Photoemission (2)
Surface Science

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Surface/Interface in scales

10^6 m (10^3 km)

10^3 m (km)

10^0 m (m)

10^{-3} m (mm)

Space
The Earth/Vacuum interface

Climates
Sea/Air interface

Skins
Face/Air interface

Surface/Interface in scales

10^0 m (m)

10^{-3} m (mm)

10^{-6} m (μ m)

10^{-9} m (nm)

Goods
(solid/air interface)

Cooking
(Oil/water interface)

Biomaterials surviving
in various environments

Molecules and atoms
in various conditions

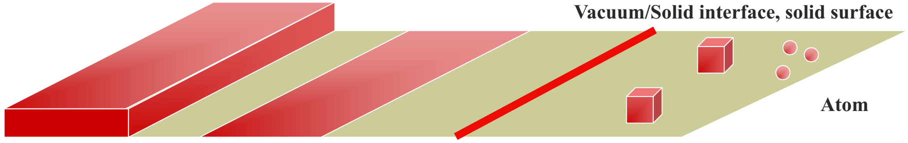
Surface/Interface in scales

- Things go on in a non-uniform system in any scale.

And there're always interfaces (surfaces) that play their roles.

- Solid/Liquid
- Solid/Gas
- Liquid/Gas
- Solid/Solid
- Solid/Vacuum
- ……..

My playground



Nanometer-scale and atomic-scale structures on a solid surface.

Chemistry

- Catalysis reaction
- Ecology
- Solutions for energy-shortage problem

Physics

- Low-dimensional physics
- Quantum dynamics
- New physics

Applied Physics

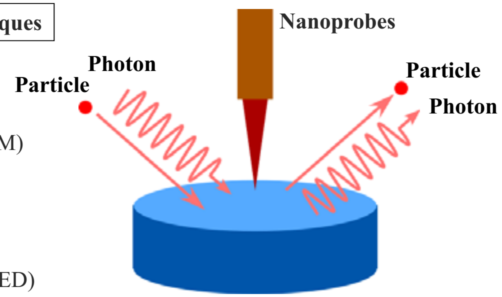
- Bottom-up nanotechnology
- Atom technology
- New technological developments

Advantage of surface science:

- **Visualization of atomic configuration and electron density (LDOS) distribution in atomic scale**
- **Direct determination of electronic structure (band, Fermi surface, etc…)**

Surface Analyses

Varieties of Surface analysis techniques



Given examples…….

Nanoprobes

Scanning Tunneling Microscope (STM)
Atomic Force Microscope (AFM)

Particle-in / Particle-out

He scattering
Low-energy electron Diffraction (LEED)
Transmission Electron Diffraction (TED)
Refection High-Energy Electron Diffraction (RHEED)
Refection High-Energy Positron Diffraction (RHEPD)

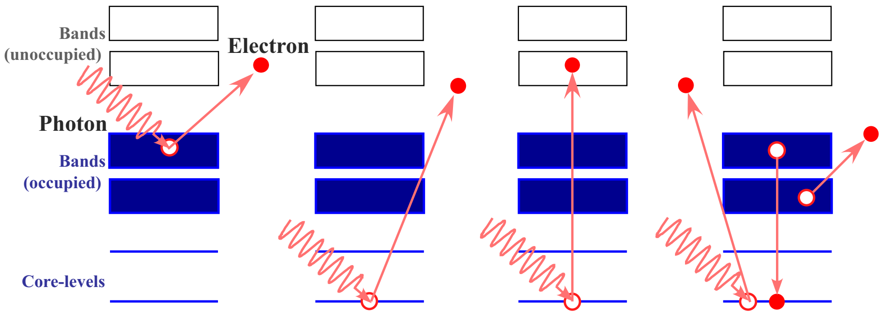
Photon-in / Photon-out

Grazing-angle incident X-ray Diffraction (GIXRD)

Surface Analyses

Photon-in / Particle-out

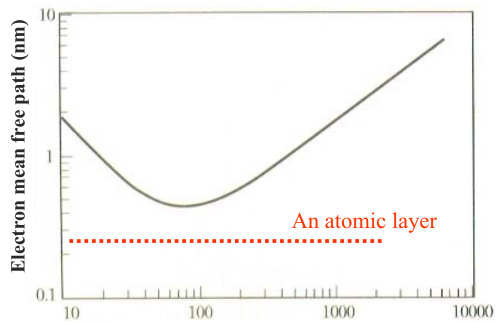
Photoemission Spectroscopy (PES), Ultraviolet Photoelectron Spectroscopy (UPS)
Core-level Spectroscopy (CLS), X-ray Photoelectron Spectroscopy (XPS)
X-ray Absorption Spectroscopy (XAS)
Auger Electron Spectroscopy (AES)



Spectroscopy with VUV~SX

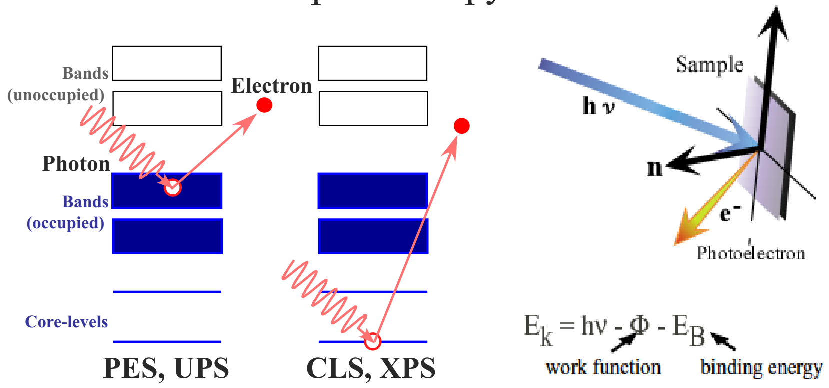
- Electron mean free path

surface-sensitive ~ bulk sensitive

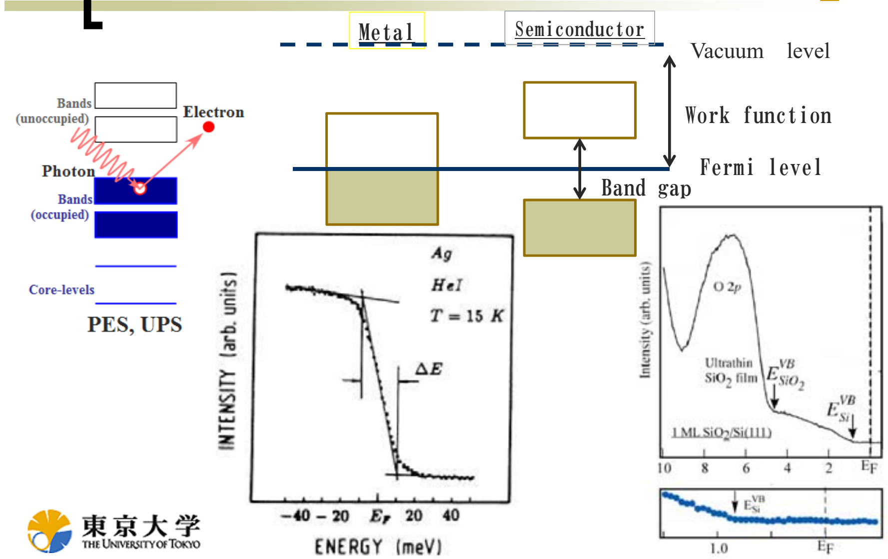


Probing electronic states

- Photoelectron spectroscopy



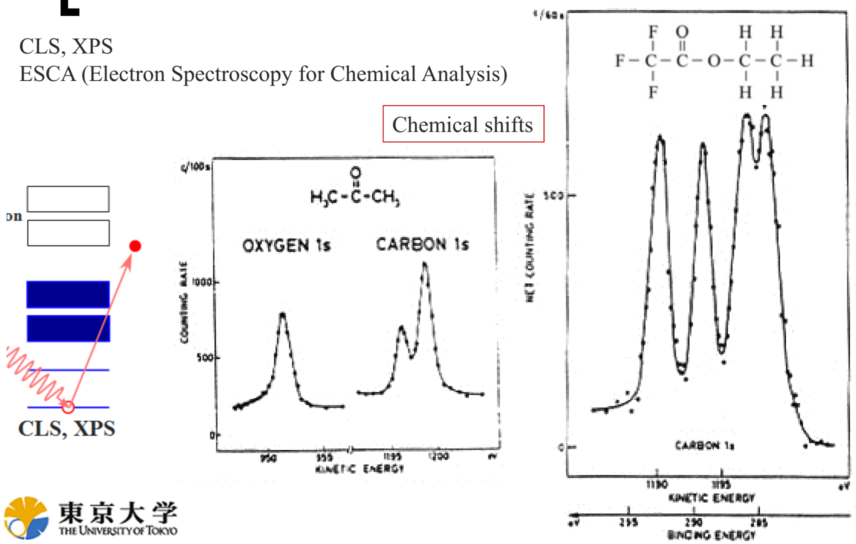
Probing electronic states



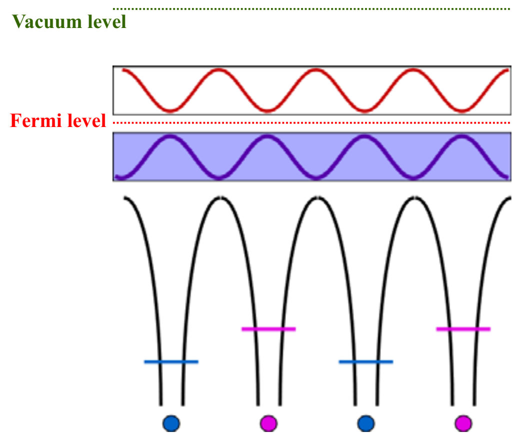
Probing electronic states

CLS, XPS

ESCA (Electron Spectroscopy for Chemical Analysis)



What can be probed by photoemission



Band Dispersions of
- partially occupied states (metal)
- fully occupied states (semiconductor)

Energy shift of core-levels
- Different elements
- Different chemical sites (environments)

Spectroscopy with VUV~SX

- **Energy range to probe**
  - **- atomic structure**
  - **- electronic structure**
  - **- spin structure**

● Diffraction
● Absorption (EXAFS,NEXAFS,MCD)
● Photoemission (ARPES, CLS, Spin-resolved PES, PED)
● X-ray emission

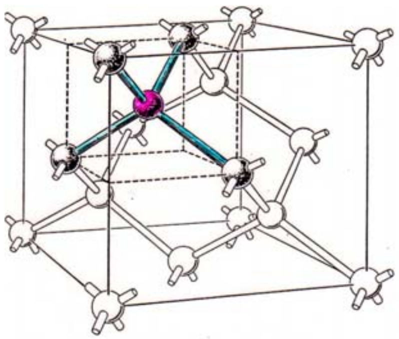
○ surface sensitive ~ bulk sensitive
○ specification of all elements
○ structure determination with high accuracy
○ spin magnetic moment, orbital magnetic moment
○ direct determination of spin-resolved electronic structure

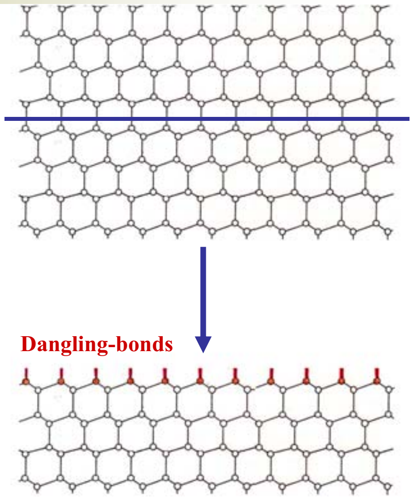
Semiconductor surface

Atomic structure

Cutting (expectation)

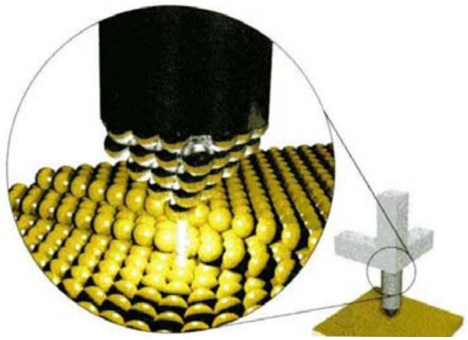
<u>Silicon (Si)</u>
Diamond structure



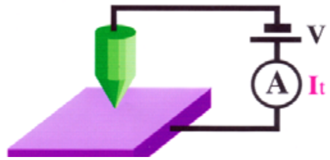


Scanning Probe Microscope

<u>Scanning Tunneling Microscope (STM)</u>



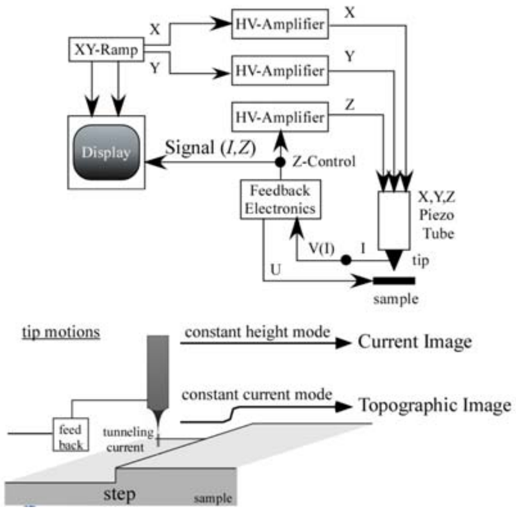
Rohrer and Binnig (1982)

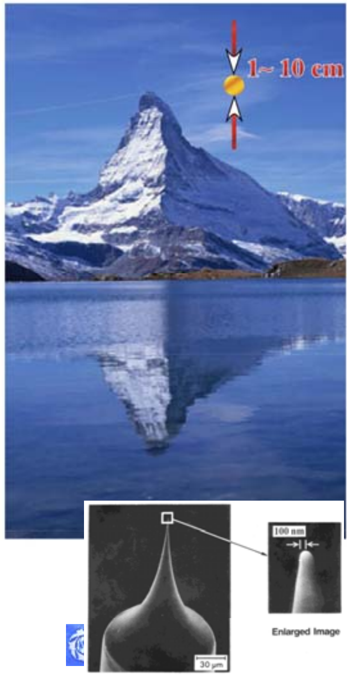


Tunneling Current $I_t \propto f(v) \cdot e^{-\sqrt{\Phi} \cdot d}$

STM

Scanning Tunneling Microscope (STM)

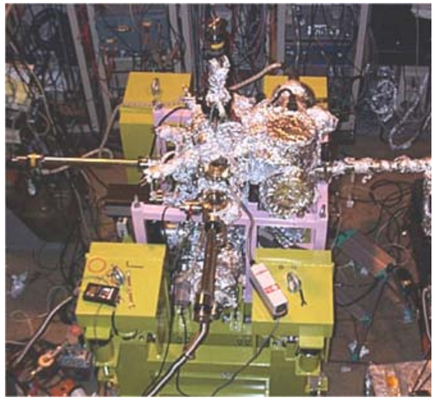




Scanning Tunneling Microscope

An experimental chamber

- the Ultra High Vacuum condition
- Isolation of vibration
- Sample surface preparation



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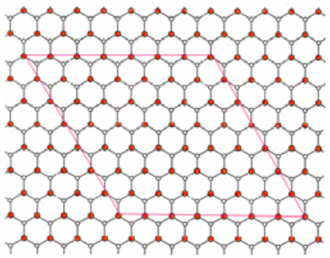
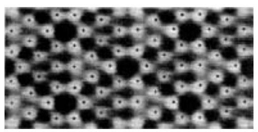
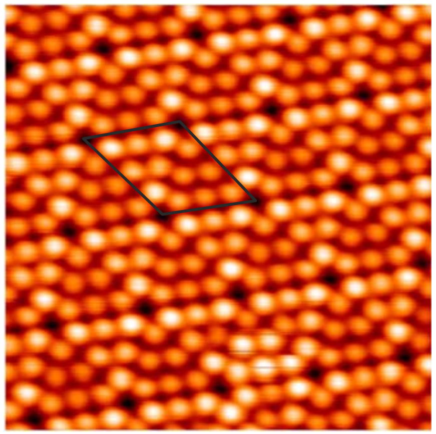
An STM image

Ideal surface





Real surface (STM image)



G. Binnig, H. Rohrer *et al.*, Phys. Rev. Lett. **50** (1983) 120.

The $7a_{1x1}$ (a_{1x1}:3.8 Å) periodicity:
The Si(111)7x7 surface

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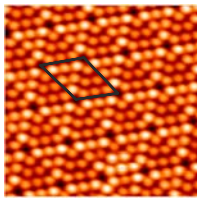
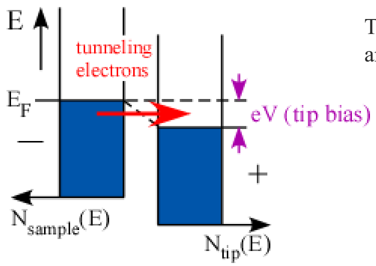
Scanning Tunneling Microscope



It's just an image of atomic scale protrusions measured through tunneling currents.

What are them?



Tunneling currents between unoccupied states and occupied states near Fermi level (EF).

↓

Protrusions in STM could be surface atoms

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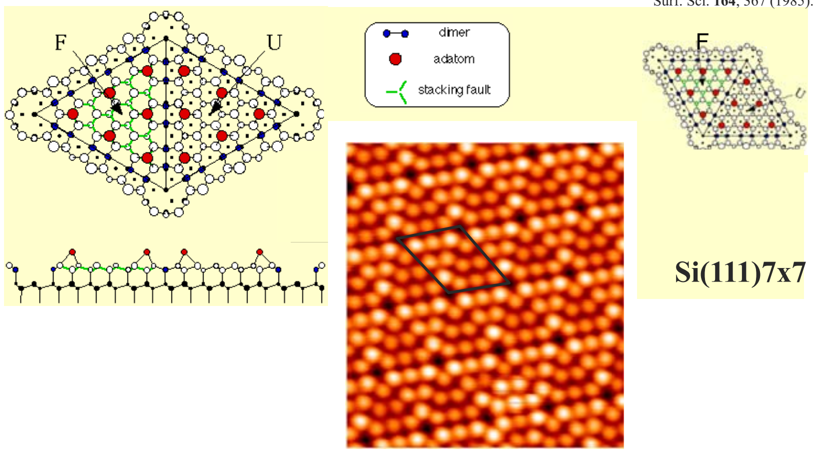
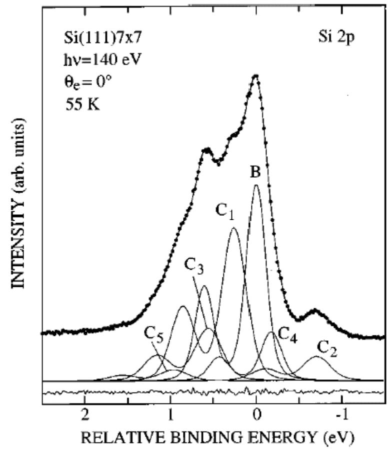
Atomic Structure

Dimaer-Aadatom-Stacking Fault (DAS) model

K. Takayanagi *et al.*, Surf. Sci. **164**, 367 (1985).

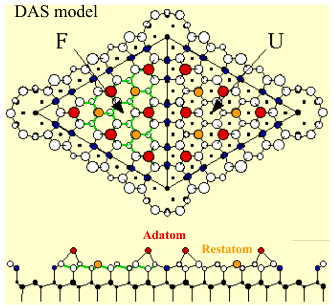


Core-levels



Surface components

C_1: Atom binding to the adatom
C_2: Rest atom
C_3: Adatom
C_4: Dimer atom
C_5: Surface impurity atom



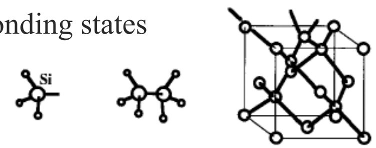
R. I. G. Uhrberg *et al.*, Phys. Rev. B **58**, R1730 (1998).

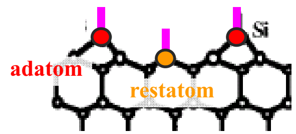
Semiconductor surface

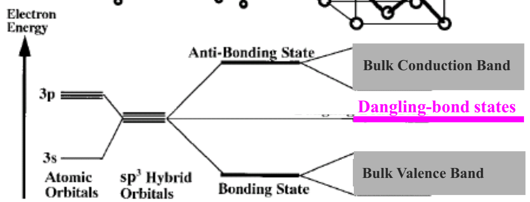
Electronic structure

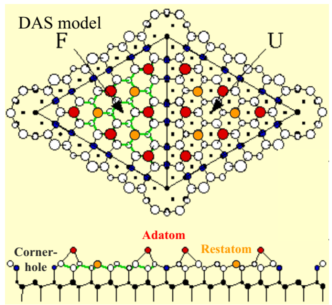
Electronic states of Si(111)7x7

- Bonding states









# of dangling bonds in the 7x7 unit cell

adatom: 12
restatom: 9
corner-hole: 1

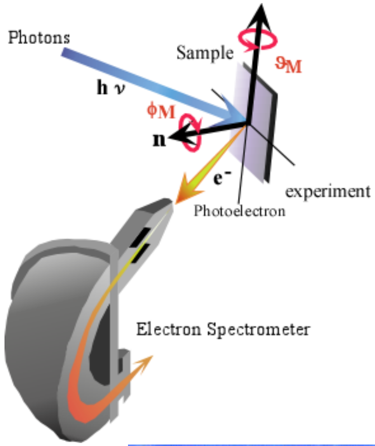
Band mapping

- Angle-resolved photoemission spectroscopy (ARPES)

$E_k = h\nu - \Phi - E_B$ (work function, binding energy)

$k_{||}(\text{Å}^{-1}) = 0.512\,\{(h\nu-\Phi-E_B)\}^{1/2} \cdot \sin\theta_e$

→ Band dispersion $(E, k_{//})$

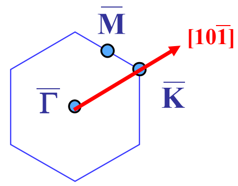


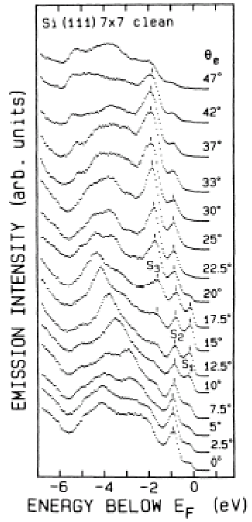
ARPES measurement

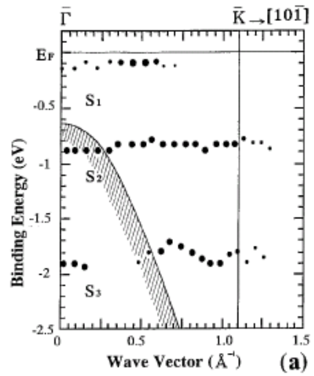
Si(111)7x7

Conventional measurements

Energy spectra at various angles along symmetric crystal axis

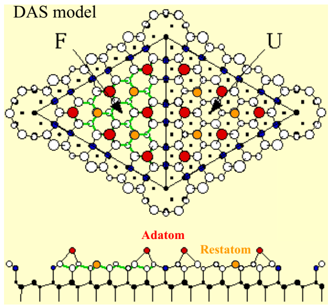


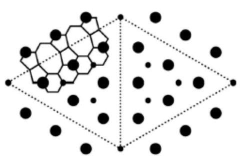


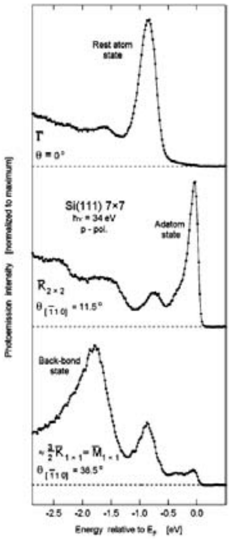


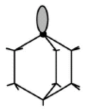
P. Martensson *et al.*, Phys. Rev. B **36**, 5974 (1987).

Dangling bonds

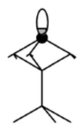








Rest atom state (Fully occupied)



Adatom state (Partially occupied)

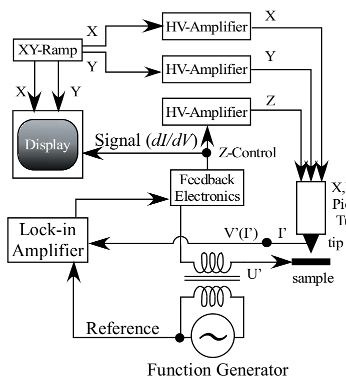
- Charge transfer
- Metallic surface

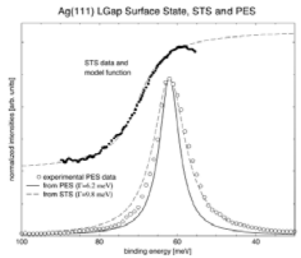
R. Losio *et al.*, Phys. Rev. B **61**, 10845 (2000).

Scanning Tunneling Spectroscopy

G. Nicolay *et al.*, Phys. Rev. B **62** 1631 (2000).

Scanning Tunneling Spectroscopy (STS), dI/dV





Bias Modulation: $V' = V + \varepsilon\sin\omega t$

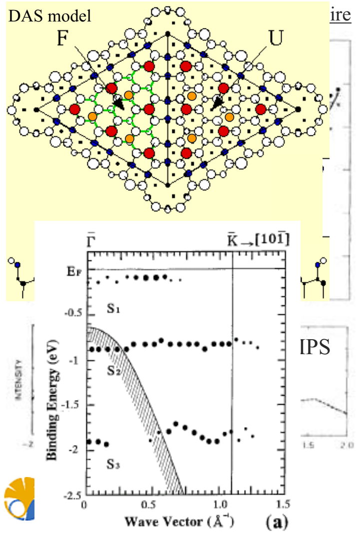
Current Modulation: $I(V+\varepsilon\sin\omega t) = I(V) + \frac{dI}{dV}\varepsilon\sin\omega t$

Detection by phase matching

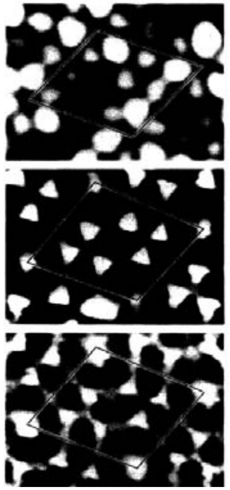
$\frac{dI}{dV}$ ∝ LDOS (Local Density Of States)

C. Bai, *Scanning Tunneling Microscopy and its Application* (Springer,1992)

Scanning Tunneling Spectroscopy



Differential Current Imaging Tunneling Spectroscopy



Adatom state @ - 0.35 V

Rest atom state @ - 0.8 V

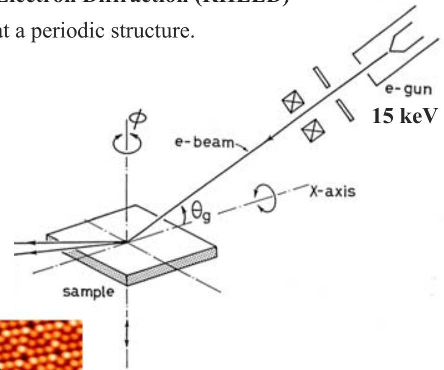
Back bond state @ - 1.7 V

R. J. Hamers *et al.*,
Phys. Rev. Lett. **56**, 1972 (1986).

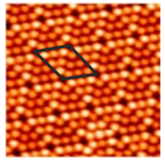
Electron Diffraction

Reflection High-Energy Electron Diffraction (RHEED)

(Electron) Wave diffracts at a periodic structure.

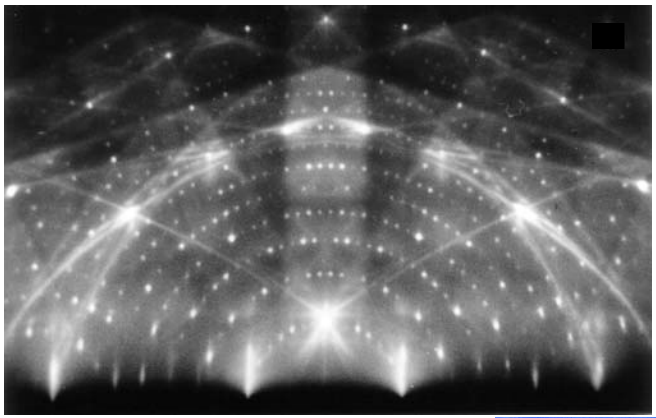


Si(111)7x7

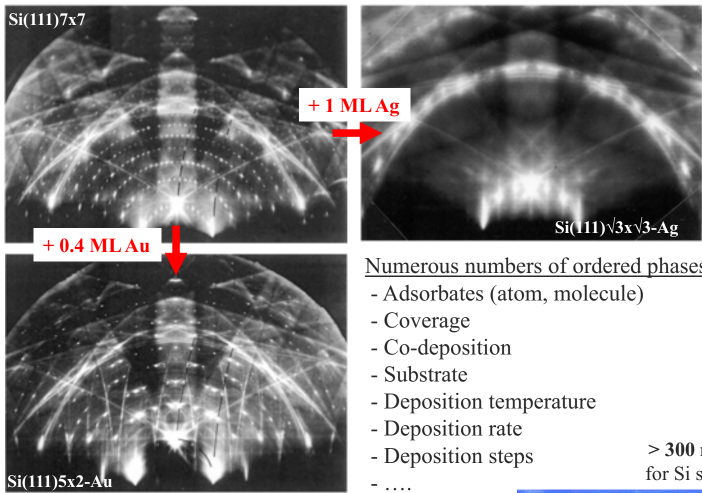


Reflection High-Energy Electron Diffraction

- RHEED pattern of Si(111)7x7 at 15 keV



Variations of ordered surface phases



Numerous numbers of ordered phases
- Adsorbates (atom, molecule)
- Coverage
- Co-deposition
- Substrate
- Deposition temperature
- Deposition rate
- Deposition steps
- ….

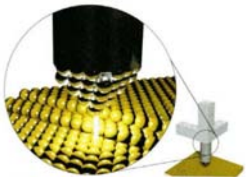
> **300** reported
for Si substrate

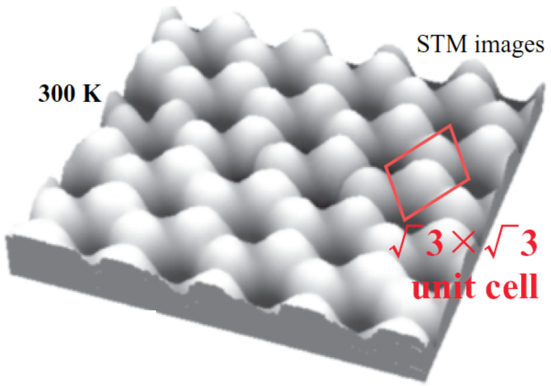
S. Hasegawa *et al.*,
Prog. Surf. Sci. **60**, 89 (1999).

Si(111)√3x√3-Ag

- STM image

1 ML Ag deposition on Si(111)7x7 @ ~ 520℃





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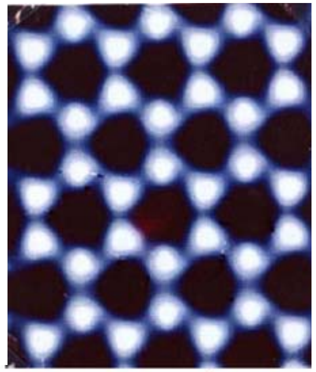
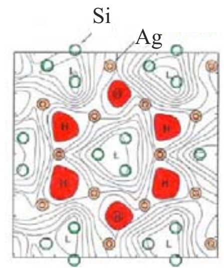
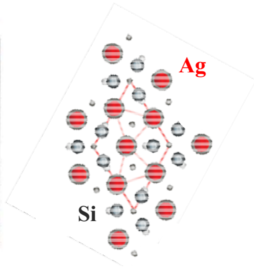
Si(111)√3x√3-Ag

- STM simulation





Tunneling current distribution



Structure model

STM protrusions do not match the atom positions.

S. Watanabe *et al.*, Phys. Rev. B **44**, 8330 (1991).

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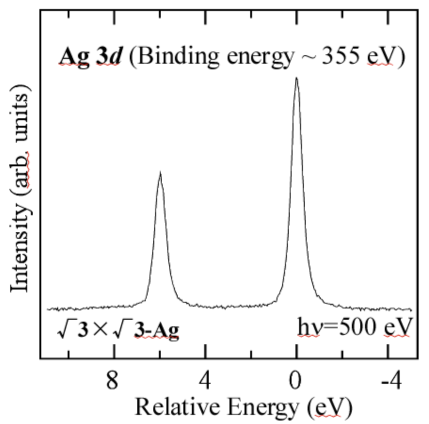
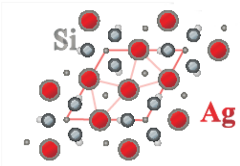
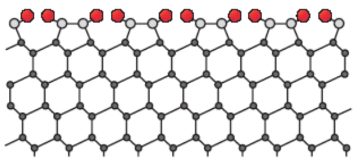
Si(111)√3x√3-Ag

- Atomic Structure and CLS spectra







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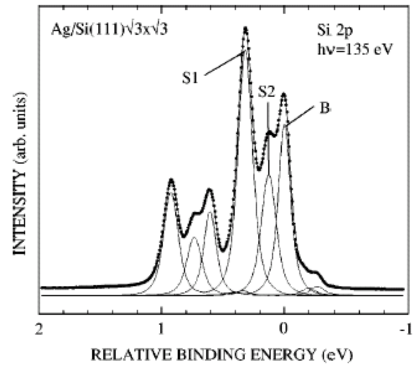
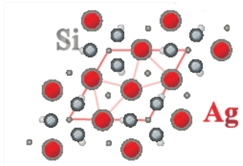
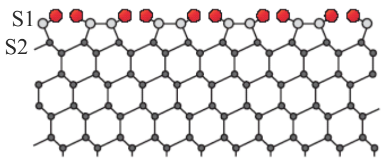
Si(111)√3x√3-Ag

- Atomic Structure and CLS spectra







R.I.G Uhrberg *et al.*, Phys. Rev. B **65**, 081305(R) (2002).

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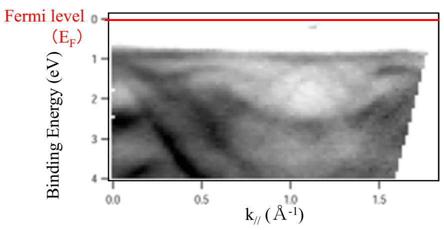
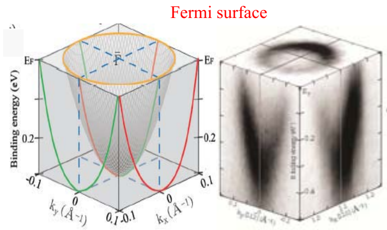
Si(111)√3x√3-Ag

- Electronic Structure



- Metallic surface-state band in the bulk band gap



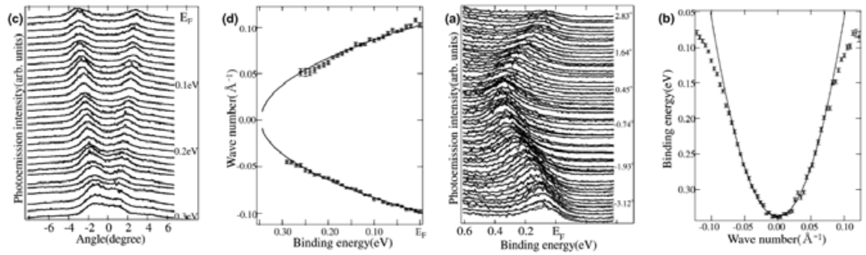
$E = \frac{\hbar^2 k^2}{2m^*}$ 2D Free-Electron-Like State

Si(111)√3x√3-Ag

- Electronic Structure

Angle-Distribution Curves (ADC)

Energy-Distribution Curves (EDC)



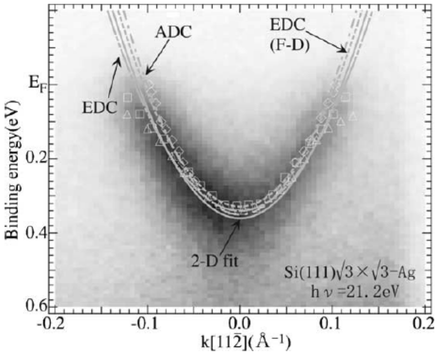
Si(111)√3x√3-Ag

- Electronic Structure

2D-fit

$$\chi^2 = \sum_i \left(\frac{E(k_i) - E_i}{w_i} \right)^2$$

$$E = \frac{\hbar^2 k^2}{2m^*} + E_0$$

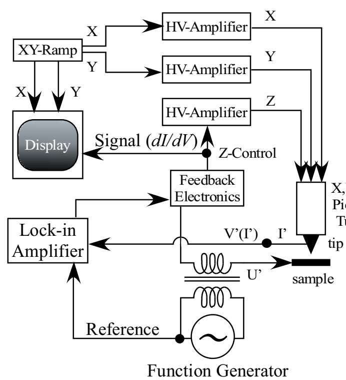


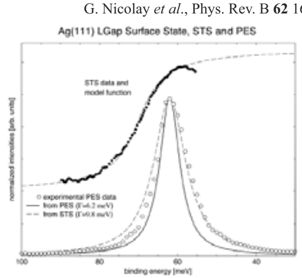
	m^*/m_e	E_0 (eV)	k_F ($Å^{-1}$)
EDC	0.16 ± 0.02	0.32 ± 0.03	0.11 ± 0.01
ADC	0.10 ± 0.03	0.32 ± 0.03	0.10 ± 0.01
2-D	0.12 ± 0.02	0.33 ± 0.03	0.10 ± 0.01

Scanning Tunneling Spectroscopy

G. Nicolay *et al.*, Phys. Rev. B **62** 1631 (2000).

Scanning Tunneling Spectroscopy (STS), dI/dV





Bias Modulation: $V' = V + \varepsilon \sin\omega t$

Current Modulation: $I(V + \varepsilon \sin\omega t) = I(V) + \frac{dI}{dV}\varepsilon \sin\omega t$

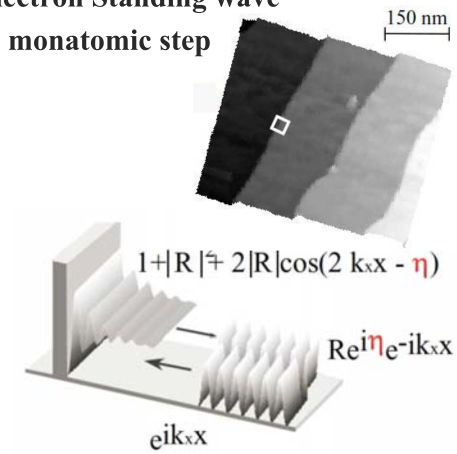
Detection by phase matching

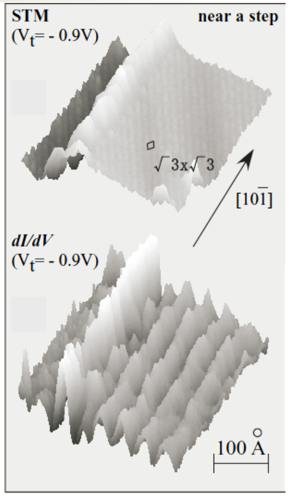
$\frac{dI}{dV}$ ∝ LDOS (Local Density Of States)

C. Bai, *Scanning Tunneling Microscopy and its Application* (Springer,1992)

Si(111)√3x√3-Ag

- Electron Standing wave at monatomic step





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I. Matsuda *et al.*, Phys. Rev. Lett. **93**, 236801 (2004).

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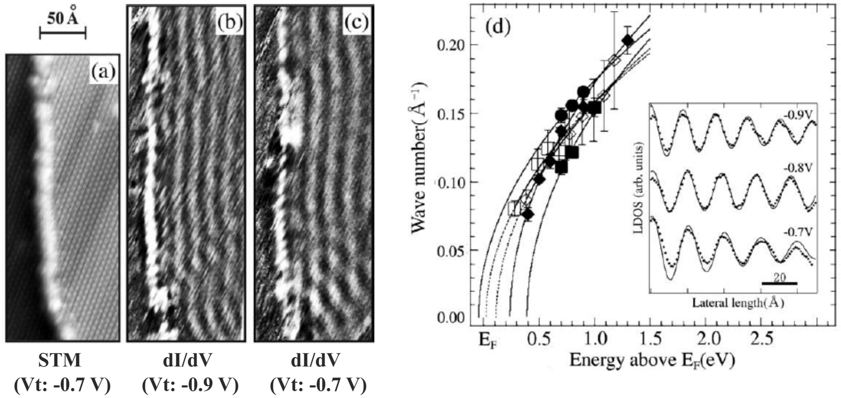
Si(111)√3x√3-Ag

- Electron Standing wave



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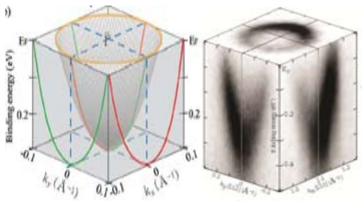
Si(111)√3x√3-Ag

- The 2-D Free electron metallic band



$$E = \frac{\hbar^2 k^2}{2m^*} + E_0$$

The values of m^*/m_e, E_0, k_F for analyses done by EDC, ADC, 2D fit, EDC corrected by the Fermi–Dirac distribution function, and STS

	m^*/m_e	E_0 (eV)	k_F (Å^{-1})
EDC	0.16 ± 0.02	0.32 ± 0.03	0.11 ± 0.01
ADC	0.10 ± 0.03	0.32 ± 0.03	0.10 ± 0.01
2-D	0.12 ± 0.02	0.33 ± 0.03	0.10 ± 0.01
EDC(FD)	0.15 ± 0.02	0.31 ± 0.03	0.11 ± 0.01
STS	0.13 ± 0.03		

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Metal surface

Electronic structure

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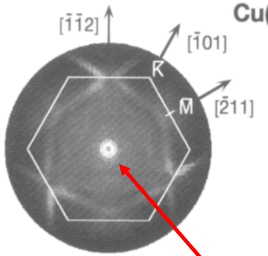
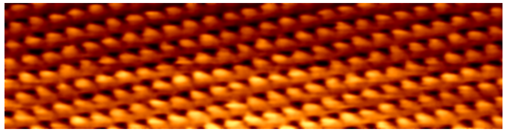
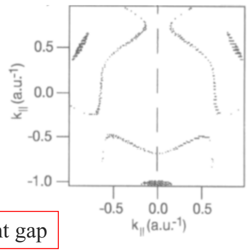


Cu(111)

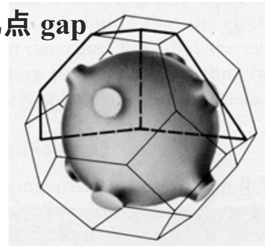


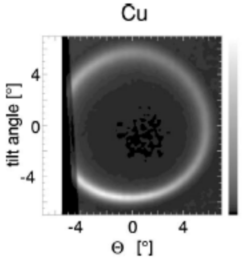


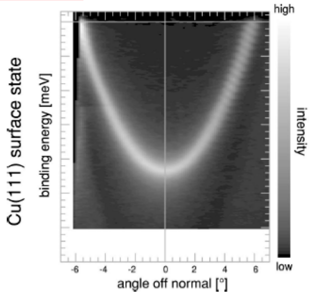
Cu(111)

Surface state in L point gap

L点 gap

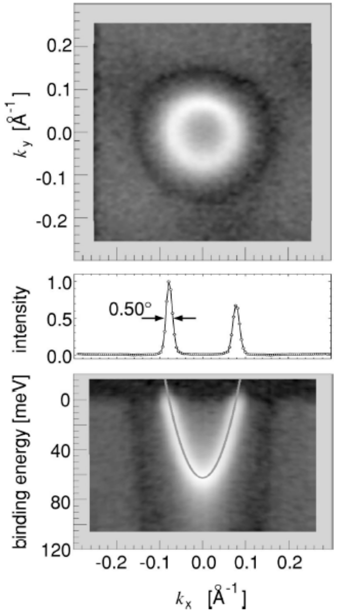


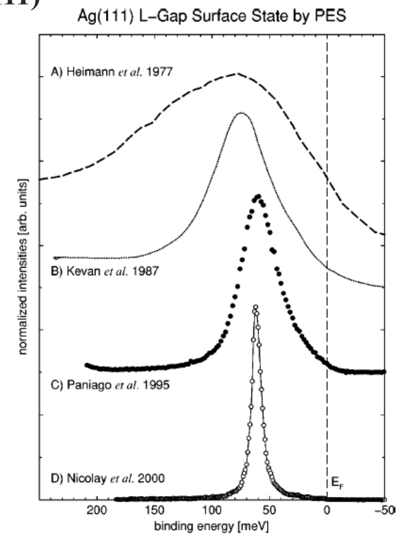




F. Reinert *et al*., Phys. Rev. B **63**, 115415 (2001).

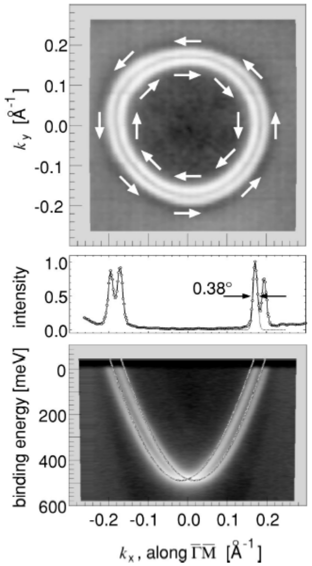
Ag(111)





F. Reinert *et al*., Phys. Rev. B **63**, 115415 (2001).
G. Nicolay *et al*., Phys. Rev. B **65**, 033407 (2001).

Au(111)



Appearance of the two surface-state bands

J. Henk *et al*., Phys. Rev. B **68**, 165416 (2003)

Surface Rashba effect

E. I. Rashba, Sov. Phys. Solid State 2, 1109(1960)

Kramers degeneracy : E(k,↑)=E(k,↓)

Time reversal symmetry: E(k,↑)=E(-k,↓)

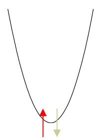
~~Space inversion symmetry: E(k,↑)=E(-k,↑)~~

Breakdown at a surface

Spin-split bands

$$-\frac{\hbar^2}{2m}\nabla^2\psi(\vec{r}) = E\psi(\vec{r})$$

$$E = \frac{\hbar^2 k^2}{2m}$$



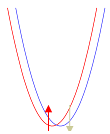
Spin-Orbit Coupling Hamiltonian

Pauli matrix

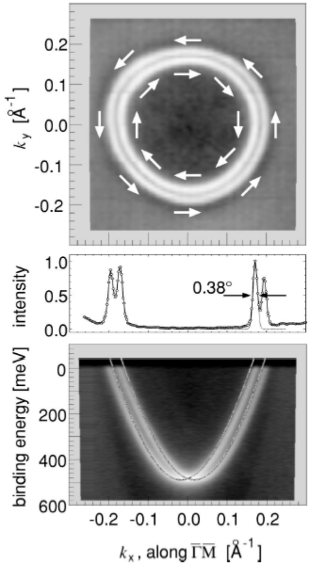
$$H_{SOC} = \frac{\hbar}{4m_e^2c^2}\vec{\sigma}\cdot(\nabla V\times\vec{p})(\propto \vec{s}\cdot\vec{L})$$

Electric field (0,0,E_z)

$$E = \frac{\hbar^2 k^2}{2m} \pm \alpha\hbar k$$



Au(111)



Spin-orbit splitting

$$H_{SOC} = \frac{\mu_B}{2c^2}(\mathbf{v} \times \boldsymbol{\mathcal{E}}) \cdot \boldsymbol{\sigma},$$

$$E^{\uparrow,\downarrow}(k) = E_0 + \frac{\hbar^2 k^2}{2m^*} \pm \alpha k = E_0' + \frac{\hbar^2 (k \pm k_0)^2}{2m^*},$$

↓

Spin-slit surface-state band

↓

Spin-resolved photoemission spectroscopy

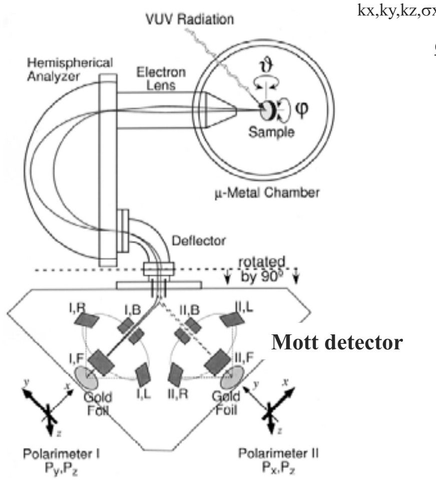
J. Henk *et al*., Phys. Rev. B **68**, 165416 (2003)

Fermi surface mapping with spin-resolved photoemission spectroscopy

H. Moritz *et al*., J. Elec. Spec. Rel. Phenom. **124**, 263 (2002).

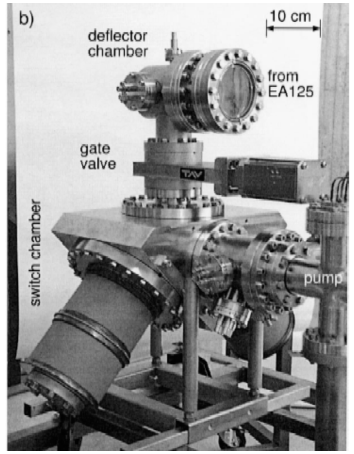
kx,ky,kz,σx,σy,σz are determined with synchrotron radiation

COmplete PHotoEmission Experiment (COPHEE)

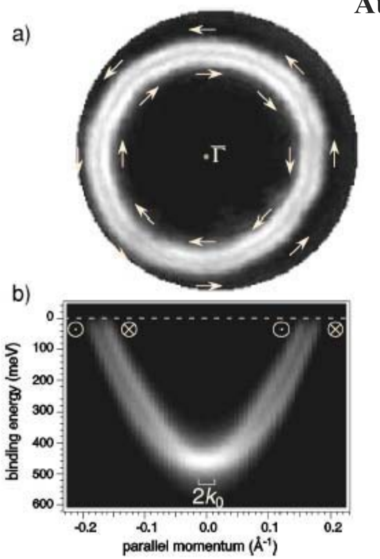


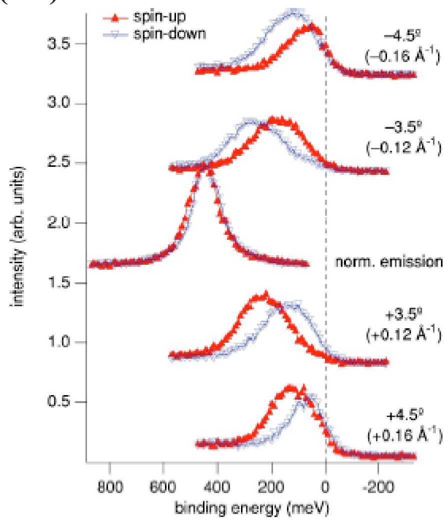
Mott detector

Fig. 4. Schematic view of COPHEE, the COmplete PHotoEmission Experiment. Electrons photoemitted from a sample by UV radiation are energy- and angle-selected by an electrostatic analyzer and detected in two orthogonal Mott polarimeters. In an electrostatic beam deflection system the spin direction is conserved and polarimeter I measures the polarization components P_y and P_z, while polarimeter II measures P_x and P_z. The beam is switched between the two to allow quasi-simultaneous data collection. The labels of the detectors are used in Eq. (10) in the text. The polarimeter system is shown rotated by 90° for graphical clarity.



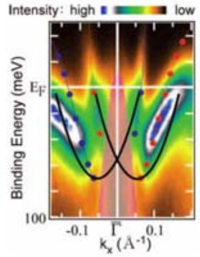
Au(111)





M. Hoesch *et al*., Phys. Rev. B **69**, 241401(R) (2004)

Surface Rashba effect



A band diagram of the Bi(111) surface states taken at photon energy of 21.2 eV.[11, 12] Dispersion curves of the theoretical calculation results and the simple Rashba model are overlapped on the figure.

Table 1. Rashba parameters for various crystal surfaces[18]: Atomic number (Z), the Rashba constant ($|\alpha_R|$), the Rashba momentum (k_R), the Rashba energy (E_R).

Surface	Z	$\lvert\alpha_R\rvert$(eVÅ)	k_R(Å^{-1})	E_R(meV)	Ref.
Ag(111)	47	0.03	0.004	<0.2	13, 14)
Au(111)	79	0.33	0.012	2.1	14, 15)
Bi(111)	83	0.56	0.05	14	16)
$\sqrt{3}\times\sqrt{3}$-Pb/Ag(111)	82/47	1.42	0.03	21	17)
$\sqrt{3}\times\sqrt{3}$-Bi/Ag(111)	83/47	3.05	0.13	200	18)

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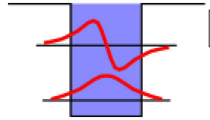
Metal films

Electronic structure

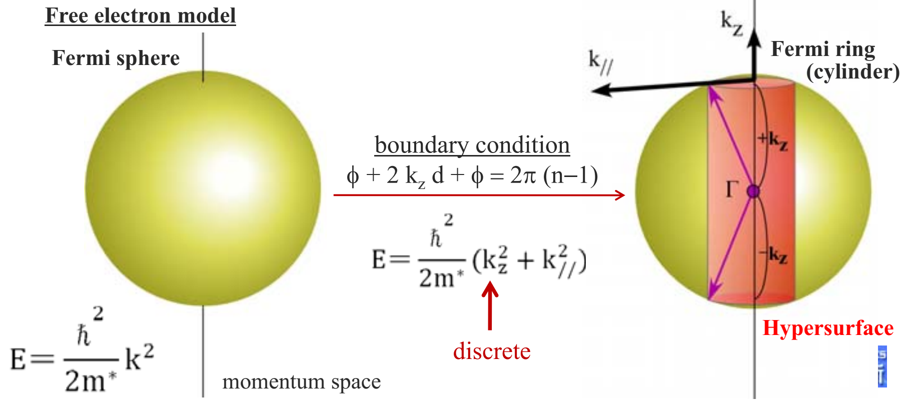
- Quantum Film

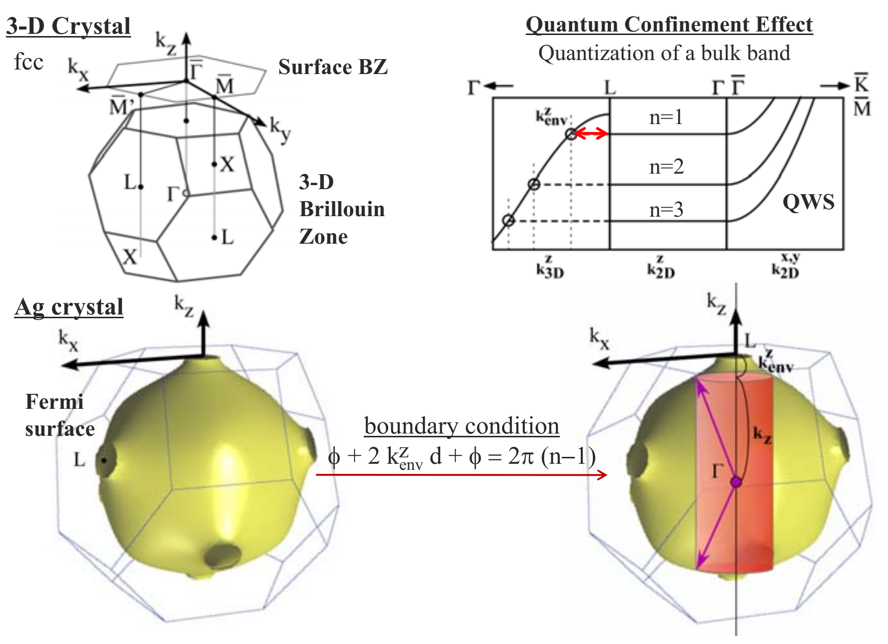
Quantum Size effect, Quantum Confinement Effect



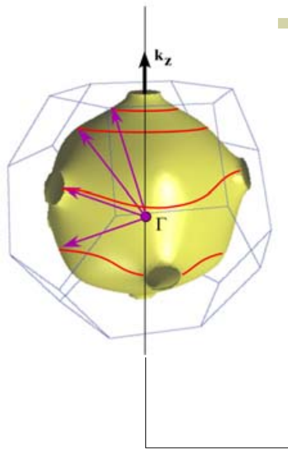
A problem of particles (electrons) in a box

Energetically quantized electronic states
Quantum Well States (**QWS**)



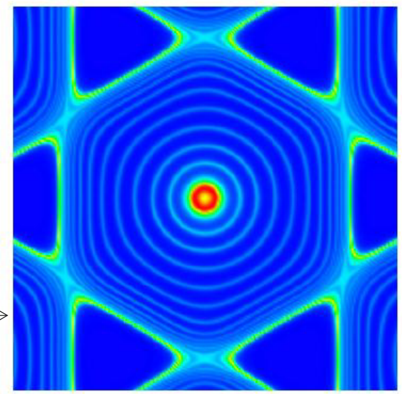


Uktrathin Ag(111) film (quantum film)



Fermi surface of Ag(111) slab calculation

(15 ML-Ag(111) free-standing slab)

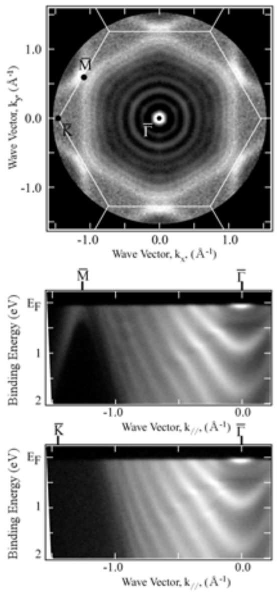


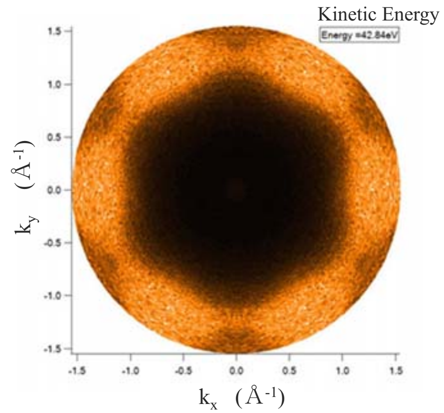
6-fold symmetry

Summation of the wave functions of + kz and -kz

weight: spectral intensity

Epitaxial 15ML-Ag(111) film on Si(111)





In addition to band features expected,
new features, kinks, hexagons at $\bar{\Gamma}$, are observed.

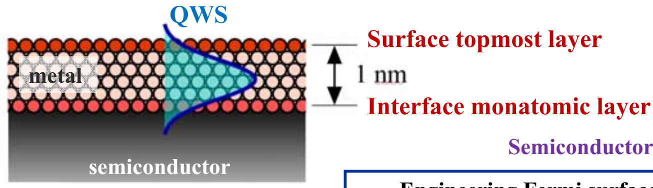
Our interests

<u>**Quantum Size effect, Quantum Confinement Effect**</u>

Thickness : <u>Semiconductor</u>
de Broglie wave, ~ 100 nm
<u>Metal</u>
Fermi wavelength, **~ 1nm**

Large ratio of a surface (interface) monatomic layer to film atomic layers: > 1 / 10

Ultrathin film (2-D growth)



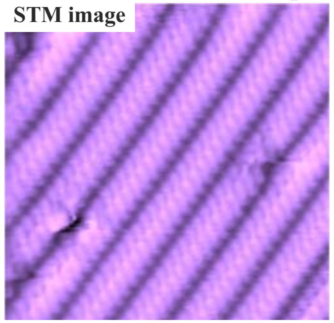
Semiconductor Surface Science

Engineering Fermi surface topology
Electronic topological transition
by an interface monatomic layer

Choice in Semiconductor Surface Science

<u>A periodic array of atomic wires:</u>

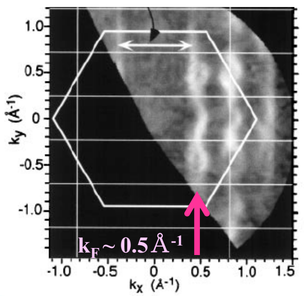
STM image

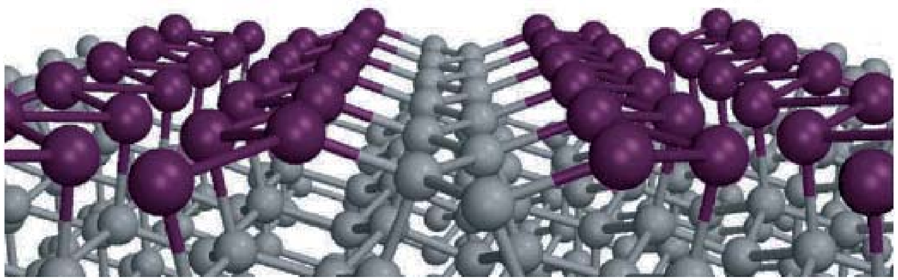


Si(111)4x1-In

a_{int} = 1.3 nm

Photoemission Fermi surface

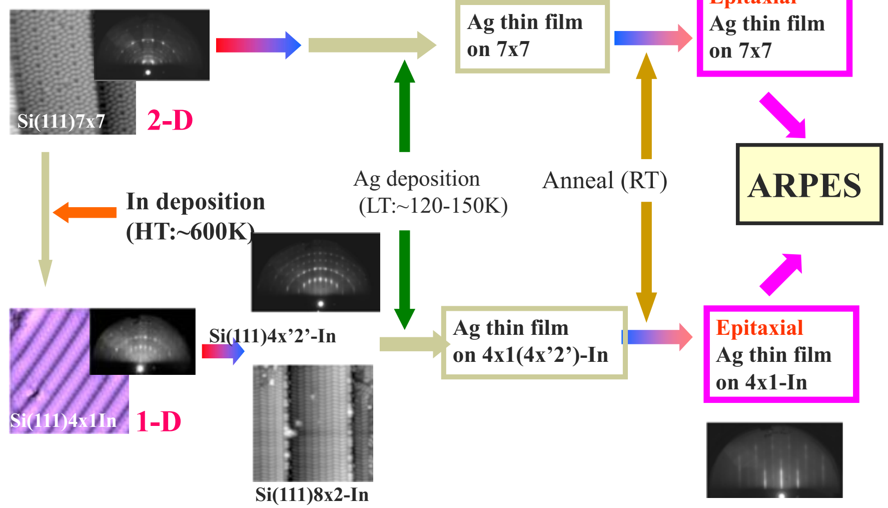




Experiments

Exchange of interface layer between film and substrate

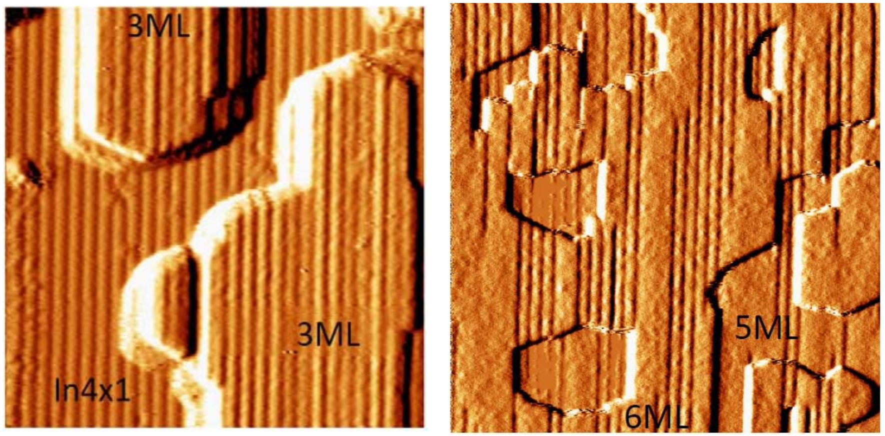
Substrate: vicinal Si(111) (1.8° -off)



Results & Discussions

STM: Ag film / Si (111)4x1-In

T. Uchihashi *et al*., Phys. Rev. Lett. **96,** 136104 (2006)



Results & Discussions

BL3.2 VUV Elettra, Italy

hv=50eV room temperature

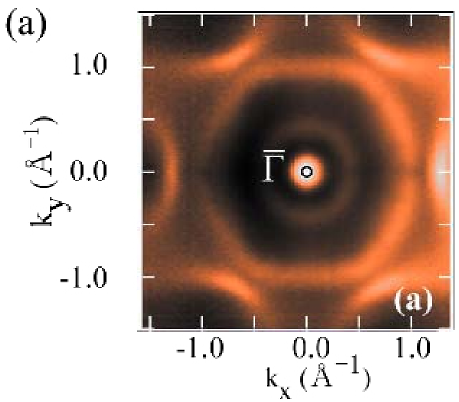
Ag film (~1nm) / Si (111)4x1-In **Ag film (~1nm) / Si (111)7x7**

Results & Discussions

BL3.2 VUV Elettra, Italy

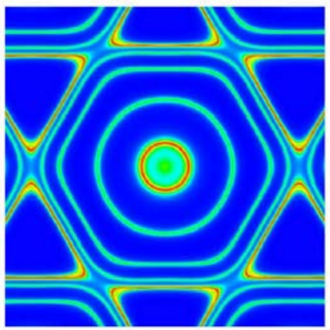
ARPES: Ag film (~1nm) / Si (111)7x7

Photoemission Fermi surface



Calculation

(6 ML-Ag(111) free-standing slab)



weight:
spectral intensity

$\phi_{vac} + 2k_z d + \phi_{sub} = 2\pi n$ ⇠⇢ $2k_z d + 2\phi_a = 2\pi n$

Different k_z(E) or E(k_z)

Results & Discussions

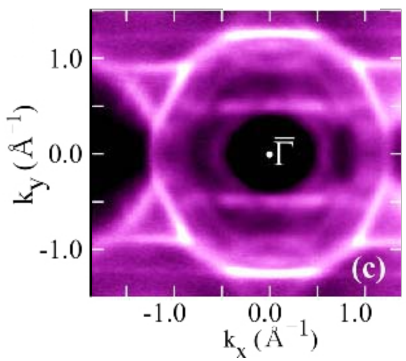
BL3.2 VUV Elettra, Italy

ARPES: Ag film (~1nm) / Si (111)4x1-In

hv=50eV

room temperature

Photoemission Fermi surface



Solid Surface

Playgrounds for low-dimensional physics

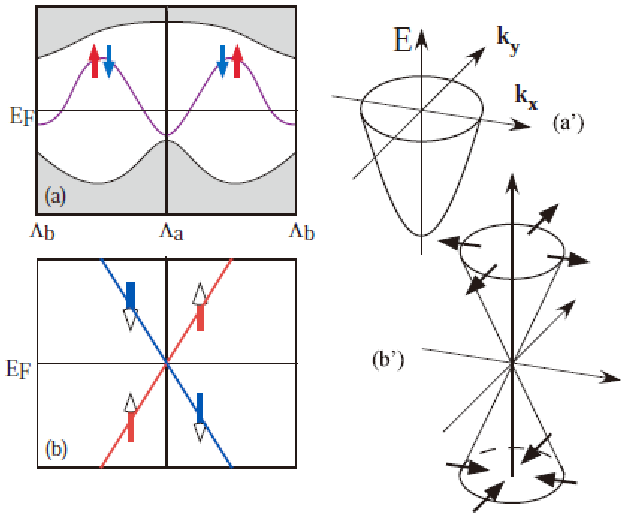
Surface electronic structures

Schroedinger electron

$$\frac{\mathbf{p}^2}{2m}\Psi = E\Psi$$

Dirac-Wely electron

$$(c\alpha\cdot\mathbf{p})\Psi = E\Psi$$



Surface electronic structures

Spin-orbit interaction

Dirac equation:

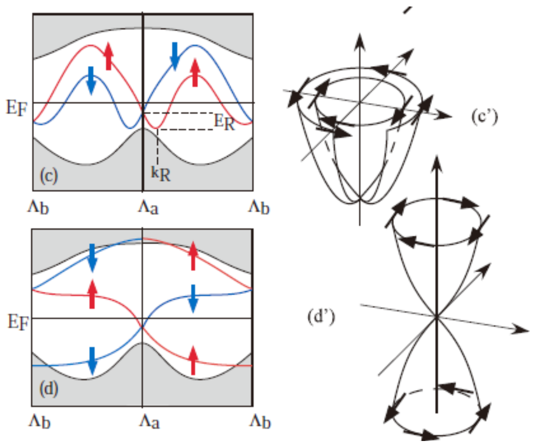
$$\left[\frac{\mathbf{p}^2}{2m} - \frac{e\hbar\sigma\cdot\mathbf{p}\times\xi}{4m^2c^2} + \frac{e\hbar}{2m}\sigma\cdot\mathbf{B} - \frac{e\hbar^2}{8m^2c^2}\nabla\cdot\xi\right]\Psi = E\Psi$$

Surface Rashba effect

$$E^{\uparrow\downarrow}(k) = \frac{\hbar^2k^2}{2m} \pm \frac{\hbar^2}{2m^2c^2}\left(\frac{\partial V}{\partial z}\right)k$$

$$= \frac{\hbar^2k^2}{2m} \pm \frac{\hbar^2}{m}k_Rk = \frac{\hbar^2k^2}{2m} \pm \alpha_Rk$$

Quantum Spin Hall Phase



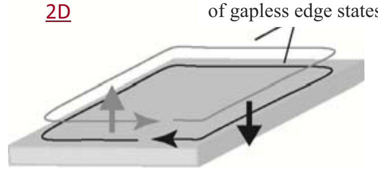
Quantum spin Hall phase (topological insulator)

Kane,Mele, PRL(2005), Bernevig, Zhang, PRL (2005)

- bulk = gapped (insulator)
- gapless edge states -- carry spin current, topologically protected robust against nonmagnetic impurities
- spin analogue of the quantum Hall effect "new state of matter"
- no field required

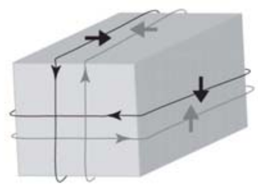
2D

Spin current (Kramers pair of gapless edge states)



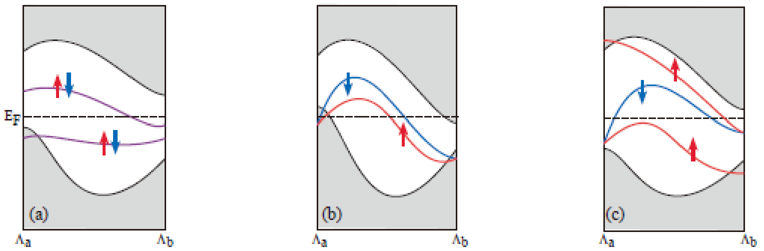
1D-edge states

3D



2D-edge states surface states

Surface electronic structures



Typical surface states within the bulk band gap (ex. Si, Ge)

- Schockley states
- Tamm states

- spin-degenerate

Z_2 invariants: zero

Surface states of (semi)metal crystals with strong spin-orbit interaction (ex. Bi, Au)

-Rashba effect

- spin-split

Z_2 invariants: zero

Edge-states of topological insulators (ex. $Bi_{0.9}Sb_{0.1}$)

-Odd number of Fermi level crossings

- spin-split

Z_2 invariants: nonzero

Topological band theory

Z_2 topology in band structure

Parity: $\delta_i = \pm 1$

$\delta_i = \prod_{m=1}^{N} \xi_{2m}(\Gamma_i)$ With inversion symmetry

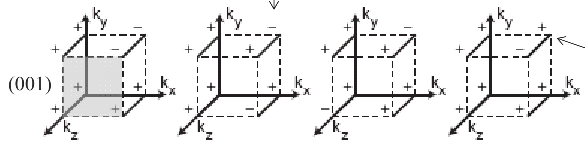
Parity eigenvalue
+1: symmetric
-1: asymmetric

$\delta_i = \frac{\sqrt{\det[w(\Gamma_i)]}}{\mathrm{Pf}[w(\Gamma_i)]}$ No inversion symmetry

$w_{mn}(\vec{k}) = \langle u_{-k,m} | \Theta | u_{k,n} \rangle$

Time-reversal operator

1/8 of the 3D-Brillouin Zone (BZ)



time-reversal invariant, satisfying $-\Gamma_i = \Gamma_i + \boldsymbol{G}$

$$(-1)^{\nu_0} = \prod_{i=1}^{8} \delta_i .$$

expressed as the product over all eight points

Z_2 topological numbers: products of the parity eigenvalues

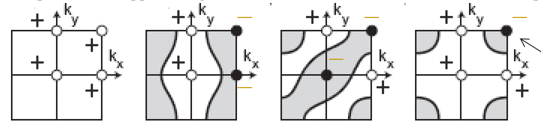
0; (001) 0; (011) 0; (111) 1; (111)

$$(-1)^{\nu_k} = \prod_{n_k=1;\, n_{j\neq k}=0,1} \delta_{i=(n_1 n_2 n_3)} .$$

given by products of four δ's for which Γ_i reside in the same plane

(001) 2D-BZ
with Fermi arcs of surface states enclosing the specific Λ points

If the two k-points have opposite signs, the Fermi surface crosses between the two points.



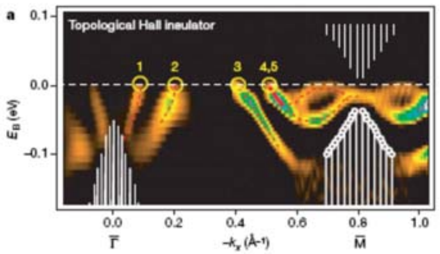
time-reversal invariant momenta, Λ

The $Bi_{1-x}Sb_x$ case

$Bi_{0.9}Sb_{0.1}$

Experiment ARPES

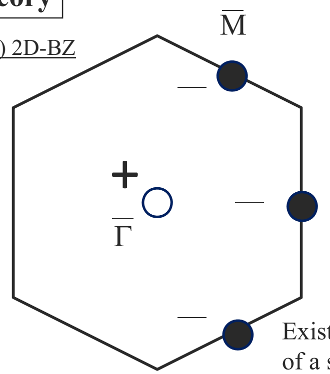
theory: Fu et al., Phys. Rev. Lett. ('07)
exp.: Hsieh et al., Nature ('08)



Odd number (five) of Fermi points between Γ and M.

Theory

(111) 2D-BZ

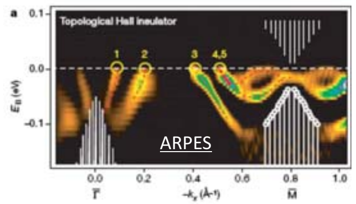


Agreement

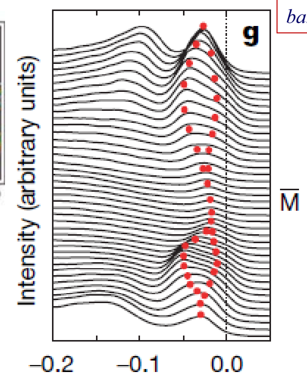
Existence of Fermi crossing of a spin-nondegenerate band between Γ and M.

Motivation

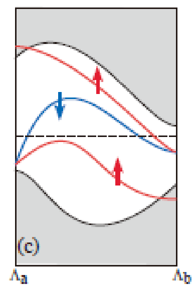
$Bi_{0.9}Sb_{0.1}$



theory: Fu et al., Phys. Rev. Lett. ('07)
exp.: Hsieh et al., Nature ('08)



Elaborate band structure?



Spin-polarized band structure?

Spin- and angle(momentum)-resolved photoemission spectroscopy

How do we determine momentum of electrons?

Electron spectrometers from VG, Scienta, Omicron, Specs….

How do we determine their spin coordinates?

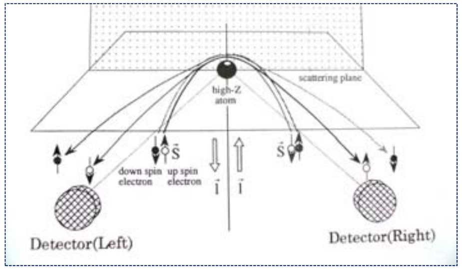
Spin detector , Spin polarimeter

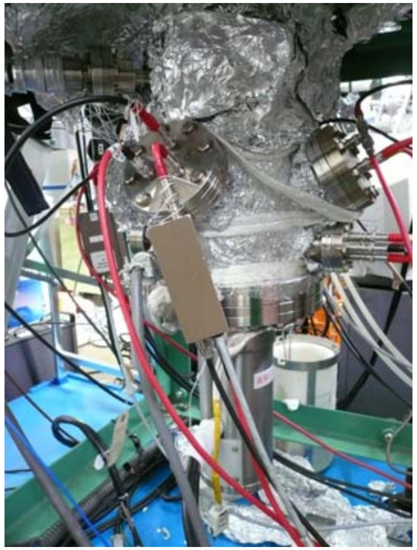
Spin-detector (Mott detector)

25 kV-Compact Mott detector

by A. Kakizaki *et al*.

S. Qiao, *et al*., Rev. Sci. Instrum., **68**, 4390 (1997).

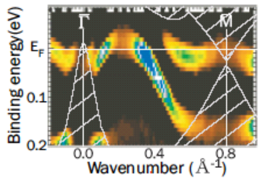


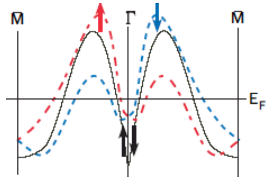


- 25 keV electrons
- spin-orbit interaction
- Au target

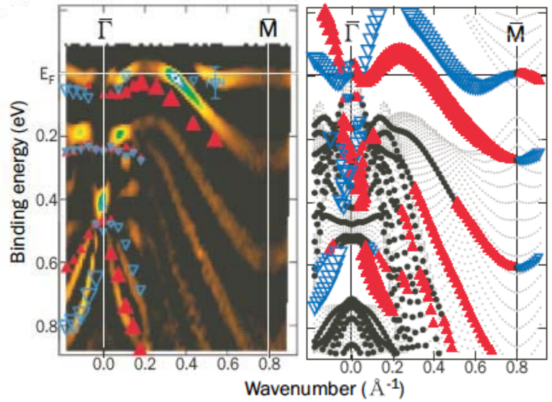
Spin-detector (Mott detector)

Spin-resolved band mapping of Bi crystal film with a 25 kV-Compact Mott detector





Rashba effect
of the surface state

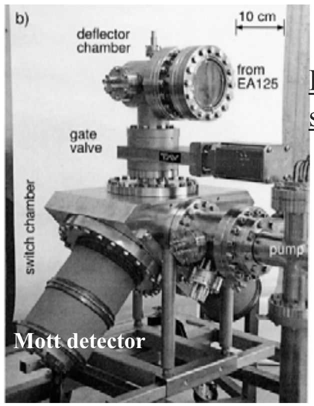


T.Hirahara *et al*., Phys. Rev. B **76**,153305 (2007).

Spin-detector (Mott detector)

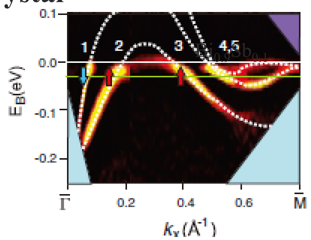
Spin-resolved band mapping of $Bi_{1-x}Sb_x$ crystal with a Compact Mott detector

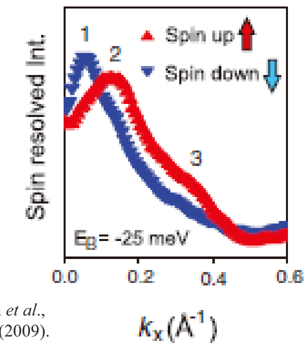
COmplete PHotoEmission Experiment (COPHEE)



Low
spin efficiency

ΔE=
100~200meV





H. Moritz *et al*.,
J. Elec. Spec. Rel. Phenom. **124**, 263 (2002).

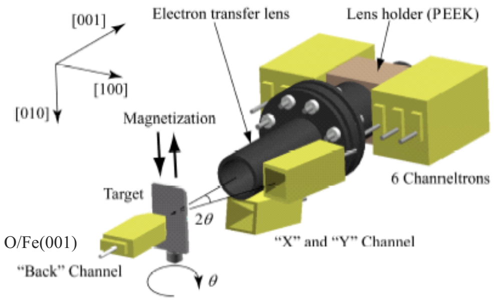
Hsieh *et al*.,
Science **323**, 919 (2009).

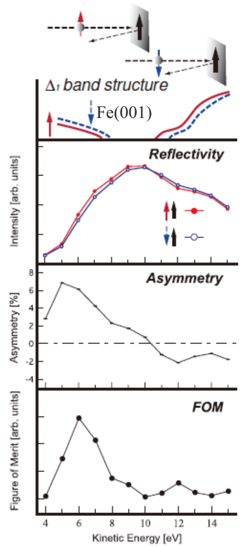
Spin-detector (VLEED detector)

Very Low- Energy Electron Diffraction (VLEED) detector

by T. Okuda *et al*.

T. Okuda, Y. Takeichi, Yuuki Maeda, A. Harasawa, I. Matsuda, T. Kinoshita, and A. Kakizaki,
Rev. Sci. Instrum. **79,** 123117 (2008).

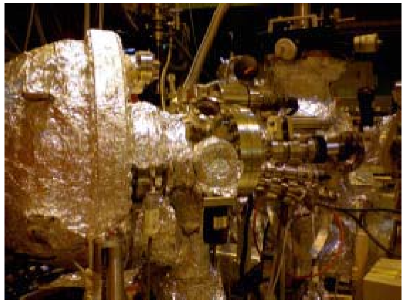


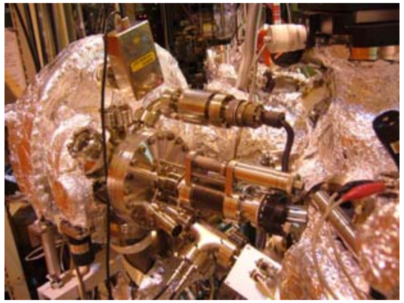


- 6 eV electrons
- exchange interaction
- Fe, O/Fe target

Spin-detector (VLEED detector)

SPECS-PHOIBOS150+VLEED detector





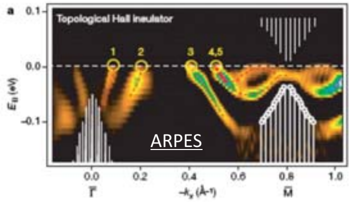
High-efficient spin detection (100 times better than the Mott detector)

→ A combination with high-resolution analyzer

$\varepsilon = (1.0 \pm 0.2) \times 10^{-2}$, ΔE< 30 meV

Motivation

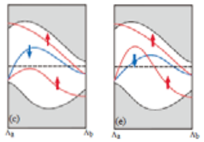
$Bi_{0.9}Sb_{0.1}$



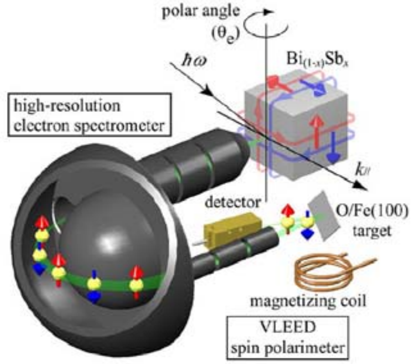
theory: Fu et al., Phys. Rev. Lett. ('07)
exp.: Hsieh et al., Nature ('08)

Odd number (five) of Fermi points between $\bar{\Gamma}$ and $\bar{M}$.

Spin-polarized band structure?



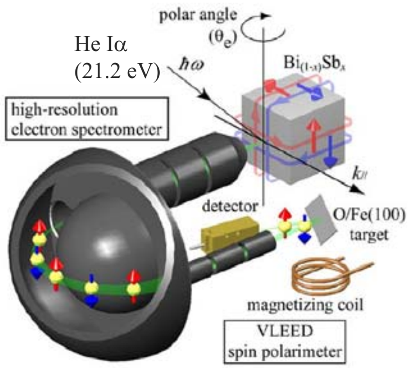
high-resolution spin-resolved photoemission spectroscopy



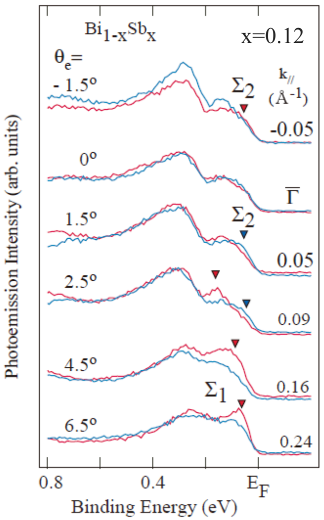
Results and Discussion

high-resolution spin-resolved photoemission spectroscopy

Measurement condition



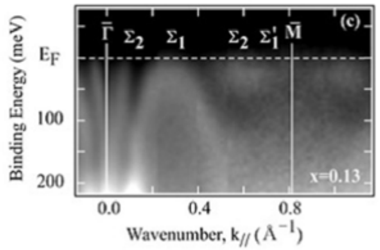
ΔE =50 meV, Δθ=±1°
T~130 K
Seff = *0.32 ± 0.04*,
determined by the polarization
of secondary electrons from Fe(001).

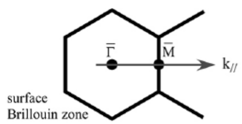


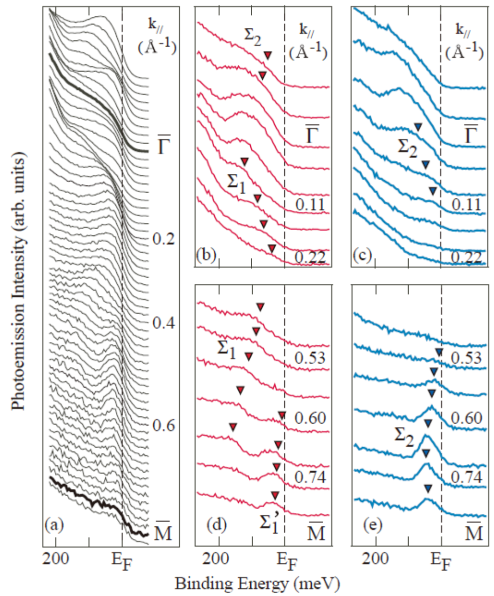
Results and Discussion

$Bi_{1-x}Sb_x$

x=0.12,0.13

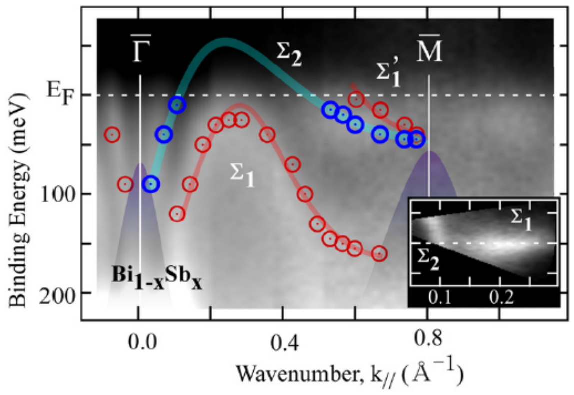


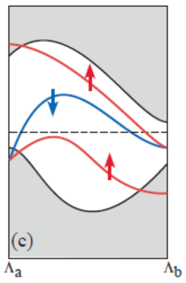




Results and Discussion

Spin-resolved band plots
on spin-integrated grayscale band diagram





Edge-states
of topological insulators
(ex. $Bi_{\sim 0.9}Sb_{\sim 0.1}$)

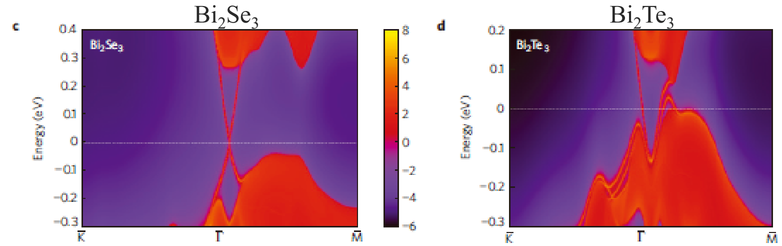
-Odd number of
Fermi level crossings

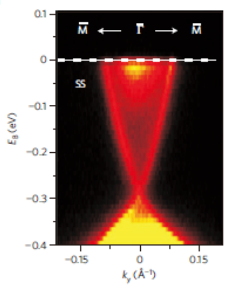
- spin-split

- **Z_2 invariants: nonzero**

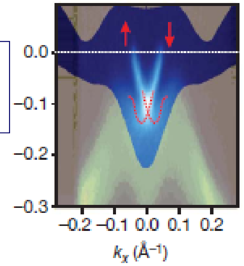
○**The second generation samples**

H.Zhang *et al.*, Nature Phys. 5 438 (2009).





Well-defined stoichiometry
Single-band (One Kramers pair)
Wide bulk band gap (300 meV, 3600 K)



Y. Xia *et al.*, Nature Phys. **5** 398 (2009).

D. Hsieh *et al.*, Nature **460** 1101 (2009).

Summary

- Surface Science is everywhere. Global to Atomic scale.
- For solid/vacuum interface (solid surface), we have advantages of
  - **Visualization of atomic configuration and electron density (LDOS) distribution in atomic scale**
  - **Direct determination of electronic structure (band, Fermi surface, spin, etc…)**
- Solid surfaces are important playgrounds for studying low-dimensional physics.

  Photoemission spectroscopies with synchrotron radiation are the important experimental tools.

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Frontier Spectroscopy experiments at SPring-8 BL07LSU:
with time-resolution and at nano-space

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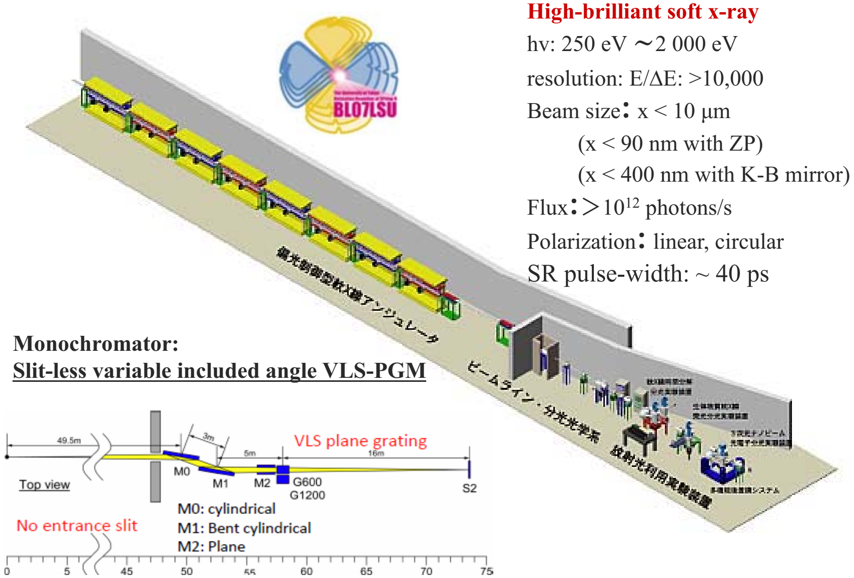
SPring-8 BL07LSU



Monochromator:
Slit-less variable included angle VLS-PGM

Specification

High-brilliant soft x-ray

hv: 250 eV ～2 000 eV

resolution: E/ΔE: >10,000

Beam size: x < 10 μm

(x < 90 nm with ZP)

(x < 400 nm with K-B mirror)

Flux: > 10^{12} photons/s

Polarization: linear, circular

SR pulse-width: ~ 40 ps

SPring-8 BL07LSU

Four spectroscopy end-stations

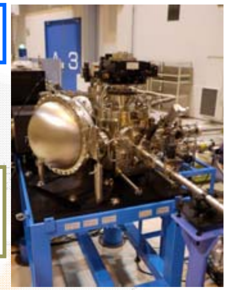
Time-Resolved soft X-ray spectroscopy station
TR-SX spectroscopy

Time-resolved angle-resolved photoemission spectroscopy with a 2D-ARTOF spectrometer and fs-pulse lasers

3D-scanning photoelectron microscope
3D nano-ESCA

Spatial resolution: 50 nm (x,y)

Depth profile: 0.1 nm (z)



Ultra high-resolution soft X-ray emission spectroscopy
HORNET

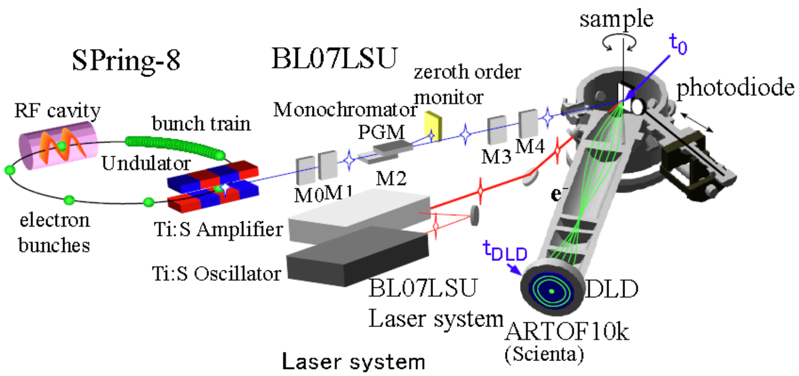
Ultimate resolution

Measurement of solid, liquid, gas

Free-Port station

Open for experimental system of users

Time-Resolved soft X-ray spectroscopy station
TR-SX spectroscopy



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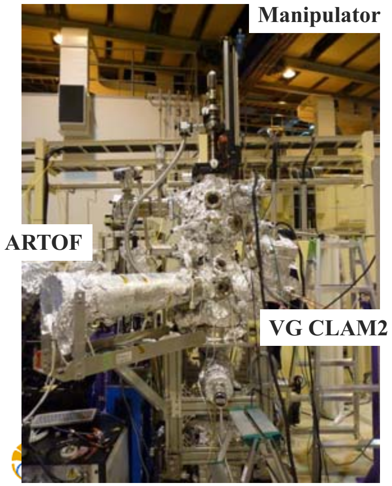
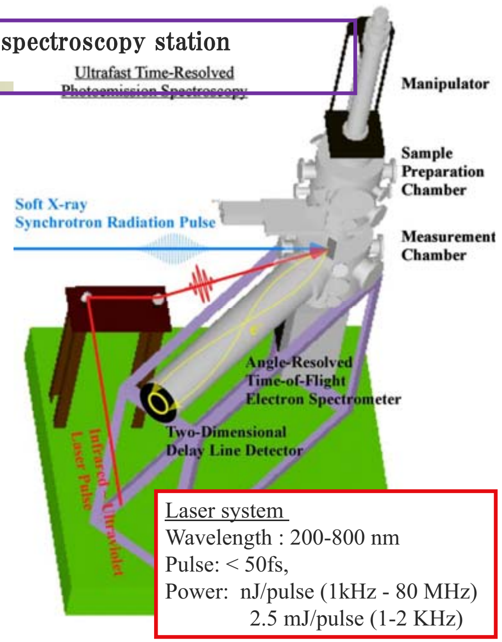
Time-Resolved soft X-ray spectroscopy station
TR-SX spectroscopy

Ultrafast Time-Resolved Photoemission Spectroscopy

The measurement system

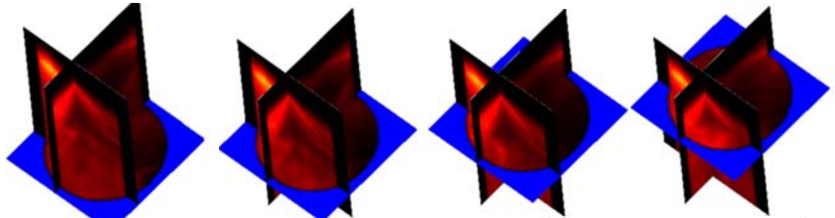




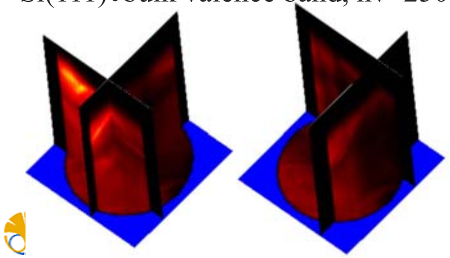
Time-Resolved soft X-ray spectroscopy station
TR-SX spectroscopy

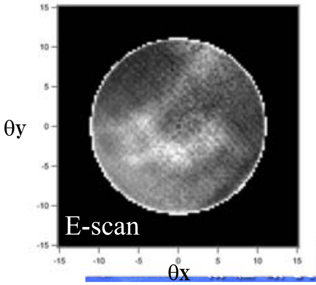
θx 、 θy range=+/- 12.5°
(θx 、 θy、 Max. range= +/- 15°)
Energy range=17.5eV

○ 2-D angle-resolved mapping without the sample rotation



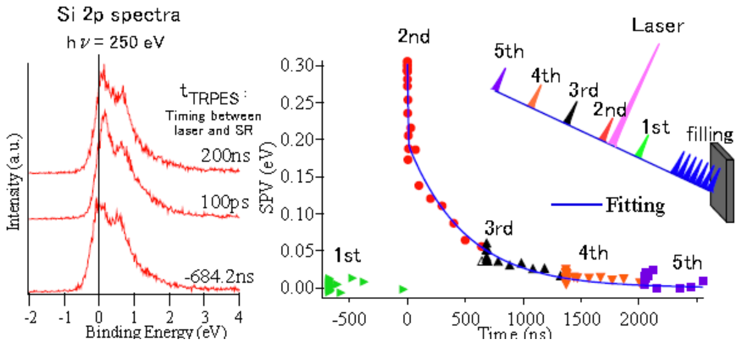
Si(111): bulk valence band, hv=250 eV





Time-Resolved soft X-ray spectroscopy station
TR-SX spectroscopy

Pump(laser)-Probe(synchrotron radiation) time-resolved photoemission experiments on relaxation after the surface photovoltage effect of Si(111)7x7



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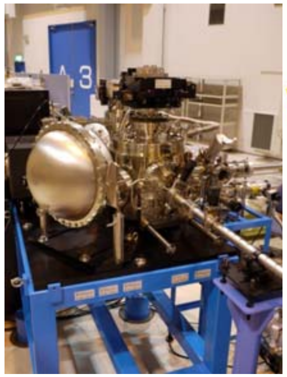
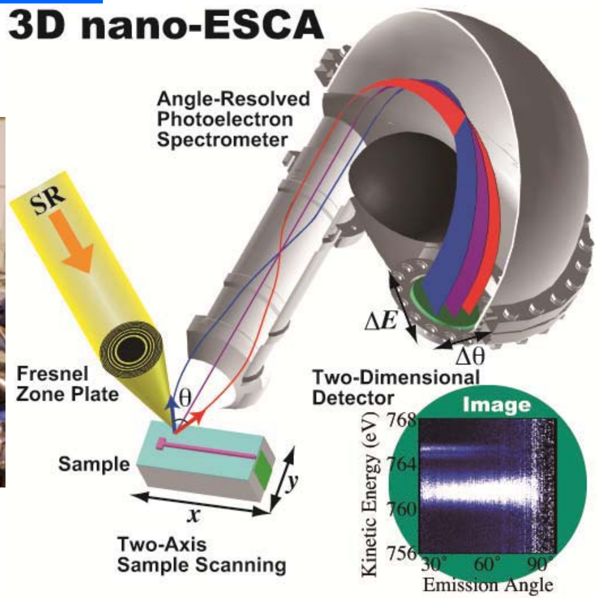
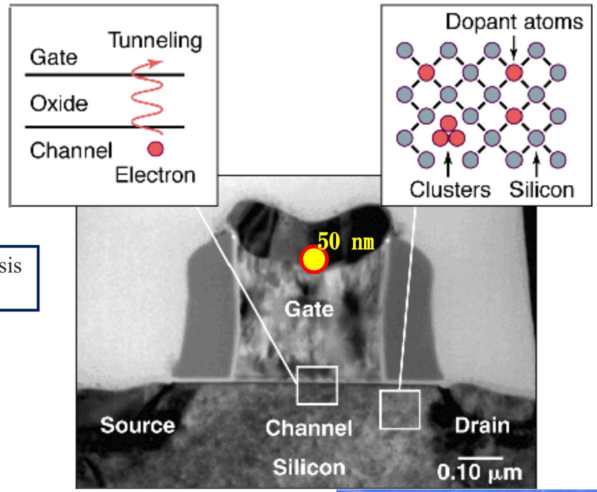
3D-scanning photoelectron microscope





3D-scanning photoelectron microscope
3D nano-ESCA

Element and chemical analysis in nano-region



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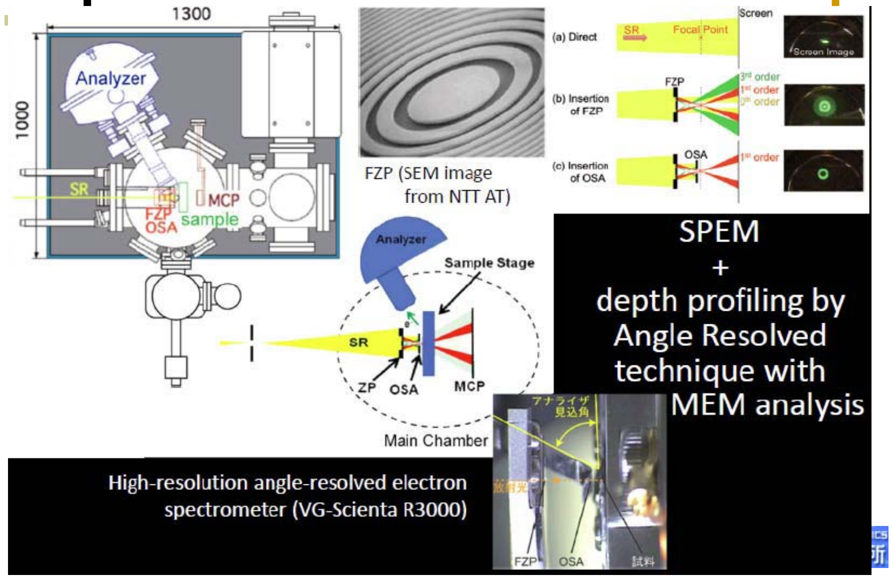
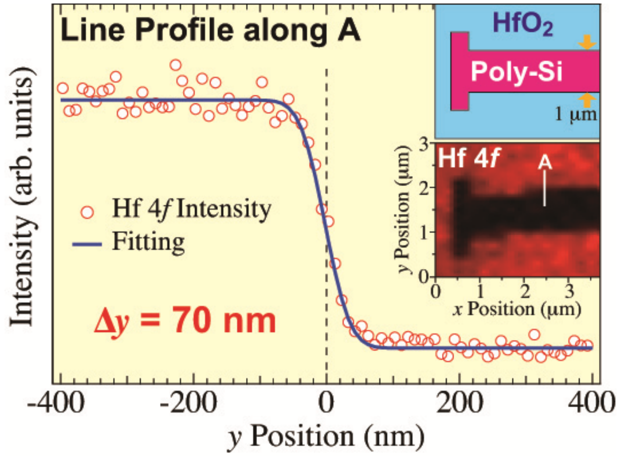
3D-scanning photoelectron microscope
3D nano-ESCA



3D-scanning photoelectron microscope
3D nano-ESCA



Thank you for your kind attentions.