PF研究会＠12.03.2011

スピン分解光電子分光による磁性薄膜の研究

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Outline

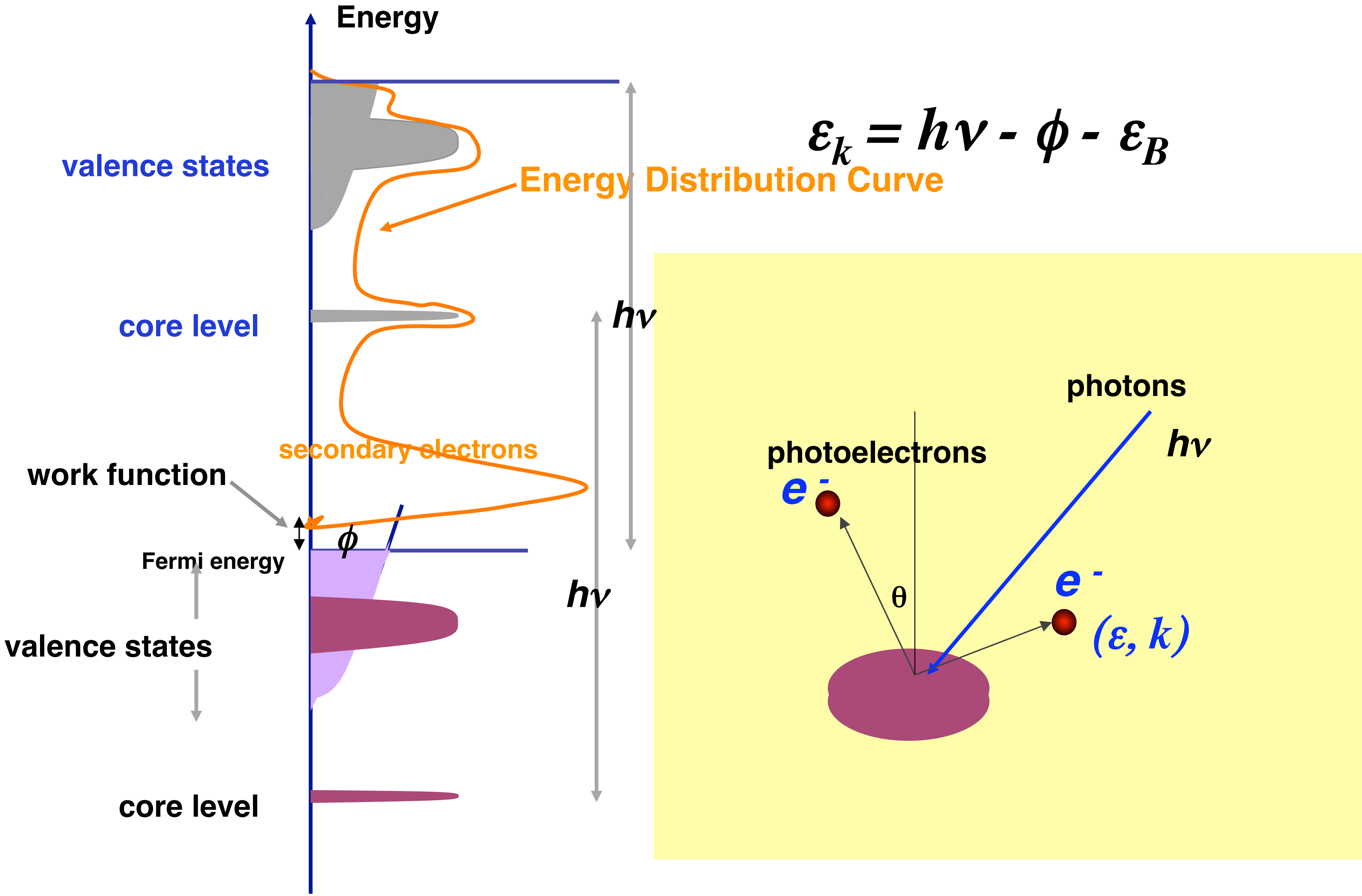
(1) Introduction
- Principles of spin-resolved photoelectron spectroscopy (SARPES)

(2) SARPES spectra of magnetic thin films

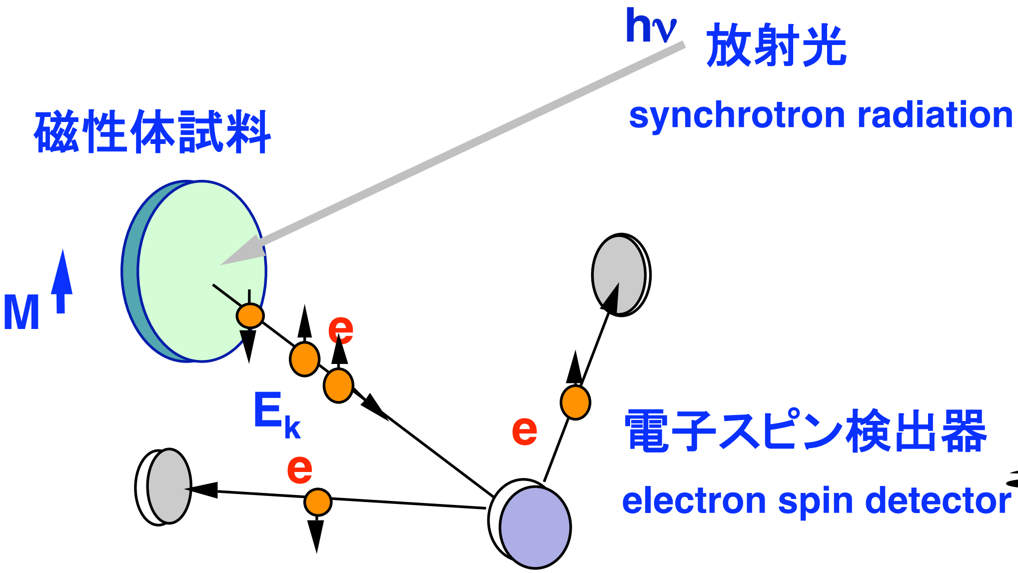
(3) Recent topics of SRPES experiments
- A new spin polarimeter adopting VLEED

(4) Future perspectives

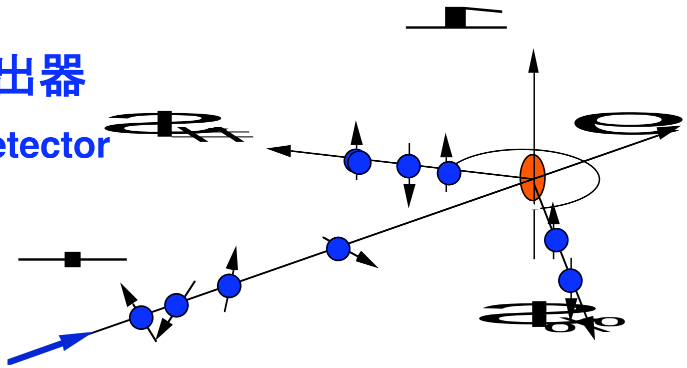
Schematics of photoelectron spectroscopy



Principles of spin-resolved photoemission experiments



Mott scattering



$$A(\theta) = (N_L - N_R) / (N_L + N_R) = S_{eff}(\theta) \cdot P$$

$$I_{\uparrow,\downarrow} = N/2 \cdot (1 \pm P)$$

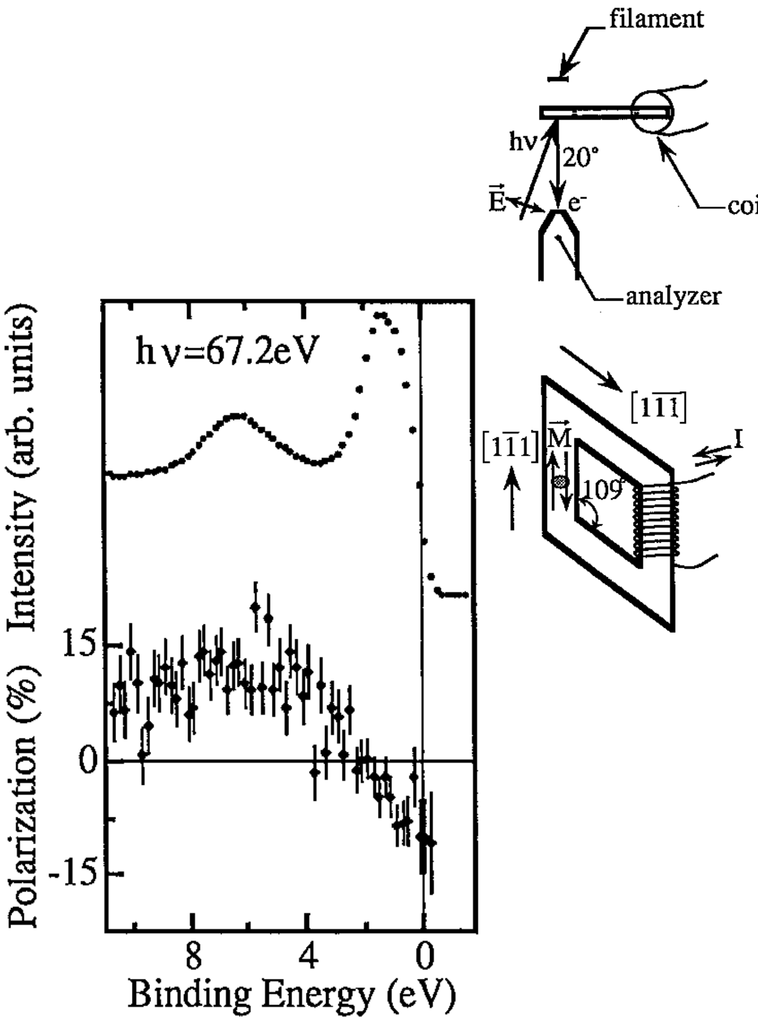
$$S_{eff} \sim 0.1, \quad I / I_0 \sim 0.01$$

$$\varepsilon = S_{eff}^{\,2} \cdot I / I_0 \sim 10^{-4}$$

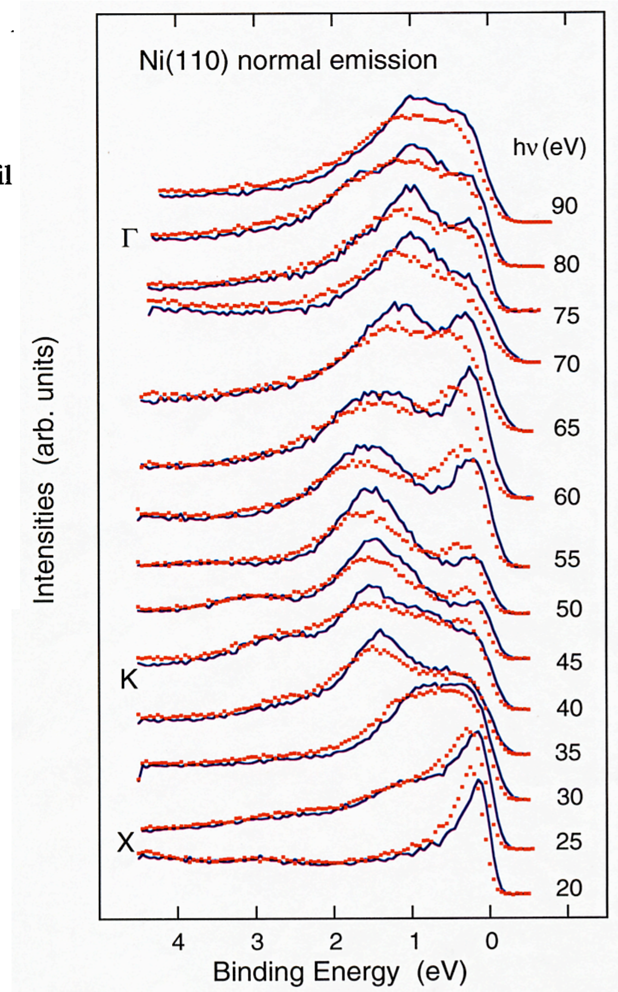
$$\Delta_{asym} = 1 / S\sqrt{I}$$

for $\Delta_{asym} < 2\%$, $I_0 > 25{,}000{,}000$

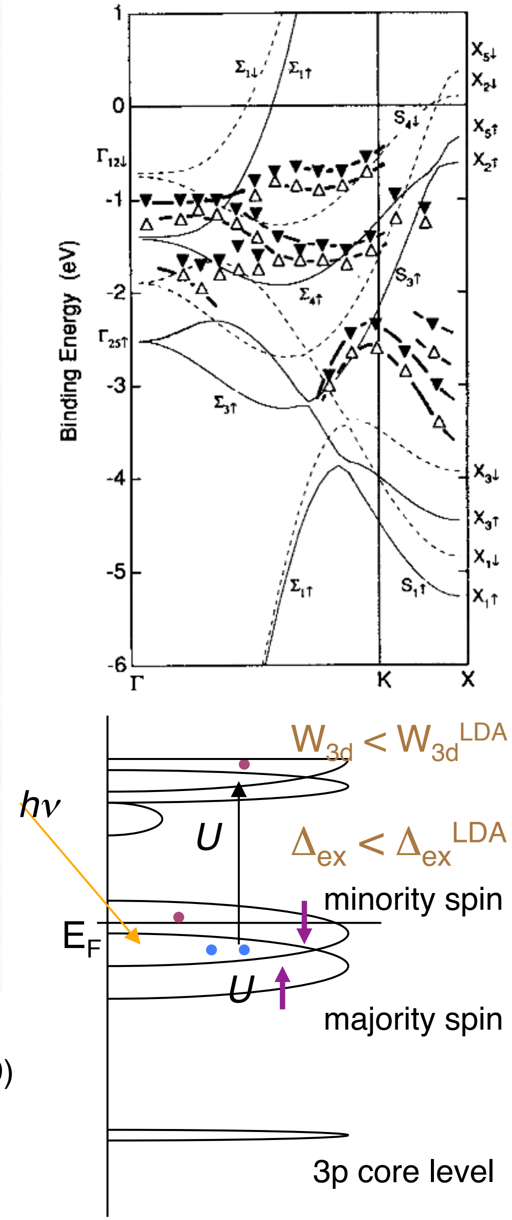
Correlation effects in SARPES of Ni(110)



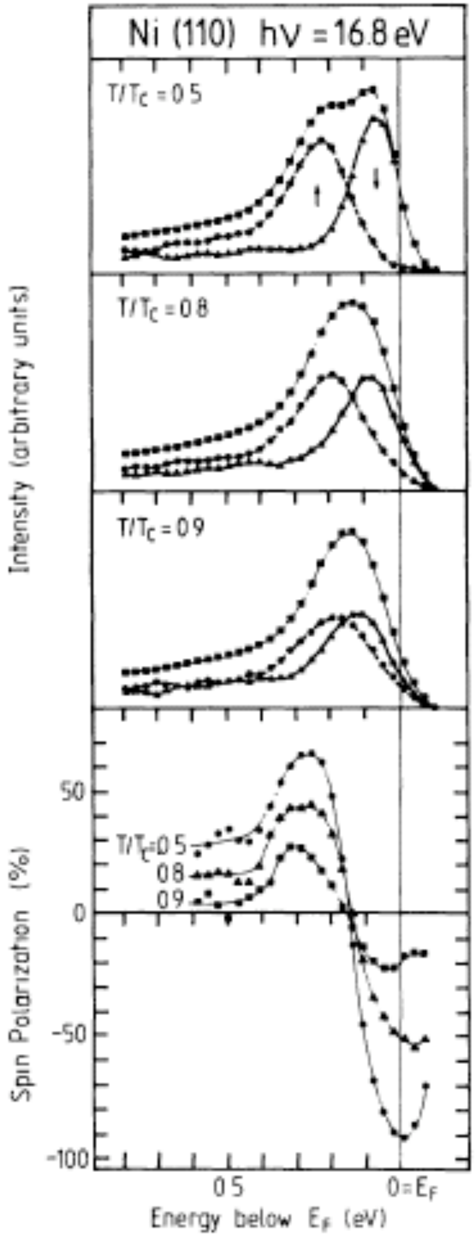
Kinoshita et al., PRB 47, 6787 (1993)



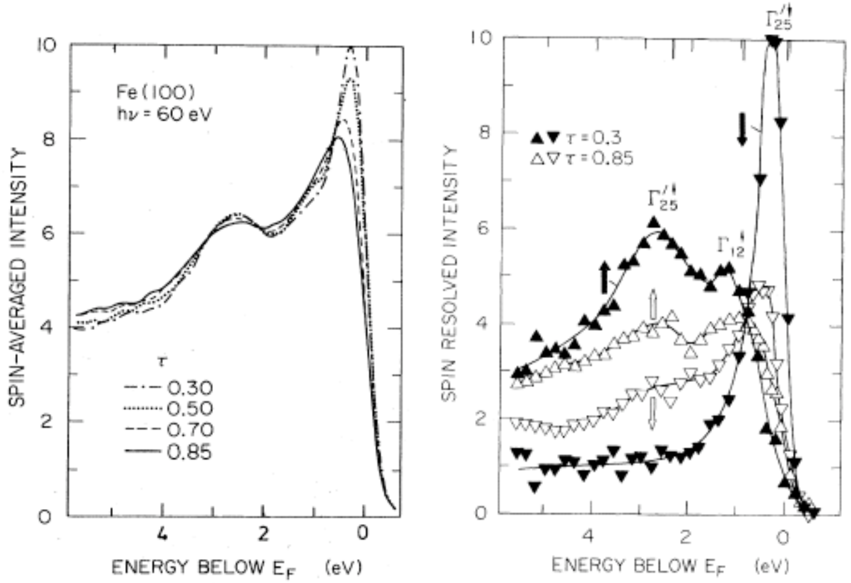
Ono et al., SSC 107, 153 (1999)



Temperature dependence of SRPES spectra of Ni and Fe

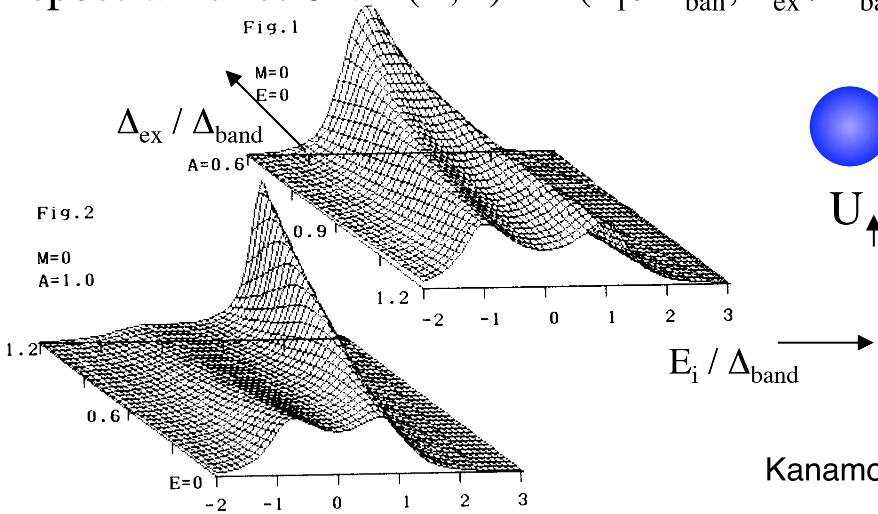


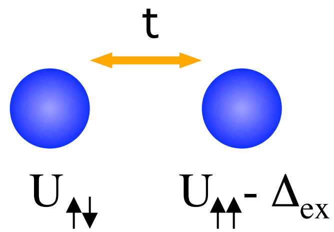
Hopster et al., PRL 51, 828 (1983)



Kisker et al., PRL 52, 2286 (1984), PRB 31, 329 (1985)

spectral function: $A(E, k) = A(E_i / \Delta_{ban}, \Delta_{ex} / \Delta_{band}, M)$

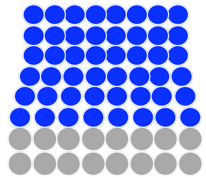


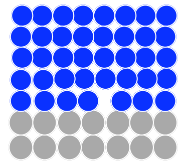


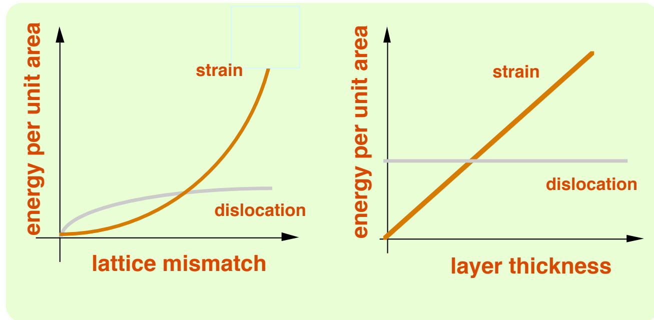
Kanamori et al. (1987)

Structure of Fe films grown on non-magnetic materials

bcc Fe(110)	Fe/Au(001)	Fe/Ag(001)	
	a = 4.07 A	a = 4.08 A	2.86 ξ √ 2 = 4.05 A
fcc Fe(100)	Fe/Cu(001)	Fe/Co(001)	
	a = 3.54 A	a = 3.61 A	
fcc-bcc Fe	Fe/Pd(001)	Fe/Rh(001)	Fe/Cu_3Au
	a = 3.89 A	a = 3.80 A	
	bcc > 10ML	bcc or fcc	fcc < 7ML

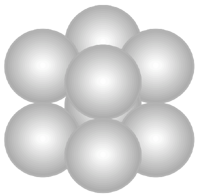

strain


dislocation



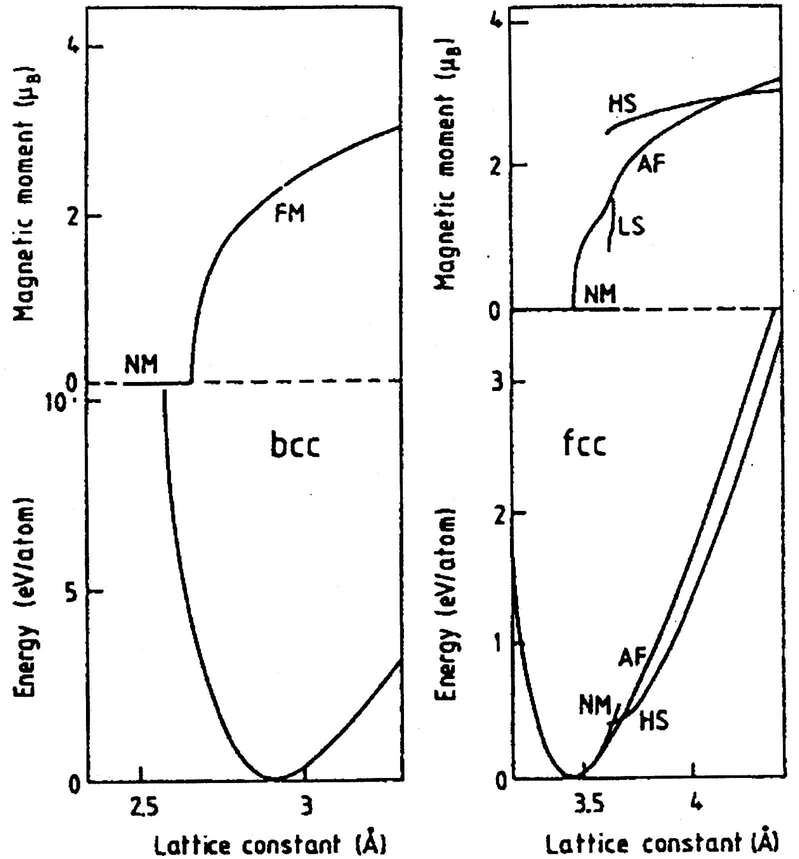
Energetics of bcc and fcc Fe

bcc Fe



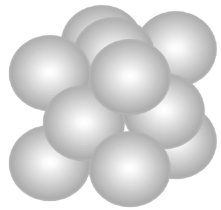
bulk Fe (α-Fe)
bcc (at RT)
a = 2.87 A

LSDA calculation



V.L.Moruzzi et al. PRB 37, 8003 (‘88)

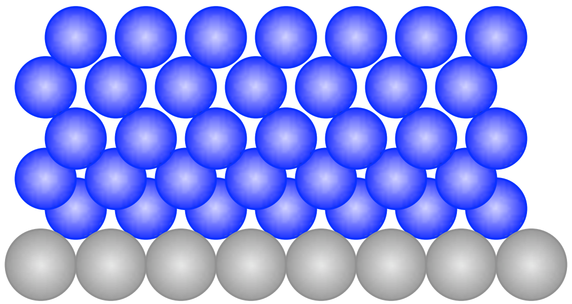
fcc Fe



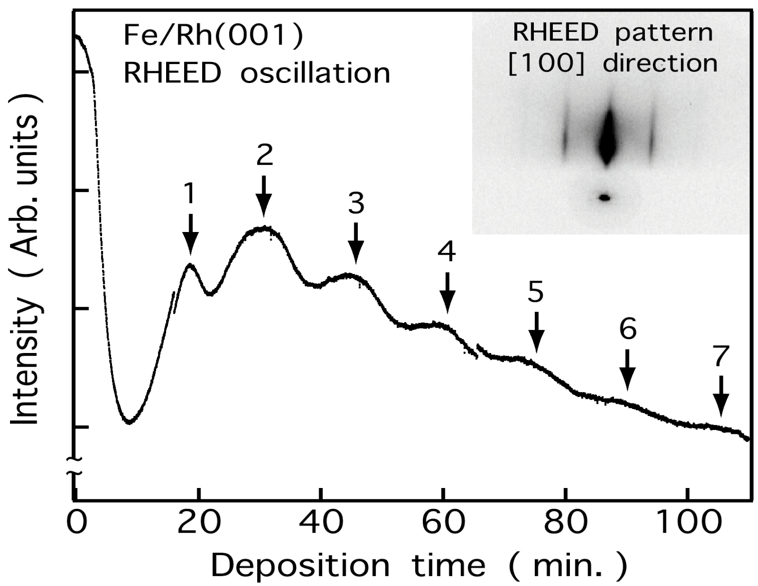
bulk Fe (γ-Fe)
fcc (at T = 900 C)
a = 3.64 A

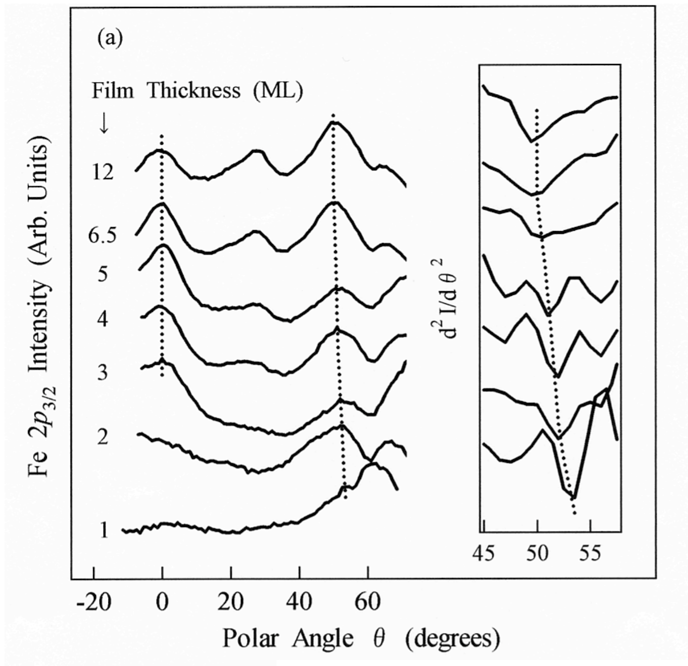
energetics : chemical bonding (bandwidth), magnetic interaction
surface energy, interfacial energy, etc.

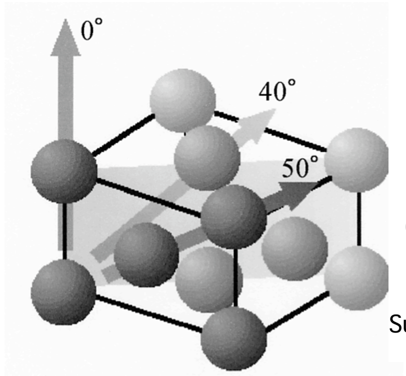
Fe 2p3/2 XPD patterns observed in Rh(010) and (110) plane

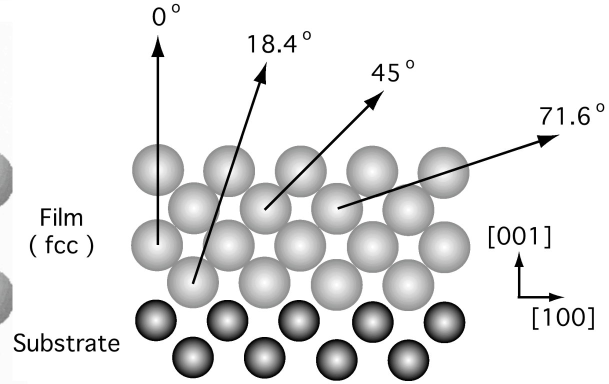


Rh(001)



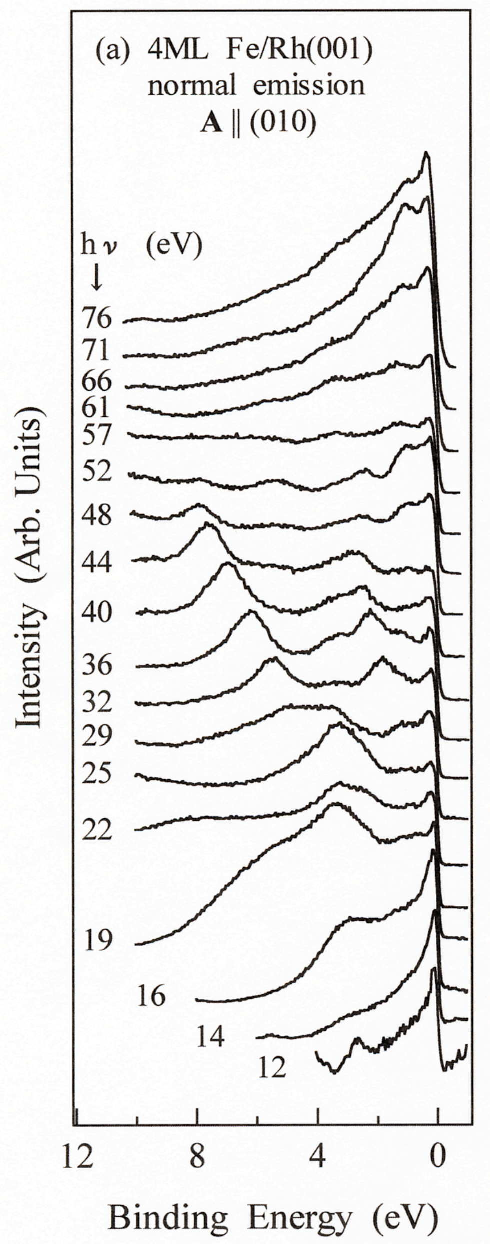


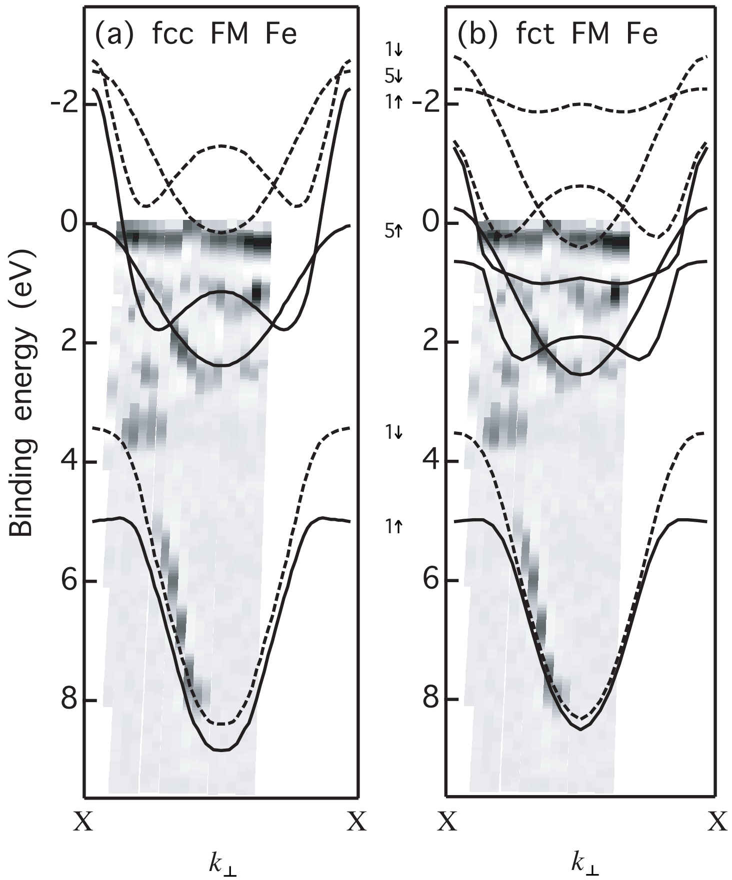


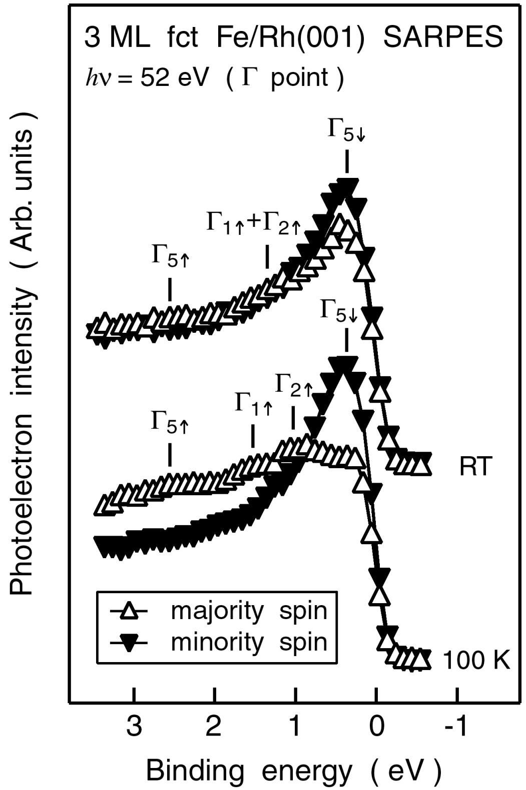


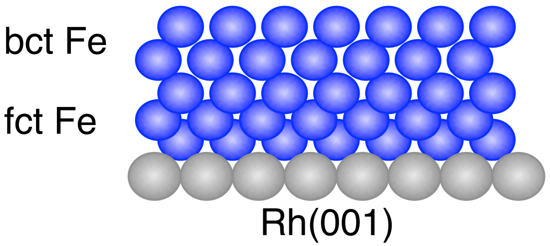
K. Hayashi et al. RPB 64, 054417 (2001)

Angle- and spin-resolved photoemission spectra



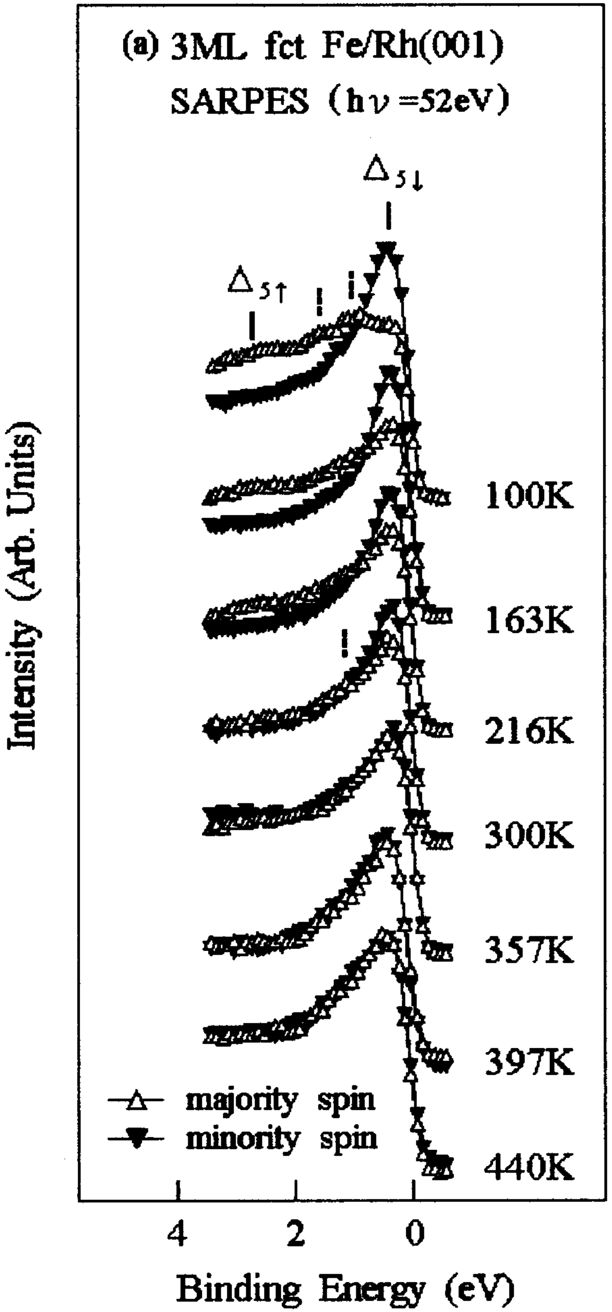


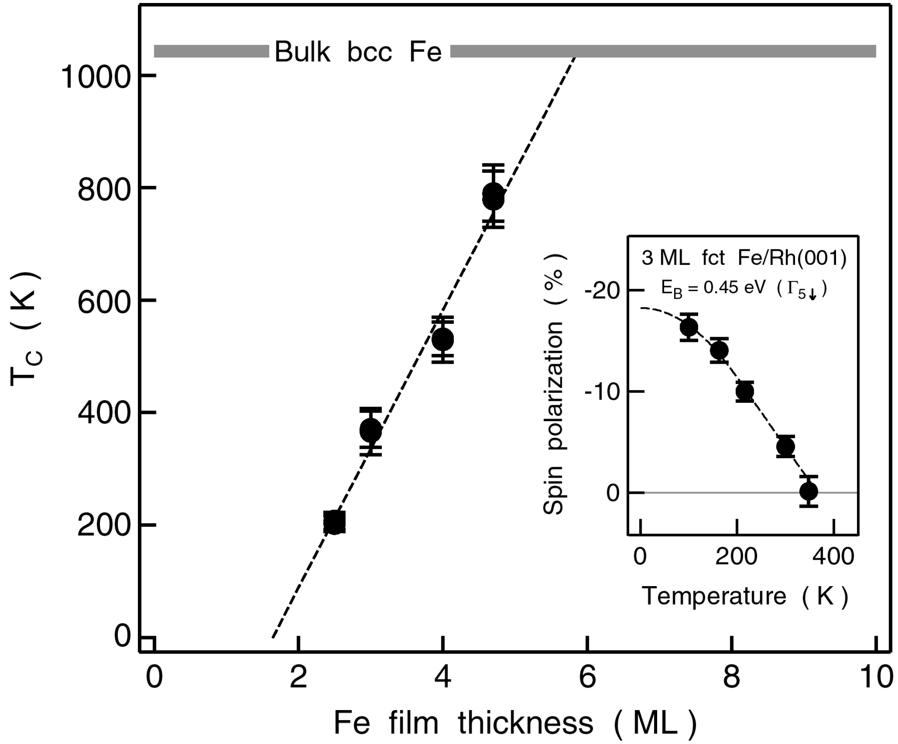


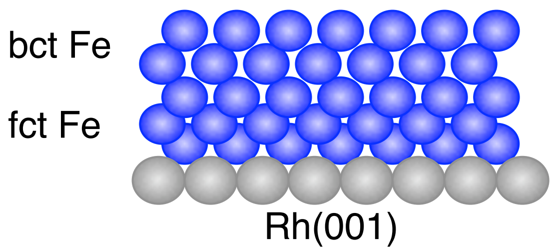


Hayashi et al. PRB 64, 054417 (2001)
JPSJ 73, 2550 (2004)

Temperature dependence of spin-resolved photoemission spectra of 3ML Fe/Rh(001)

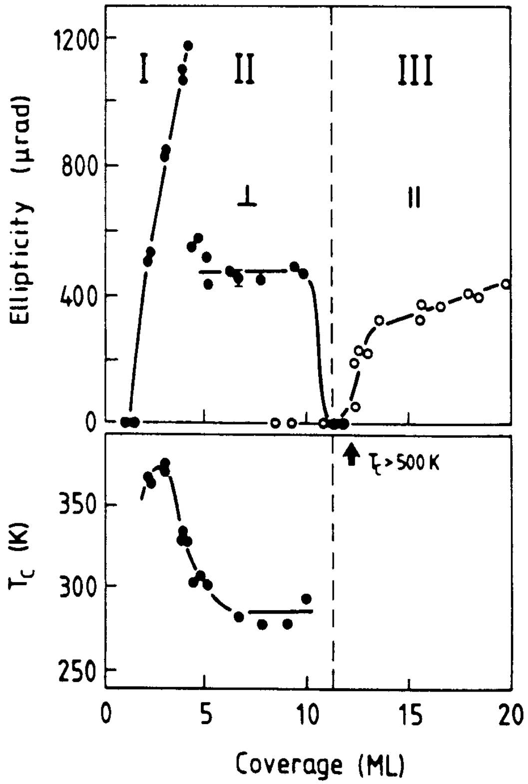




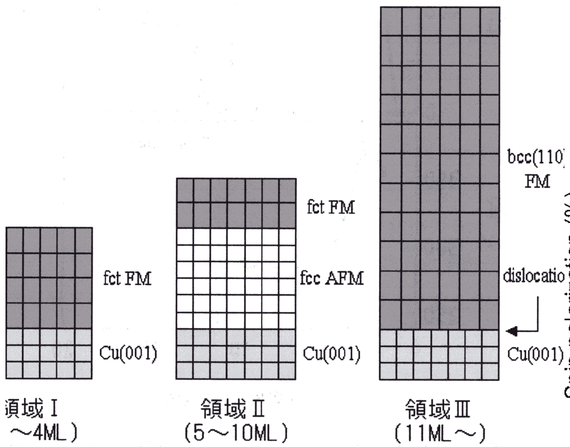


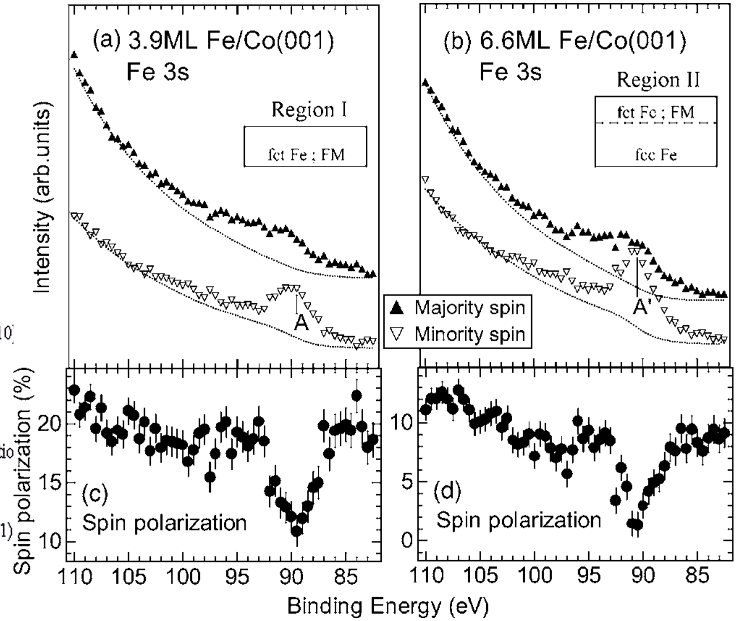
Fe films below 3ML are magnetically dead layers

Structure and magnetism of Fe films grown on Cu(001)



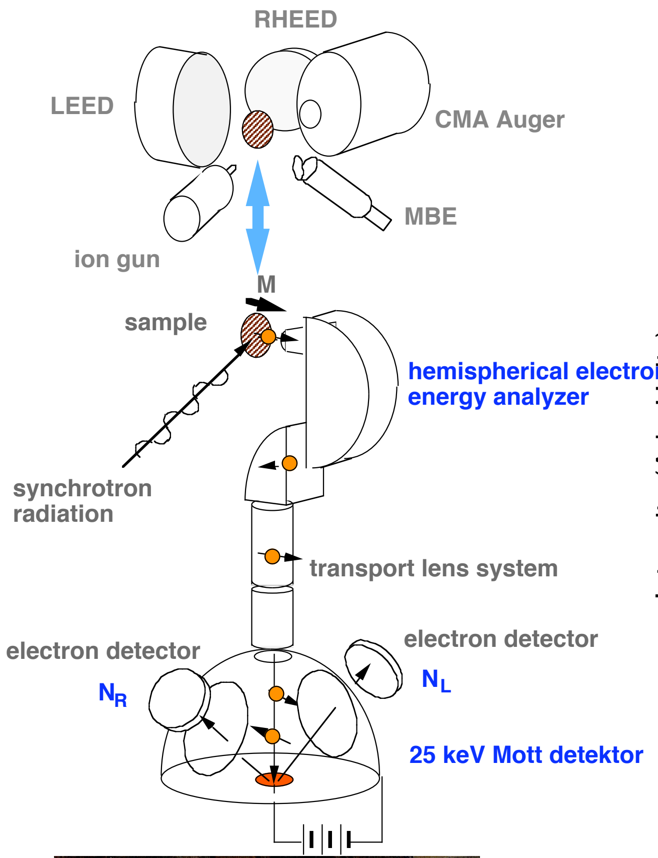
J. Thomasson et al. PRL 69, 3832 (‘92)

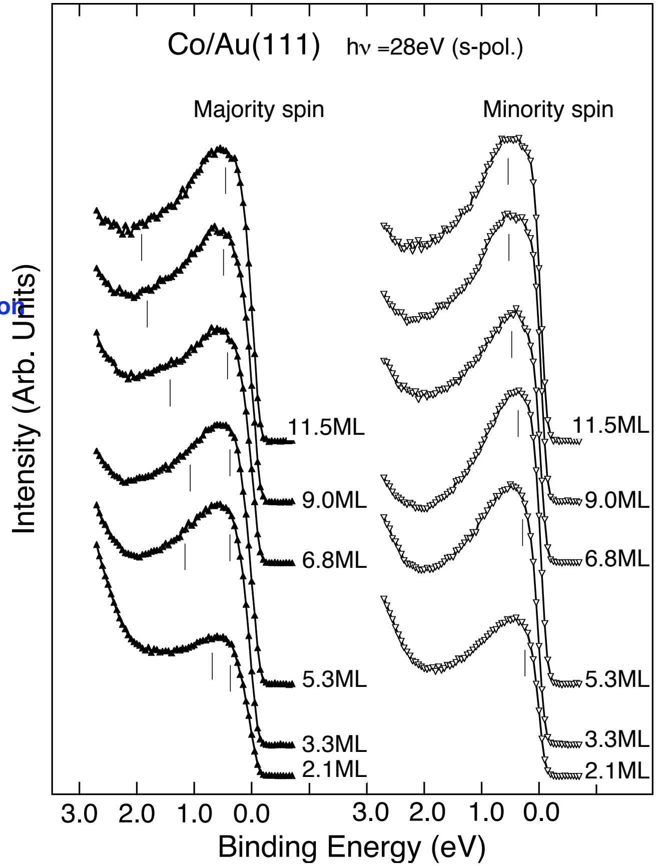




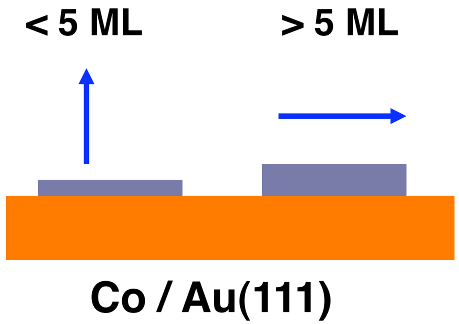
Kamakura et al., PRB 73, 094437 (2006)

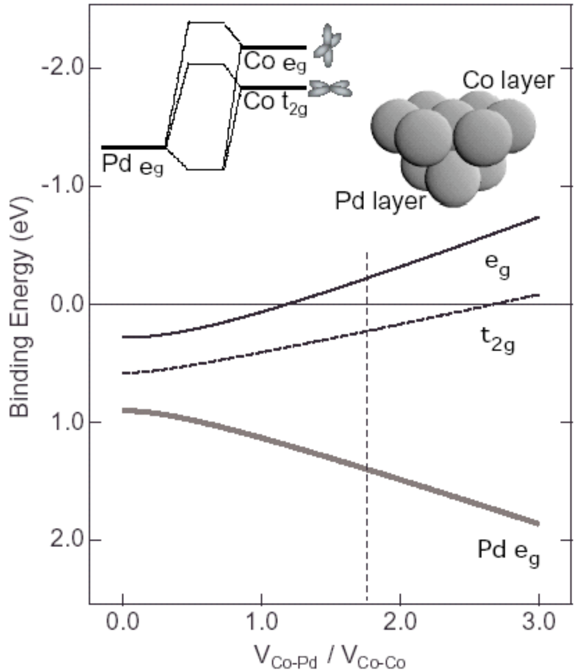
Reorientation of magnetization direction depending film thickness





Sawada et al., PRB 63, 195407 (2001)

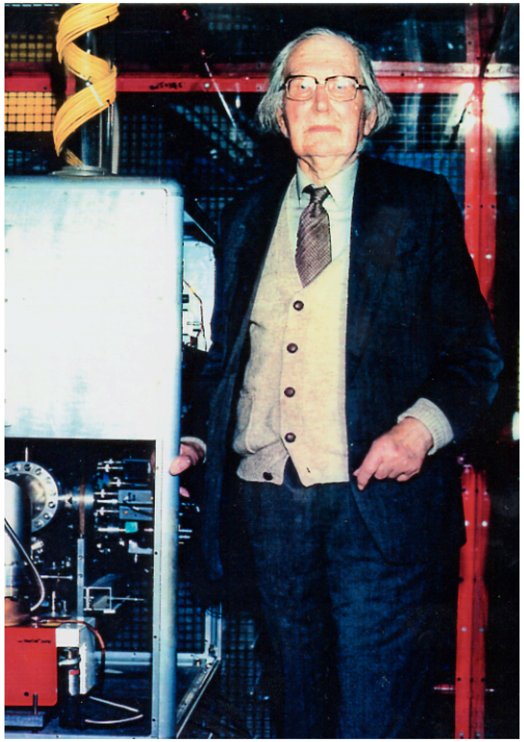




Sawada et al., JPSJ 72. 1161 (2003)

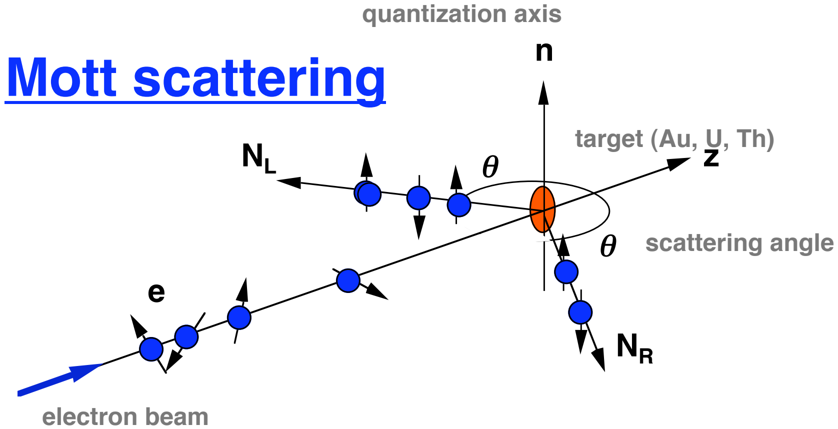
Characteristics of spin-polarimeters

spin-polarimeter	*energy*	S_{eff}	I/I_0	*figure of merit* (ε)
Conventional Mott [1]	100 keV	0.20	2.9×10^{-3}	1.1×10^{-4}
Compact Mott [2]	25 keV	0.14	9.7×10^{-3}	1.9×10^{-4}
SPLEED [3]	150 eV	0.19	2.2×10^{-3}	8.0×10^{-5}
Diffuse Scattering [4]	150 eV	0.11	9×10^{-3}	1×10^{-4}

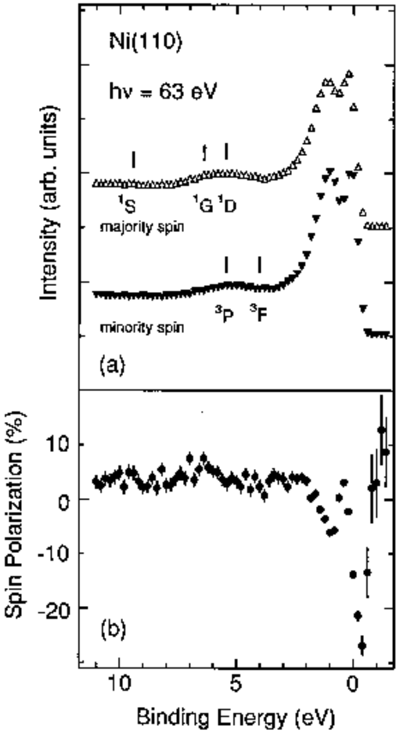


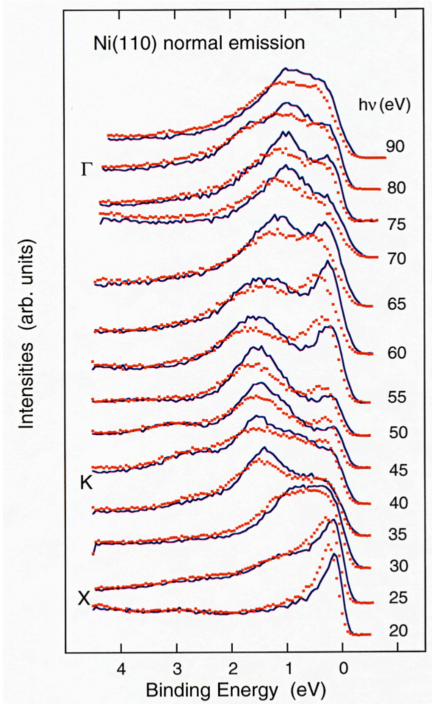
[1] J. Fujii, Ph. D Thesis, Univ. Tsukuba (1994)
[2] S. Qiao *et al.*, RSI 68, 4390 (1997).
[3] G.–C. Wang *et al.*, PRB 23, 1761 (1981).
[4] J. Unguris *et al.*, RSI 57, 1314 (1986).

Mott scattering



Examples of spin-resolved photoemission spectra





A. Kakizaki *et al.*, Phys. Rev. B 55, 6678 (1997).

Valence band satellites in Ni(110)

SHA50 + 25 keV Mott

$\Delta E \sim 200$ meV

$\Delta\theta < 2°$

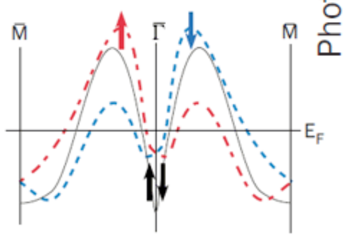
Rashba split surface energy bands in Bi(001)

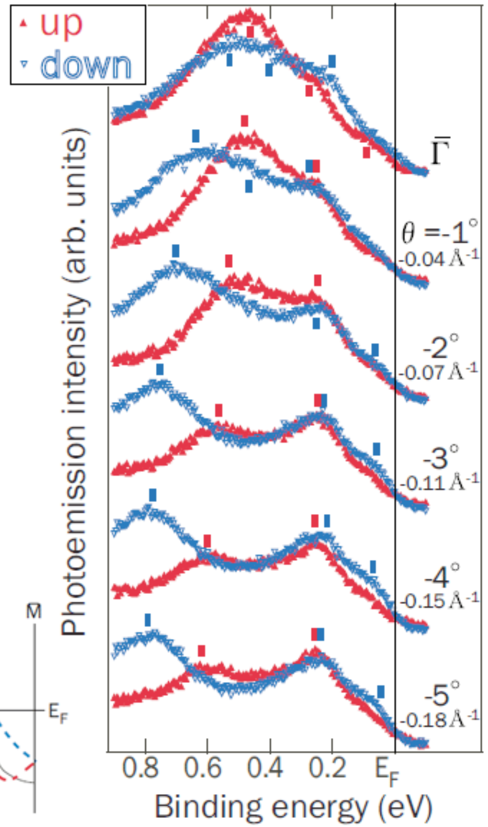
EA-125 + 25 keV Mott

$\Delta E \sim 110$ meV

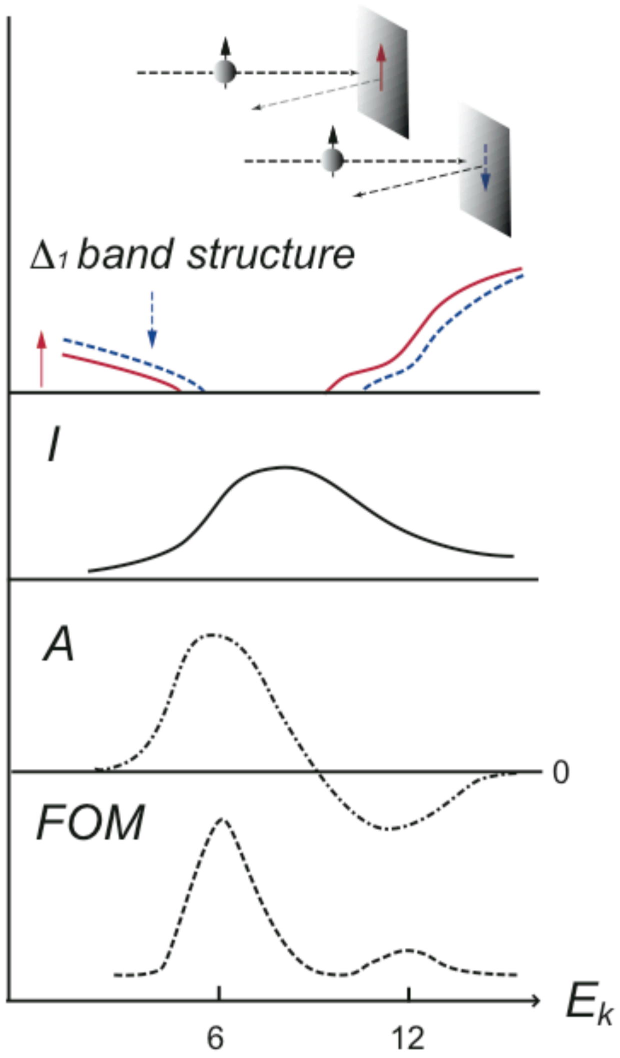
$\Delta\theta = \pm 1°$

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





Schematic of VLEED detector



VLEED detector utilizes difference in reflectivity between spin-up and spin-down electrons.

Asymmetry (A) shows maximum or minimum at the band edges of unoccupied states.

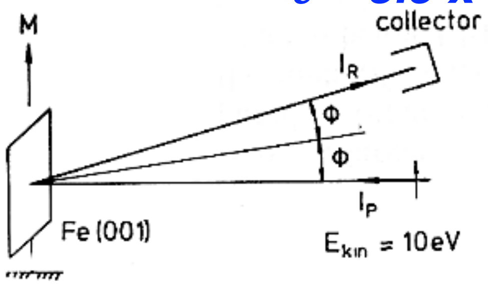
For Fe(001) target A ~ 0.2 and R ~ 0.1 at Ek ~ 10 eV.

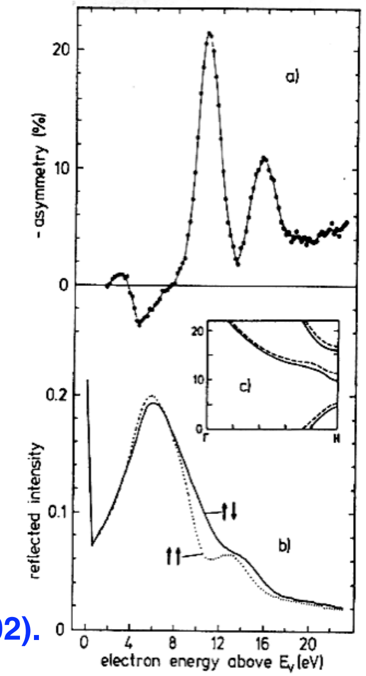
$\varepsilon \sim R \times A^2 \sim 4 \times 10^{-3}$

Development of new VLEED spin-polarimeter

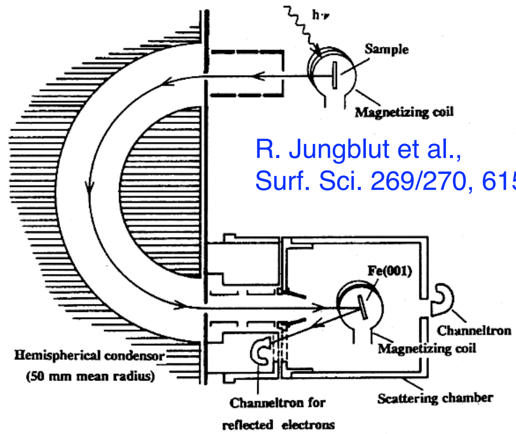
Applying reflectivity difference between spin-up and spin-down electrons from the magnetized Fe target

ε ~ 3.5 x 10 [-3]

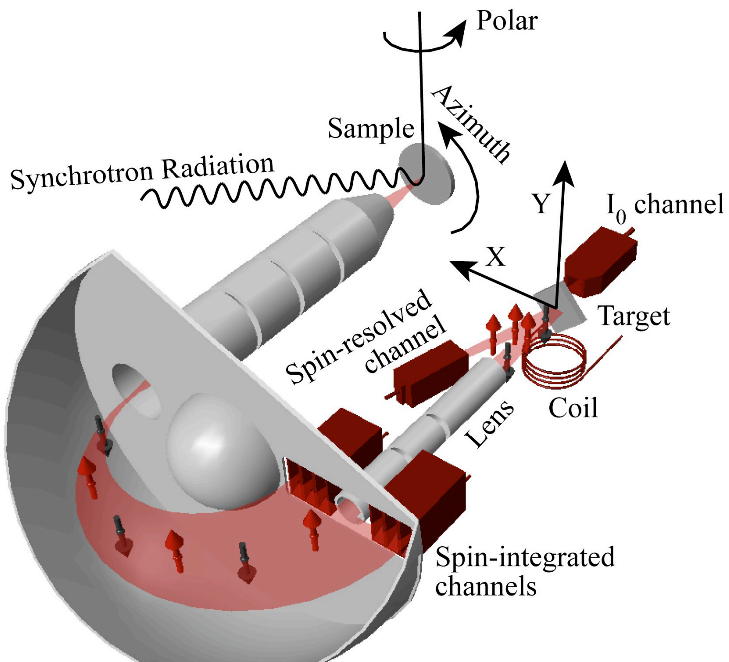




D. Tillemann et al., Z. Phys. B. 77, 1 (1989)
F. U. Hillebrecht *et al.*, Rev. Sci. Instr. 73, 1229 (2002).



R. Jungblut et al.,
Surf. Sci. 269/270, 615(1992)



Okuda et al., RSI 79, 123117 (2009)

Advantage

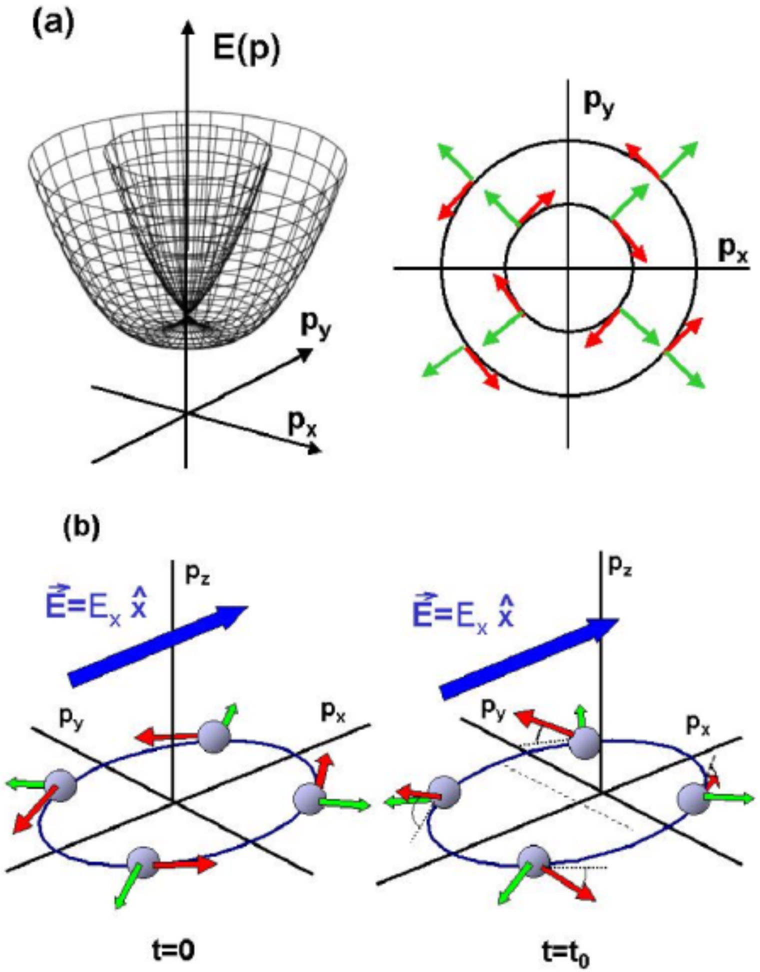
S_{eff} function is almost the same as Mott detector and the scattering probability is much higher.

Disadvantage

Fe target has to be cleaned frequently.

---> stable target for VLEED, Fe(001)-p(1x1)O

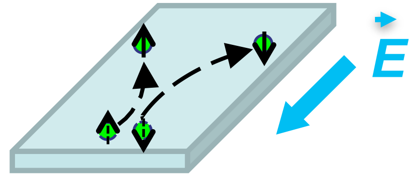
Rashba spin-splitting in surface states

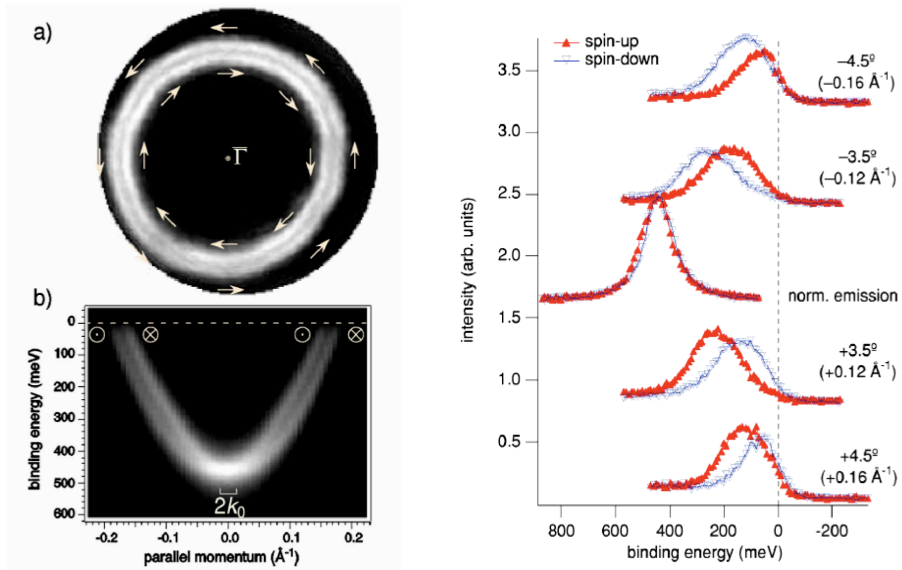


J. Sinova *et al.,* PRL. **92**, 126603 (2004).

$$H = H_0 + (h/8\pi m^2c^2)\,[(dV/dz)\,x\,\mathbf{p}]\,\mathbf{s}$$
$$= H_0 + \alpha\,[\sigma\,x\,\mathbf{k}]\,\mathbf{z}$$

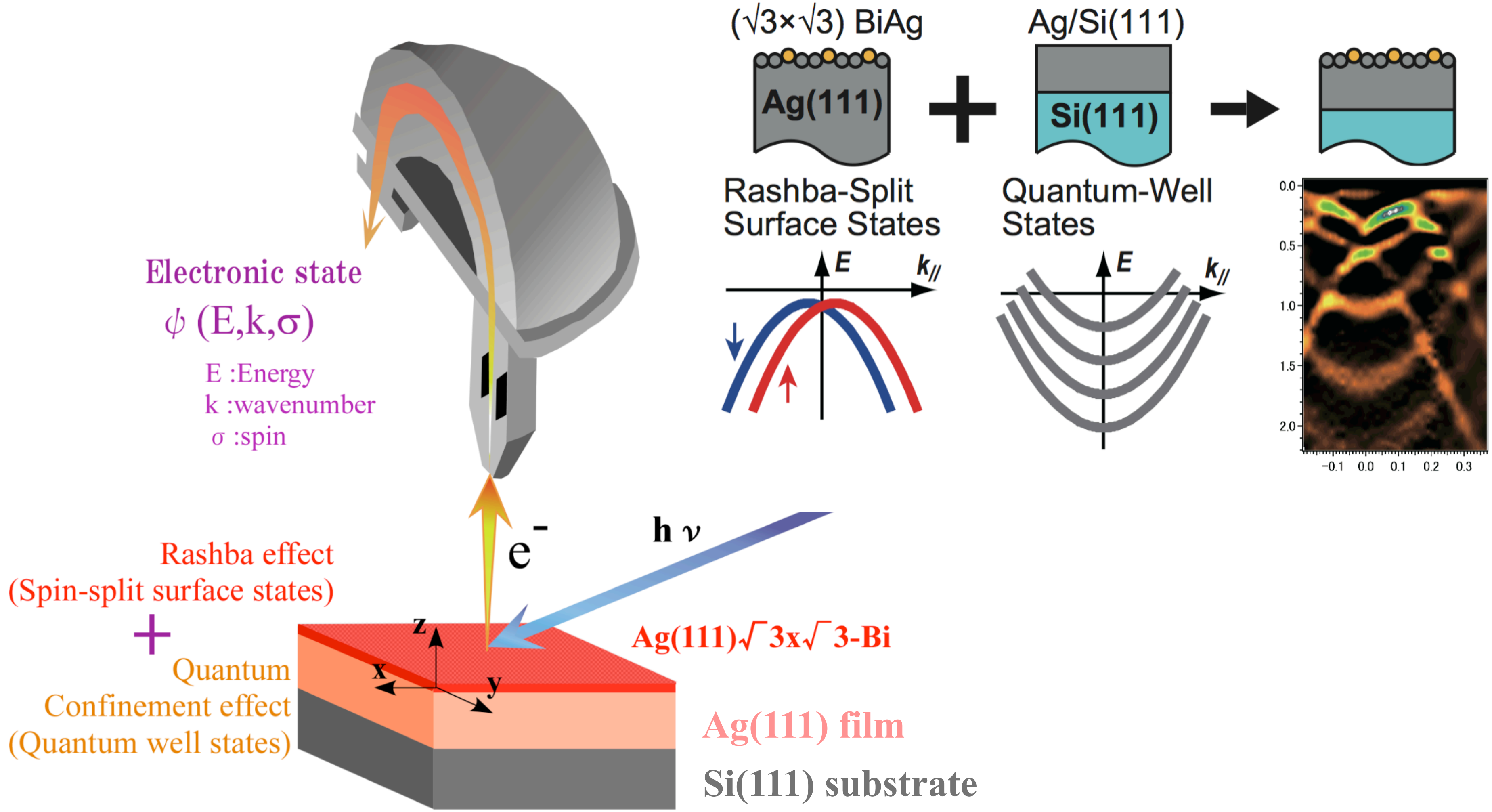
$$E(k)\pm = h^2k^2/2m \pm \alpha k$$



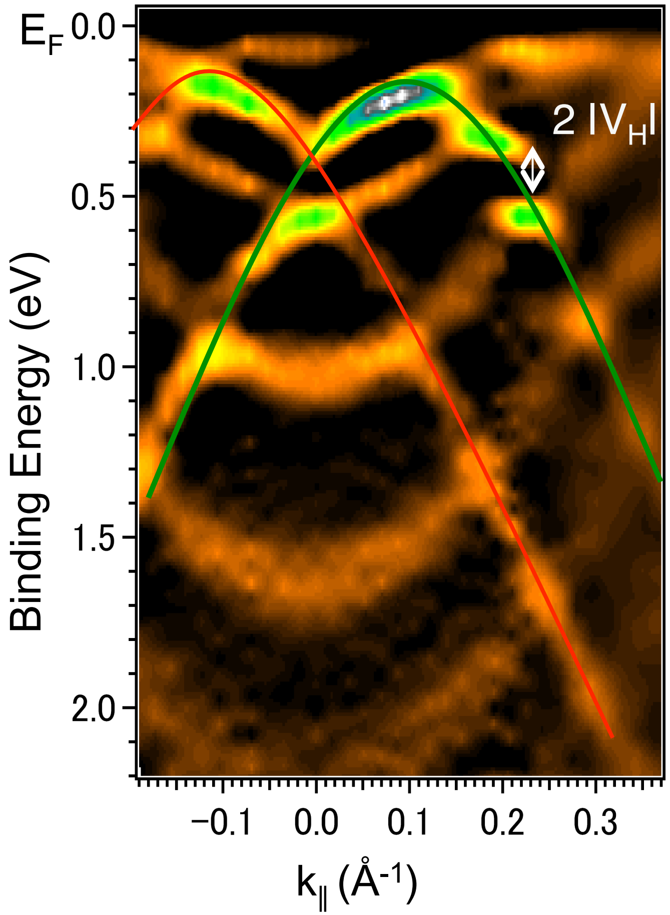


M. Hoesch *et al.*, PRB **69**, 142401(R) (2004).

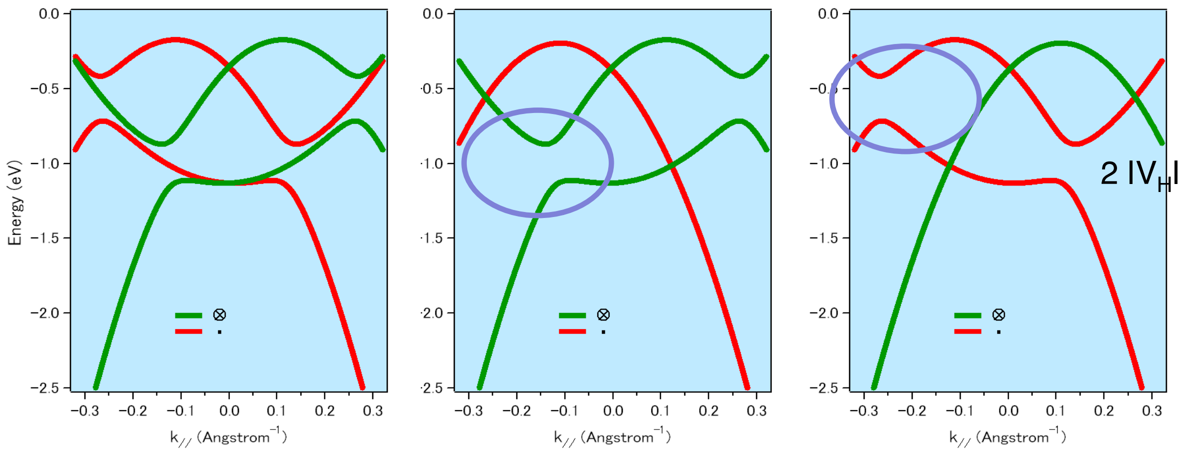
ARPES of √3 ×√3 Bi/Ag system



Hybridization between QWS of Ag and spin-split SS of Bi



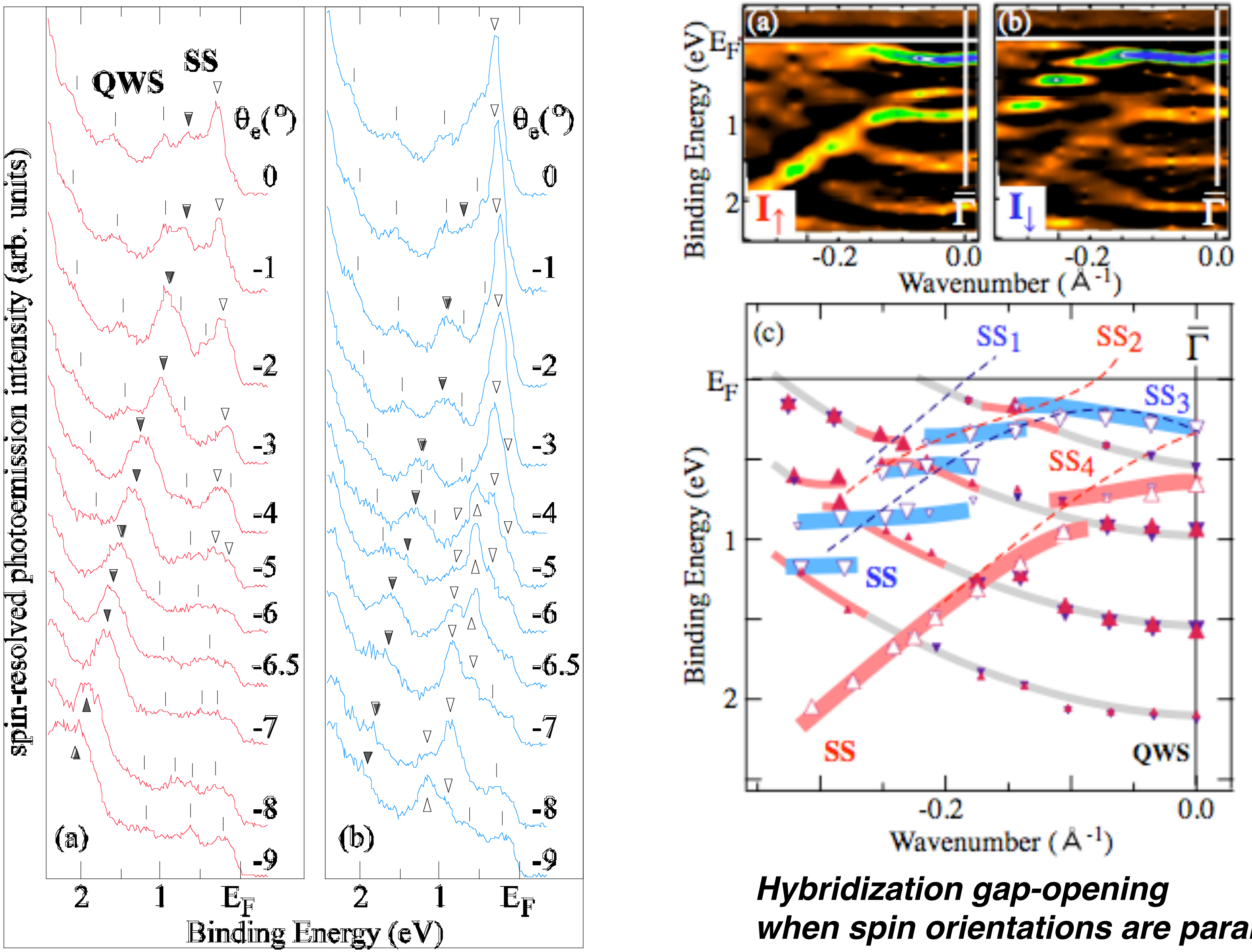
Hybridization between spin-degenerated QWSs and Rashba spin-split SSs



Is the gap spin-dependent?

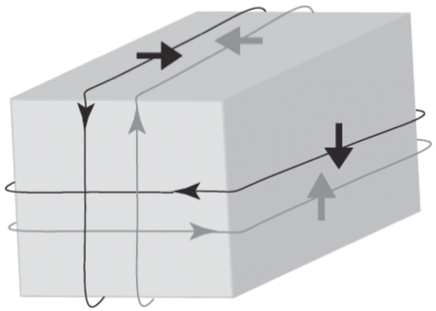
K. He et al., Phys. Rev. Lett. 101, 107608 (2008)

Spin- and angle-resolved photoemission spectra of √3 ×√3 Bi/Ag

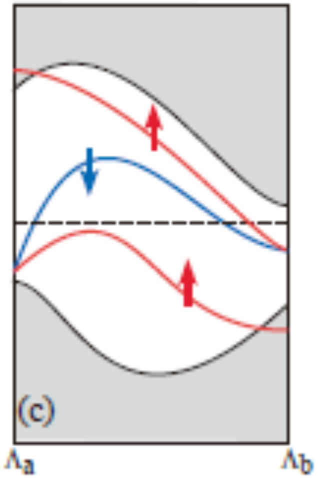


Hybridization gap-opening when spin orientations are parallel

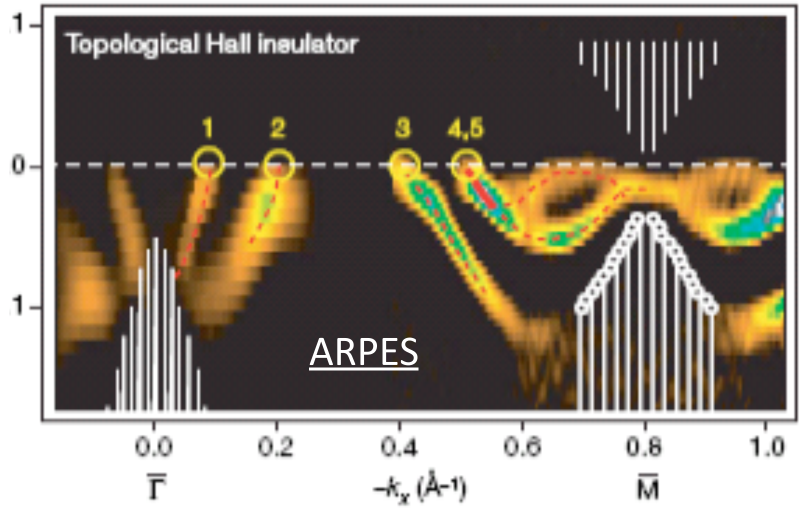
Electronic structure of $Bi_{1-x}Sb_x$

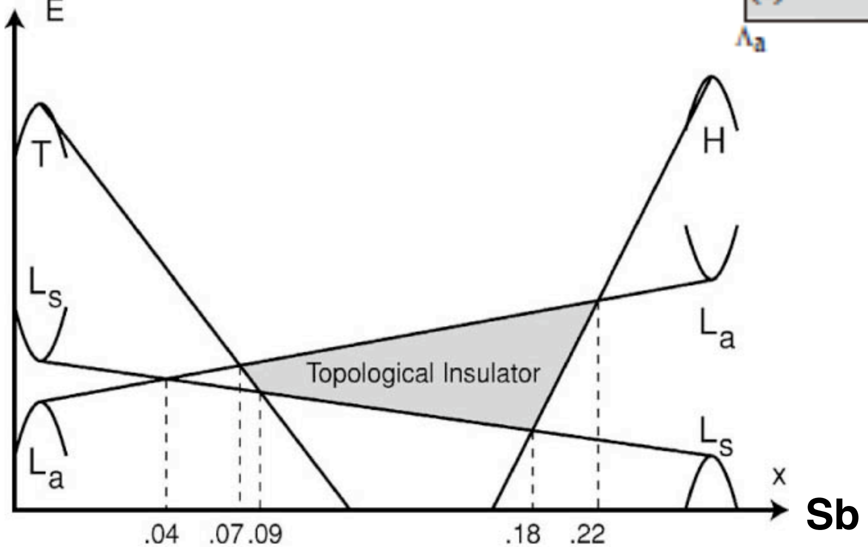


Kane and Mele, PRL 95, 146802 (2005)
Bernevig and Zhang, PRL 96, 196802 (2005)



D. Hsieh et al., Nature 452, 970 (2008)





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

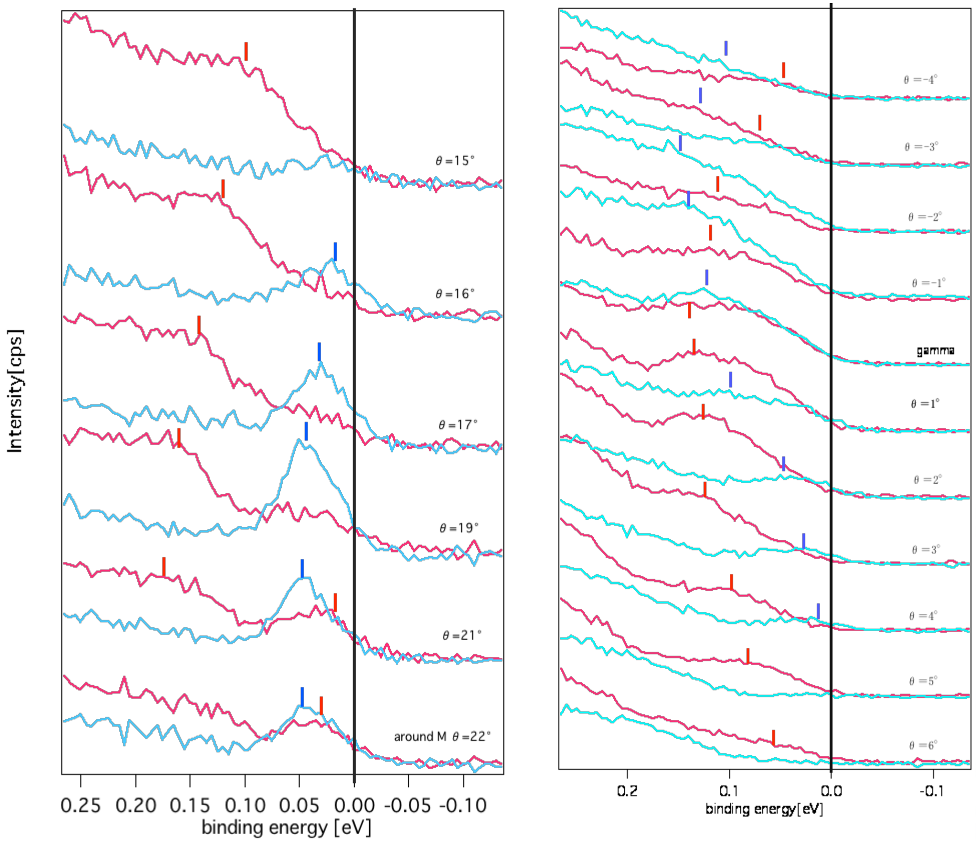
- Odd number of
Fermi level crossings

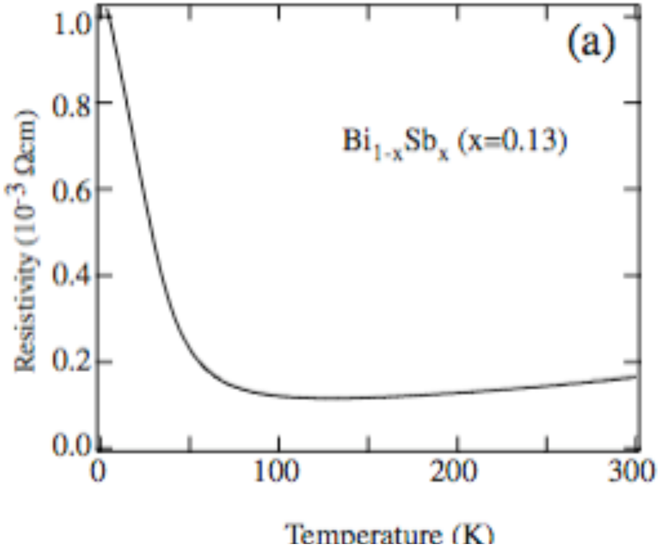
From L. Fu and C. L. Kane PRB, **76**, 045302 (2007)

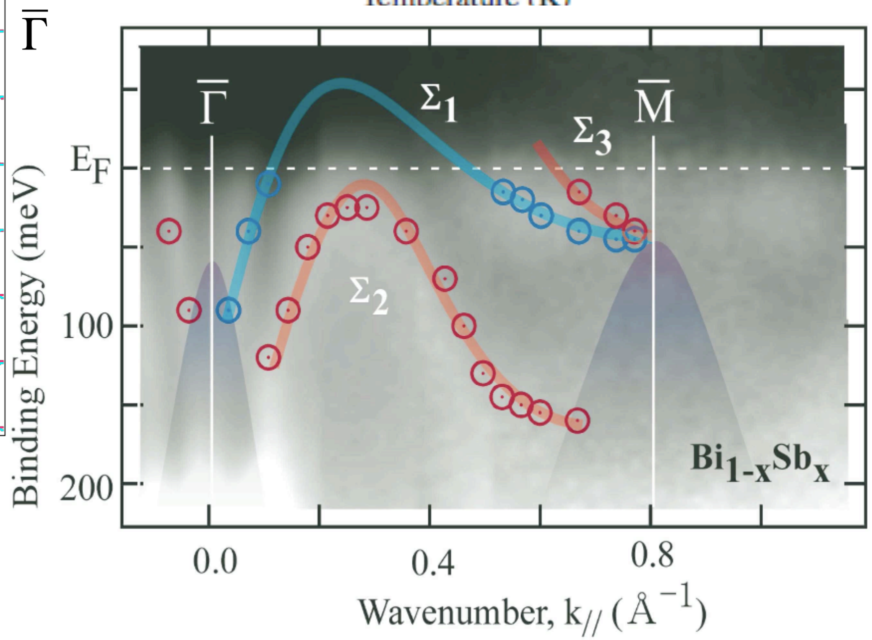
- spin-split bands ?
- is there any x-dependence in surface states?

Spin-resolved photoemission spectra of $Bi_{0.87}Sb_{0.13}$

SARPES spectra between $\bar{\Gamma}$- and $\bar{M}$-point







Nishide et al., Phys. Rev. B 81, 041309(R) (2010)

Odd number of Fermi level crossing between $\bar{\Gamma}$ and $\bar{M}$ in the Brillouin zone

Summary

 # SRPES of magnetic thin films --Fe/Rh(001), Co/Au(111))--

magnetic properties of surfaces, magnetic anisotropy, etc.

 # A new spin-resolved photoemission spectrometer adopting VLEED

$S_{eff} = 0.30$, $\varepsilon = 1.9 \times 10^{-2}$ at $E_k = 6$ eV, $\Delta E \sim 30$ meV

Precise analyses of spin-dependent electronic structures of solid surfaces and thin films

 # High-resolution spin- and angle-resolved photoemission spectra of spin-dependent surface electronic states

Spin-dependent edge states of a topological insulator

Rashba spin-split surface states

Future perspectives

(1) Spin-resolved photoelectron spectrometer

- *energy resolution* — *100 meV → below 10 meV*
- *angle resolution* — *0.1°(0.01 A^{-1}) → 0.01°(0.001 A^{-1})*
- *spatial resolution* — *1 μm → 0.01 μm*
- *efficiency (figure of merit)* — *10^{-4} → 10^{-2}*

(2) Future experiments with spin-analysis of photoelectrons

- *time resolved experiments (with pump & prove laser)*
- *spectroscopy with polarized electrons*
- *combination with photoelectron microscopy*