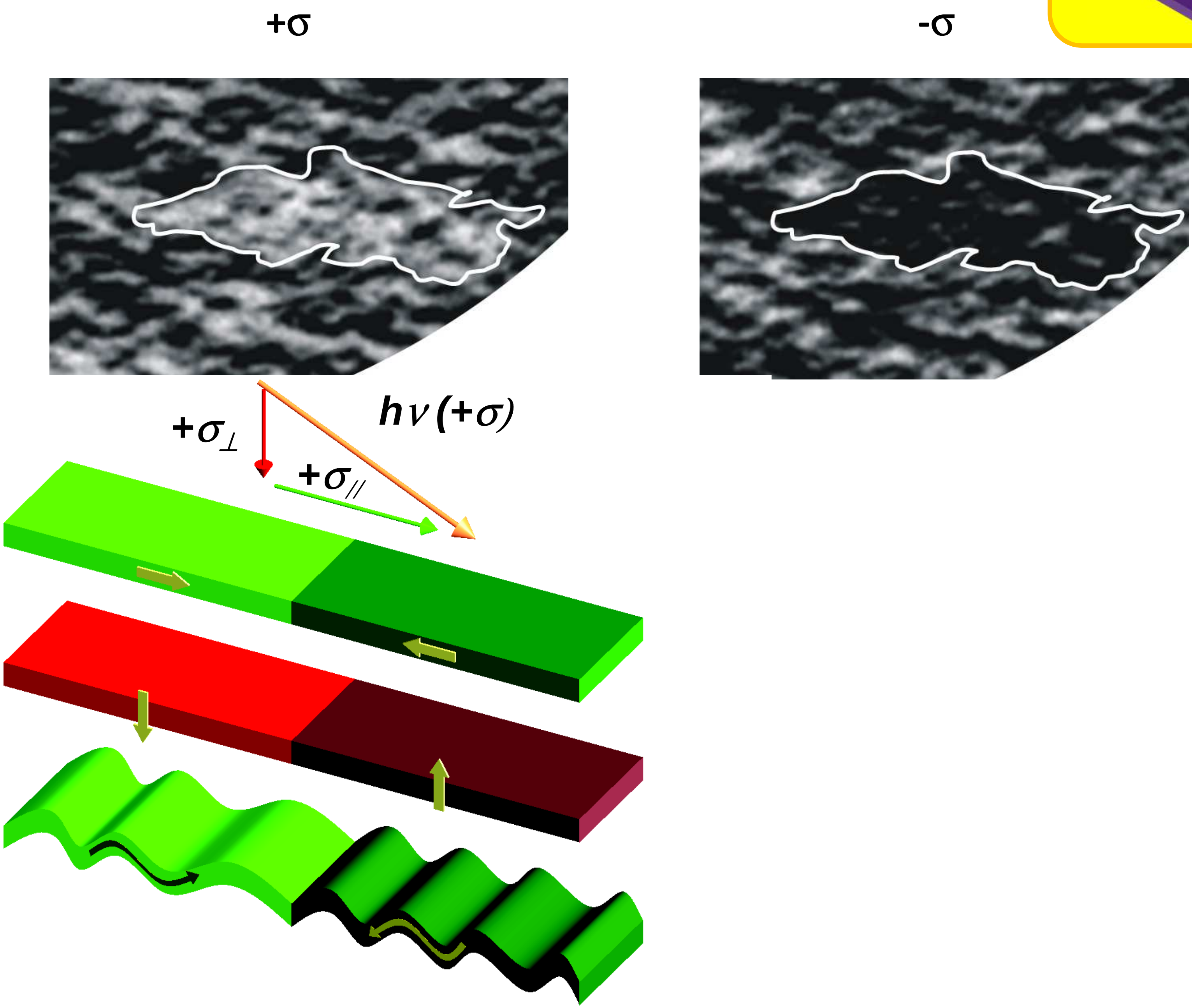
A further look in XMCD images







Insights (I)

Cu(100)/Pn/Co

- 7 nm Pn is needed to cover Cu(100) surface.

- Co shows retarded FM order when landing on Pn.

- Pn/Co :
  -- a rough interface & ill-defined magnetization directions
  -- complex spin-dependent scattering at interface
  -- current is expected to have a reduced spin polarization

General

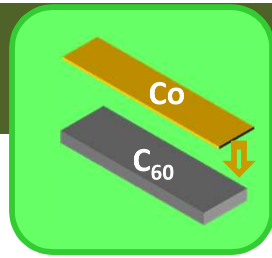
- "Homogeneity/uniformity" can be a concern in hybrid systems.

- **"Layered structure" = "*individual layers*" + "*interfaces*"**

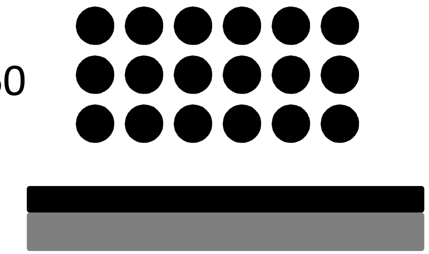
- Why FM layer would experience a retarded magnetization when it lands on an OSC layer? Any implication?

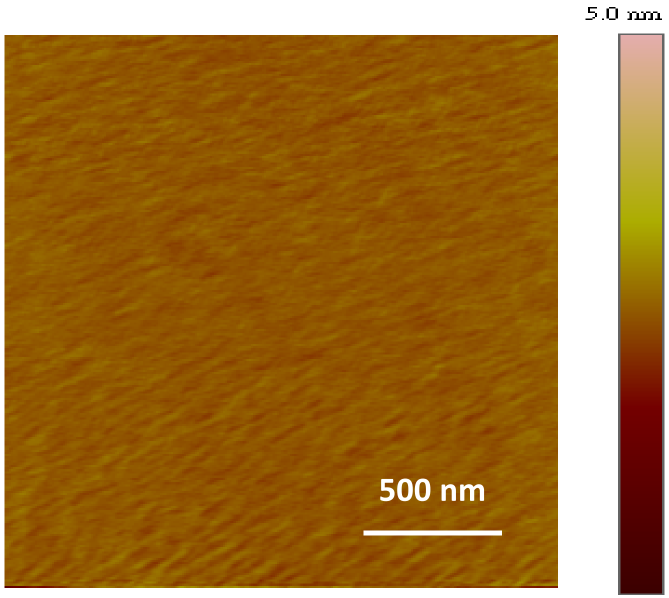
- How to resolve/minimize the impacts originated from ill-defined OSEC-FM interfaces?

Co deposited on C_{60}: Si(111)/SiO_x/C_{60}/Co

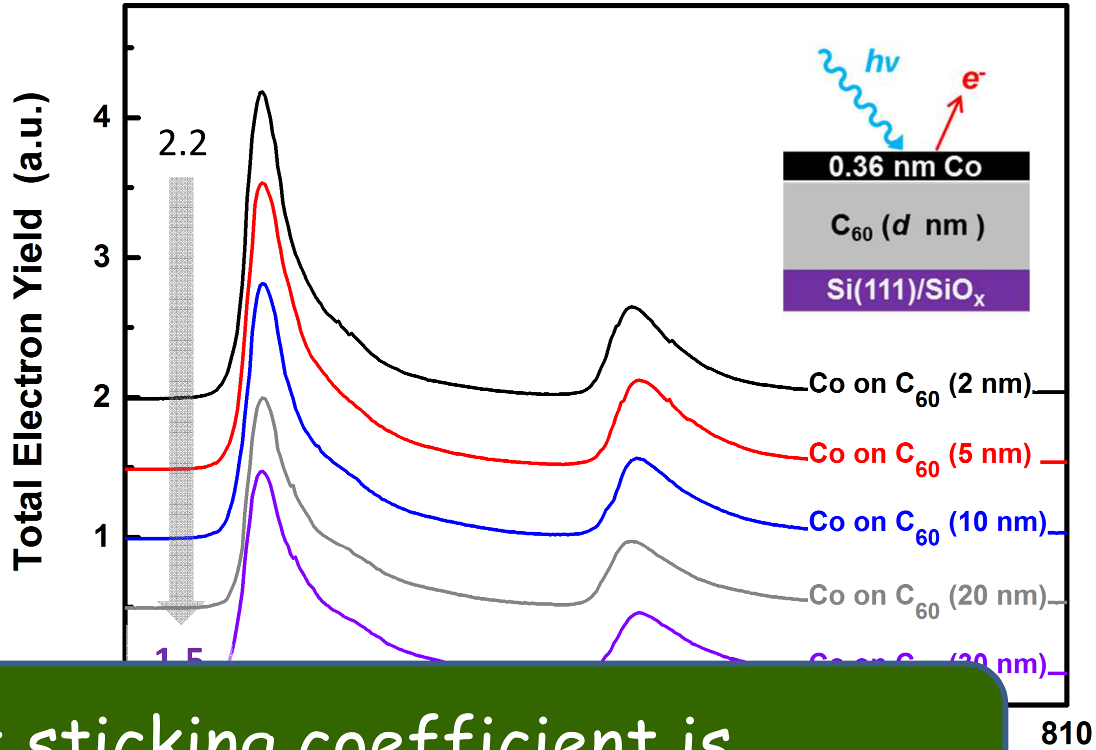


C60





Thicker C_{60} film gives weaker electron yields



A thickness dependent sticking coefficient is another possibility, but it lacks a physical ground

Insights (II)

Cu(100)/C_{60}/Co

- Unlike Pn, C_{60} film is smooth when growing on Cu(100).
- Co top layer sinks into C_{60} under layer.

General

- X-rays can "examine" what lies underneath the top surface.
- How deep can X-rays "see" depends on the detection mode (critical parameters are different between transmission and emission)
- *Empirical relations are dominated in organic spintronics for now.*
- *Needs more theoretical and experimental efforts to establish fundamental understandings.*

Summary

Many questions remain unanswered yet …

- Material dependency?
- Electronic structures at interface ?
  (properties of ultrathin film is sensitive to where it lands)
- How spins are transported in organic materials?
  (more spectroscopic & theoretic works are needed)

…

Acknowledgement

- National Tsing Hua University
  - Mr. Men-Rui Chiang
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- National Synchrotron Radiation Research Center
  - Mr. Pei-Yu Cheng
  - Dr. Yuet-Loy Chan
  - Dr. Tai-Ming Liu
  - Dr. Yao-Jane Hsu

科 技 部 Ministry of Science and Technology

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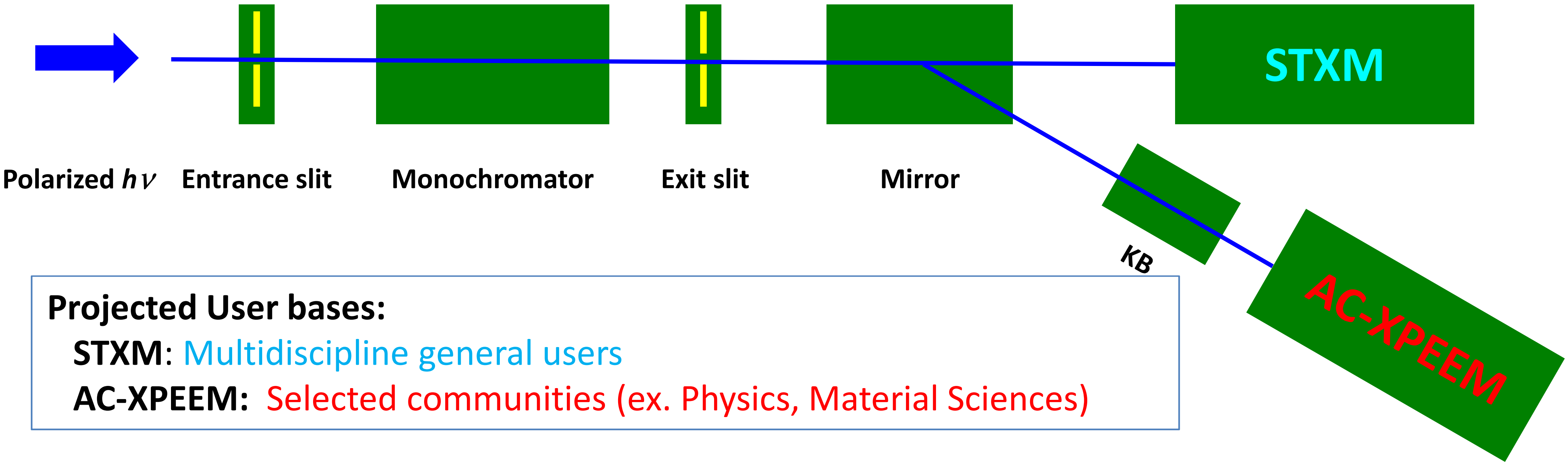
LIGHT is the main tool!
Taiwan Photon Source
(TPS)
Taiwan Light Source
(TLS)

Soft X-ray Nanoscopy beamline

Shangjr Gwo (NSRRC/NTHU)
Der-Hsin Wei (NSRRC/NTHU/NSYSU)
Yao-Jane Hsu (NSRRC/NCKU)
Chia-Hao Chen (NSRRC)

- Bulk sensitiv
- Organic/envi
  possible (wa
- "thick film" (
  on/embed i
- Image resolution: 30-50 nm (P-I)
  : 10-20 nm (P-II)

- luctivity
  ice,
  RPES in
- Image resolution: 30-50 nm (P-I)
  : 10-20 nm (P-II)



Projected User bases:
STXM: Multidiscipline general users
AC-XPEEM: Selected communities (ex. Physics, Material Sciences)

Cultivation programs & opportunities

- 先進光源暑期實習 (Junior)
- 清華大學 先進光源科技學位學程 (Graduate student)
- Short Courses & Workshops

Beside the research opportunities …

Research assistant / Postdoctoral fellow / Young Scientist

Thanks for your attention