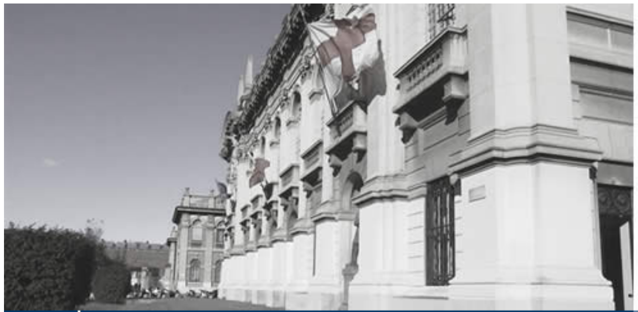


Resonant Inelastic X-ray Scattering

ESRF-Grenoble 29 June 2009

POLITECNICO DI MILANO

20 years of Inverse PhotoEmission Spectroscopy in Milano

Franco Ciccacci

Dipartimento di Fisica & Centro LNESS

(Laboratorio di Nanostrutture Epitassiali su Silicio e per Spintronica)

…getting in touch with Lucio….

1) December 1980 – Modena

Advances in Surface and Interface Physics

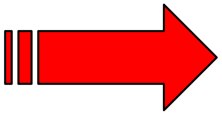
Spin polarized photoemission from Molecular Beam Epitaxy grown GaAs.
(F. Ciccacci, S.F. Alvarado, M. Campagna)

"….I am quite familiar with (Mott detectors)…."

2) February 1987 – Paris

Inverse PhotoEmission

Spin Polarized Electron Sources

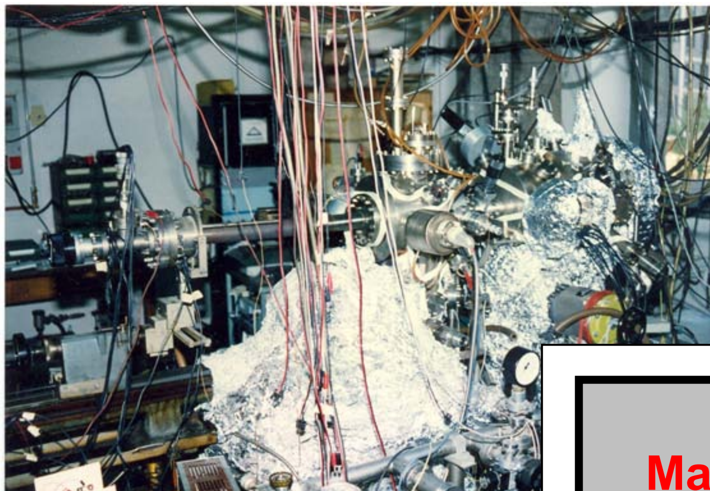


SPIPE: Spin Polarized Inverse PhotoEmission

Milano – 1988

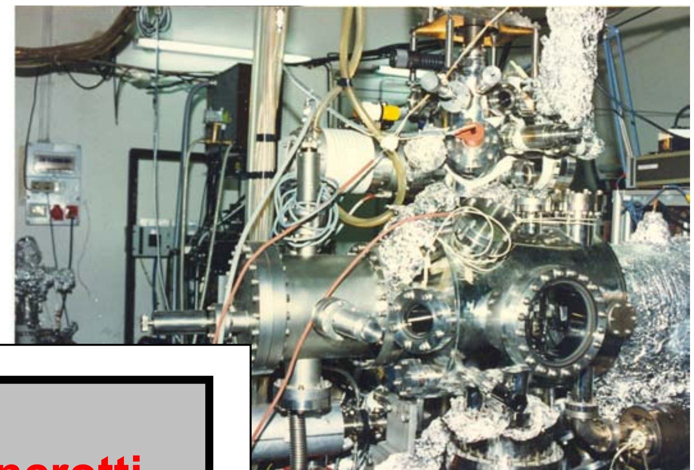
"VESI"

H discharge lamp + vacuum momochromator
He lamp, X-ray source, CMA



"BIS"

Inverse Photoemission in UV



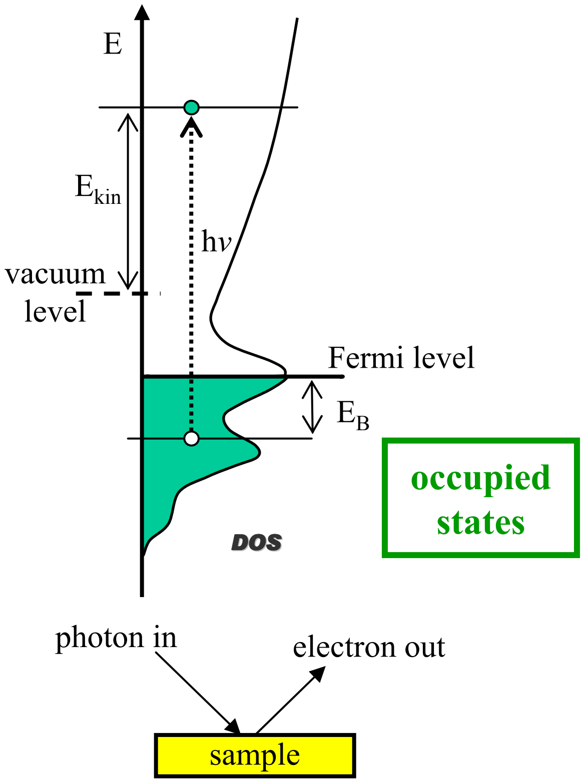
Massimo Sancrotti

"TER"

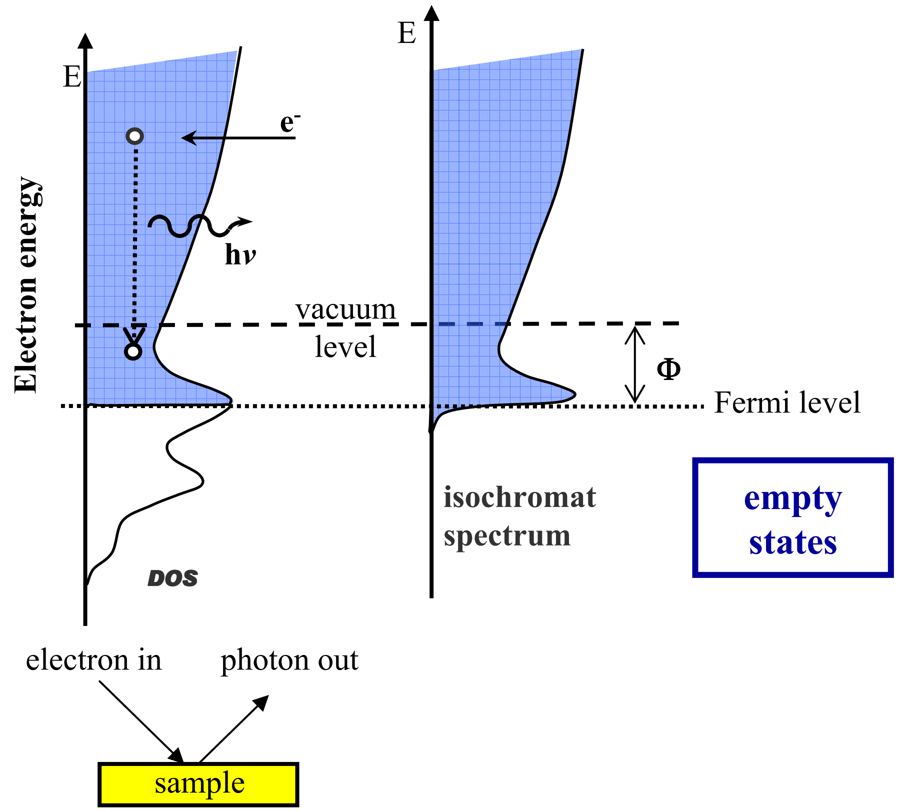
New lab for production of spin polarized electron beams

- *full autonomy*
- *room*
- *students*
- *budget: 30 MLire → ≈ 60 k€*

PhotoEmission *versus* Inverse PhotoEmission



(direct) **PhotoEmission Spectroscopy**



Inverse PhotoEmission Spectroscopy

PES ==> IPES
time reversal

- same matrix element <i|**A·p**|f>
- same cross section behaviour σ(E)
- $Y_{ph}/Y_{el} = (\lambda_{el}/\lambda_{ph})^2 \sim 10^{-5}$ in the UV

BIS – IPE

Bremsstrahlung Isochromat Spectroscopy (X-ray range)

pioneering studies: **J.A. Bearden, G, Schwarz,** Phys. Rev. B 79, 674 (1950)

modern spectroscopy tool: **J.K. Lang, Y. Baer,** Rev. Sci. Instrum. 50, 221 (1979)

Inverse PhotoEmission (UV range)

$h\nu$ = 9.8 eV	**G. Denninger, V. Dose, H. Scheidt,** Appl. Phys. 81, 375 (1979) **V. Dose,** Prog. Surf. Sci., 13, 225 (1983)
UV grating	**G. Chauvet, R. Baptist,** J. Electron. Spectrosc. 24, 255 (1981) **Th. Fauster, F.J. Himpsel,** Phys. Rev. B27, 1390 (1983)

First paper: MoS_2

Solid State Communications, Vol.66,No.6, pp.593-596, 1988. 0038-1098/88 $3.00 + .0
Printed in Great Britain. Pergamon Press pl

THE EMPTY ELECTRON-STATES IN MoS_2 :
AN INVERSE PHOTOEMISSION SPECTROSCOPY INVESTIGATION

M.Sancrotti, L.Braicovich, C.Chemelli and G.Trezzi

Politecnico di Milano - Istituto di Fisica
Piazza Leonardo da Vinci 32 - I 20133 Milano

(Received 20 February 1988 by E.Tosatti)

k-integrated Bremsstrahlung isochromat spectra, collected at different UV-photon energies ($h\nu$ = 13.2-24 eV), from 2H-MoS_2 are presented. Two structures (energy separation = 1.2 eV) of d-character are resolved close to the Fermi level. A third broad spectral feature appears at higher energy va lues and is assigned to hybridised metal-cation sp derived states. The results are compared to different electron-states calculations and are found to give support to the theoretical predictions derived within a LCAO scheme.

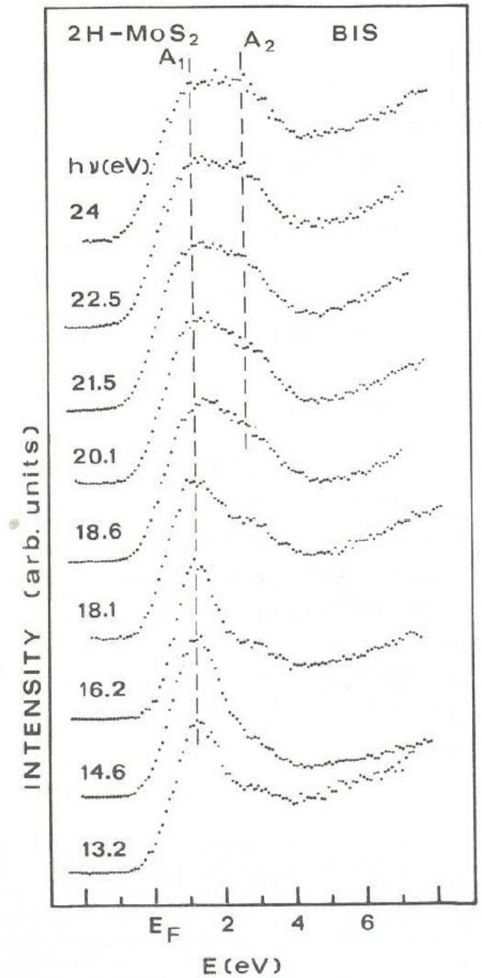


Fig 1 - k-integrated Bremsstrahlung isochromat spectra, collected at different UV-photon energy values, from MoS_2. The spectra were lined up at the Fermi level.

High efficiency IPE apparatus

639 Rev. Sci. Instrum. 62 (3), March 1991 0034-6748/91/030639-04$02.00 639

Ultraviolet inverse photoemission spectrograph with parallel multichannel isochromat acquisition

M. Sancrotti, L. Braicovich, C. Chemelli,[a)] F. Ciccacci, E. Puppin, G. Trezzi, and E. Vescovo
Istituto di Fisica-Politecnico di Milano, Piazza Leonardo da Vinci 32, I 20133 Milano, Italy

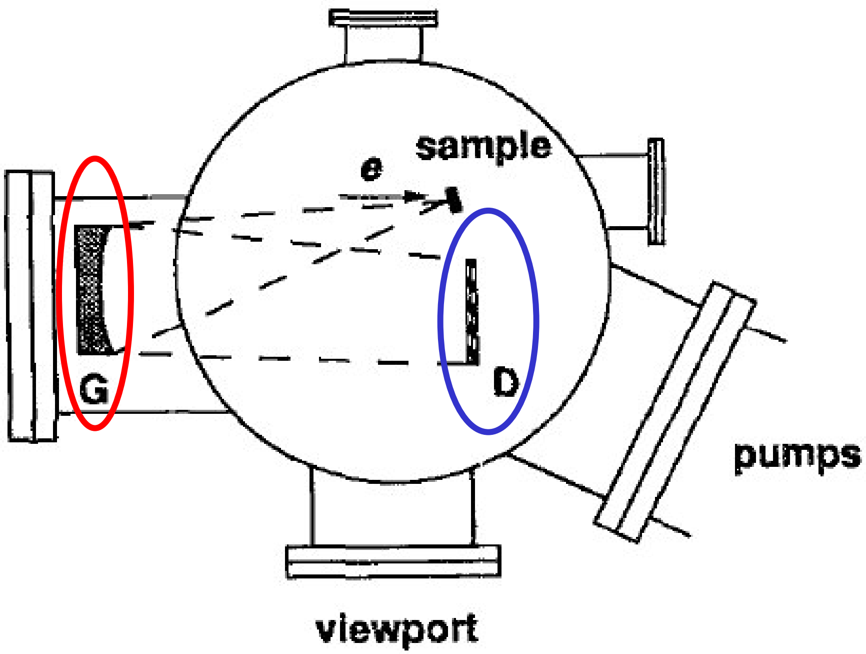


FIG. 1. Schematic view of the main chamber of the ultraviolet inverse photoemission apparatus. *e*, electron beam; G, grating; *D*, detector assembly.

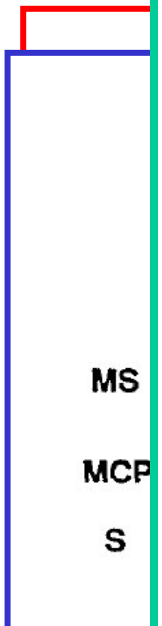


FIG. 3. De... ct- ing strips; ...nic chain for ... D, threshold s...

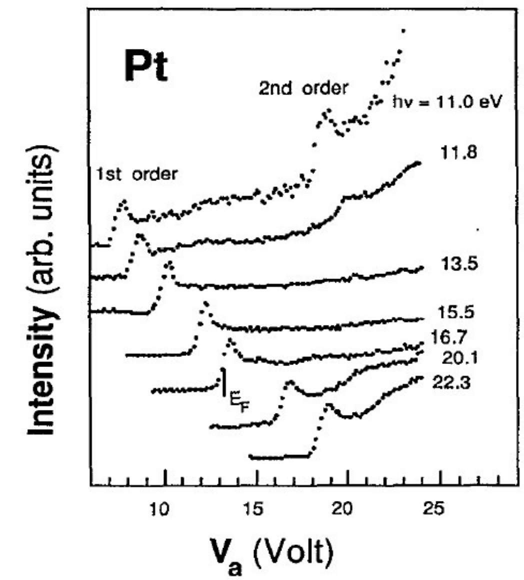


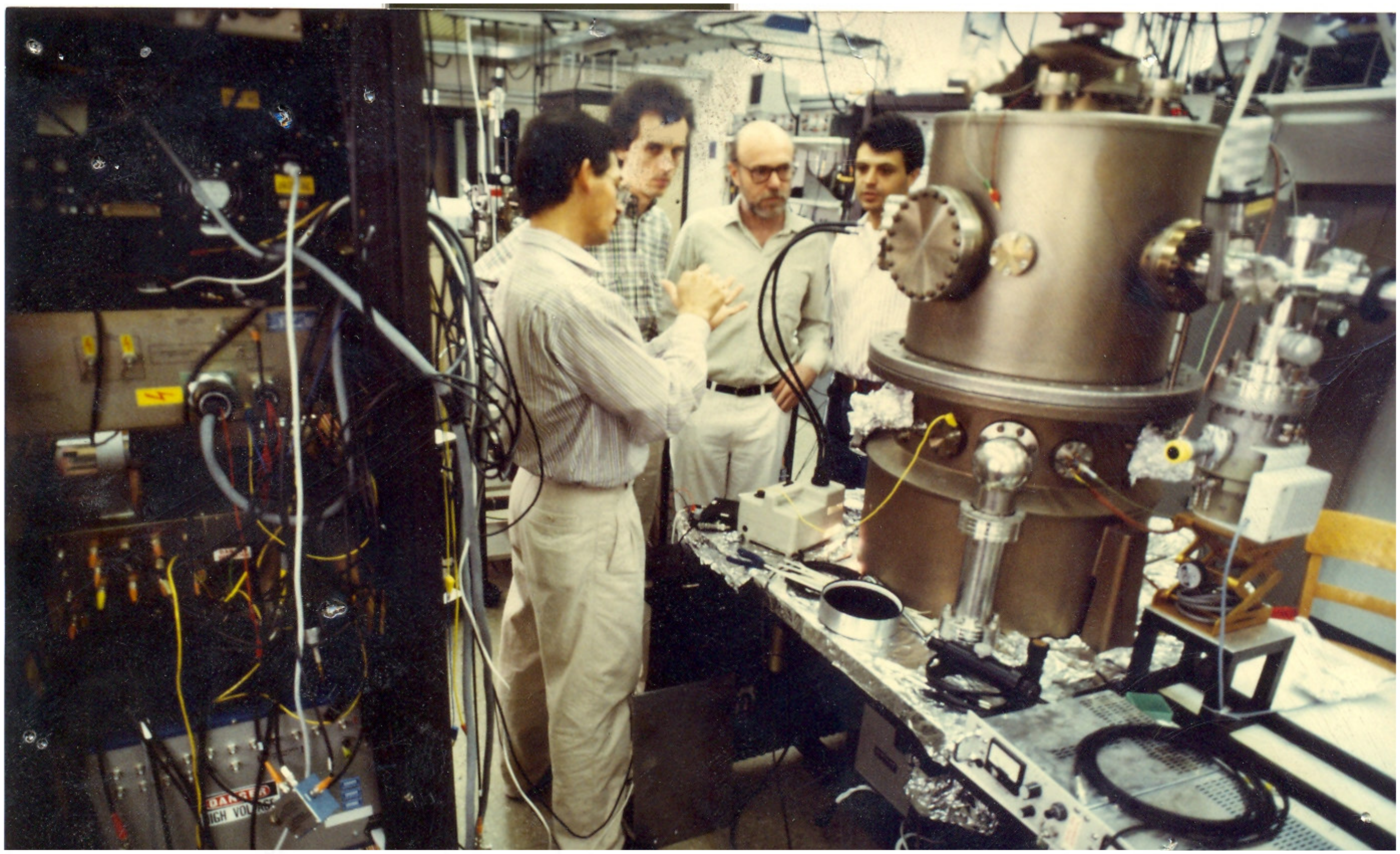
FIG. 4. Isochromat inverse photoemission spectra from polycrystalline Pt, taken at different photon energies. V_a is the electron accelerating potential: at the onset of the transition in the spectra, corresponding to E_F, $h\nu = e(V_a + \Phi)$, where e is the electron charge and Φ the electrons-emitting filament work function. Note that in our case Φ is rigorously the same for all the spectra, since they have been acquired in parallel ($e\Phi = 3.5$ eV). For the sake of clarity, only 7 out of the 12 spectra simultaneously collected are shown. Peaks due to first- and second-order diffraction are indicated. The different statistics of the spectra directly reflect differences in the relative counting rates and in turn the strong $h\nu$ dependence of the spectrograph efficiency.

Systems investigated (1988-1998)

- **Low *d*-occupancy silicides** (Ca-Si, Gd-Si)
- **Intermetallic compounds** (LaPd3, YFe2)
- **Fe oxides and sulphides** (Fe2O3, Fe3O4, FeO, FeS2)
- **Metal oxidation** (poly Fe, Co, Ni)
- **Rare earths metals** (La, Eu, Lu, Ce)
- **Rare earths-Transition metal compounds**
  ($LuCo_2$, $LuRh_2$, $LuRh_7$,Lu_7Rh_3, $CeCo_2$, $CeRh_2$, $CeRh_3$, Ce_7Rh_3, $CeIr_5$, Ce_7Ir_3)

Extensive use of photon energy dependence of photoemission cross section

Fe oxides - 1



Covalency in the electronic structure of Fe_3O_4: an ultraviolet inverse photoemission investigation

Condensed Matter
Zeitschrift für Physik B
© Springer-Verlag 1991

M. Sancrotti[1], F. Ciccacci[1], M. Finazzi[1], E. Vescovo[1], and S.F. Alvarado[2]

[1] Istituto di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci 32, I-20133 Milano, Italy
[2] IBM Research Division, Zürich Research Laboratory, Säumerstrasse 4, CH-8803 Rüschlikon, Switzerland

Received January 28, 1991

Fe oxides - 2

'HYSICAL REVIEW B VOLUME 46, NUMBER 19 15 NOVEMBER 1992-I

Ultraviolet inverse photoemission from iron monoxide and self-interaction-corrected local-spin-density calculations

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A. Svane
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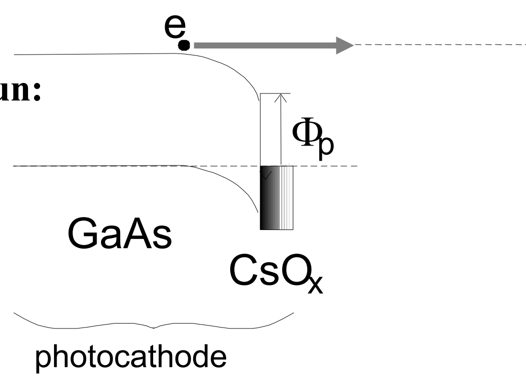
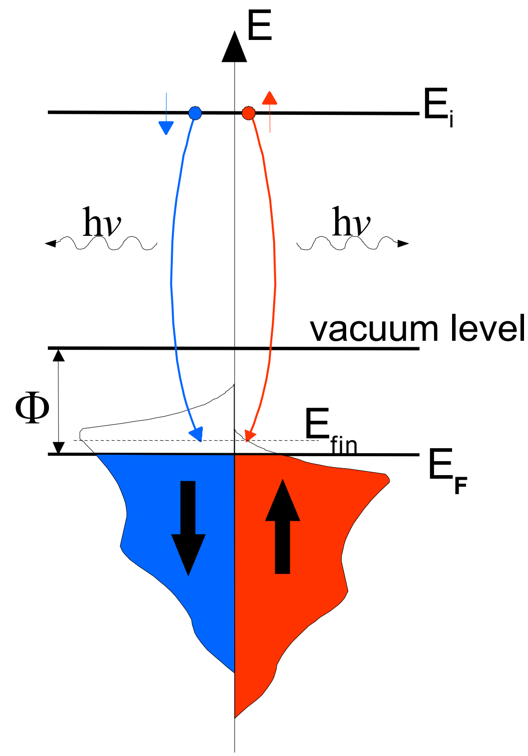
(Received 13 February 1992; revised manuscript received 1 July 1992)

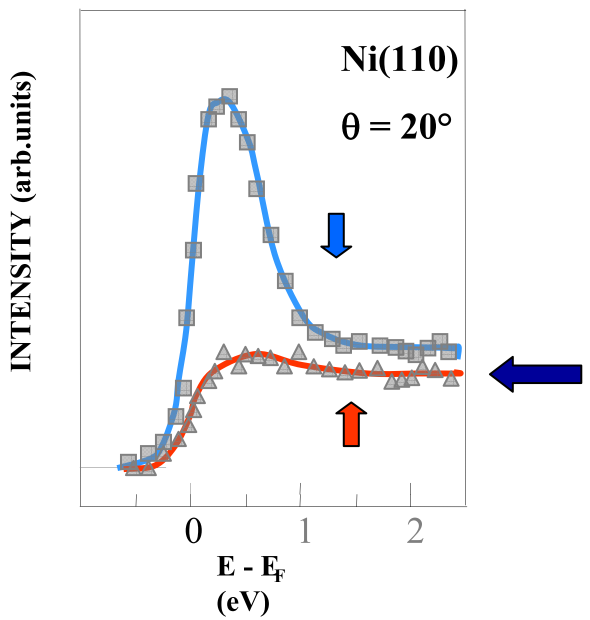
We present inverse photoemission (IP) results from Fe_xO taken in the isochromat mode at a variety of photon energies in the ultraviolet (11.5–23-eV) and the FeO partial and total density of states calculated in the self-interaction-corrected–local-spin-density approximation (SIC-LSD). The measurements show the Fe 3d contribution just above the bottom of the conduction band E_c and point out a contribution of the type $d^8\underline{L}$ ($\underline{L}$ denotes ligand hole) 12 eV above E_c; this is superimposed on oxygen (p)-derived states. The comparison with IP and with available direct photoemission results shows the advantages of SIC-LSD over LSD: in particular, the calculations give a gap and account for a distribution of the Fe 3d character in a wide energy range (15 eV) in the ground state. Moreover, the comparison with the experiment shows that SIC-LSD gives a satisfactory approximate evaluation of the Coulomb energy U and of the charge-transfer energy Δ to be used in an impurity model to treat the spectral features that cannot be described by the SIC-LSD eigenvalues ($d^6\underline{L}$ and $d^8\underline{L}$ final states in direct and inverse photoemission, respectively).

Spin Polarized Inverse PhotoEmission - SPIPE

Spin polarized electron gun:
GaAs polarized source





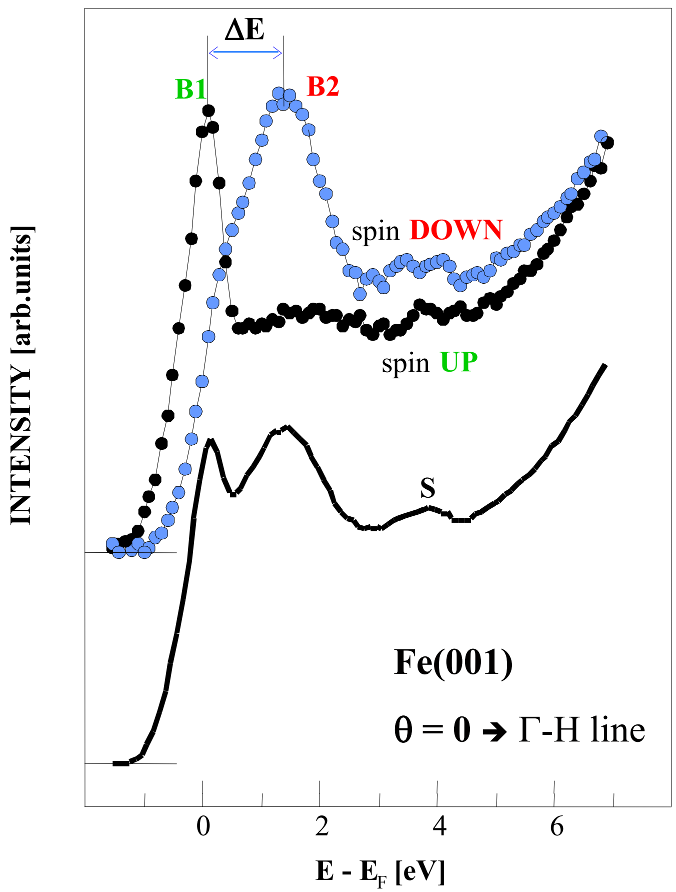


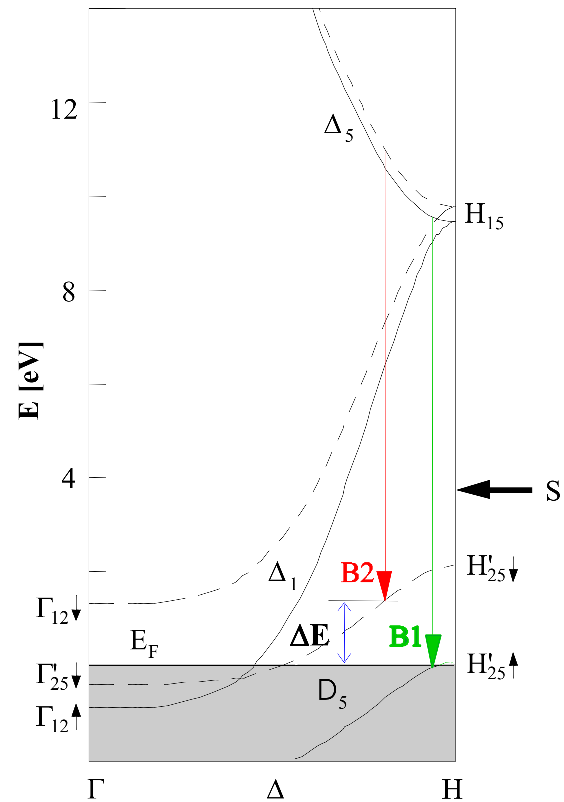
first measurements: J. Unguris, A. Seiler, R.J. Celotta, D.T. Pierce, P.D.Johnson, N. Smith, Phys. Rev. Lett. **49**, 1047 (1982)

U. Kolac, M. Donath, K. Ertl, H. Liebl, V. Dose, Rev. Sci. Instrum. **59**, 1933 (1988)

review: M. Donath, Surface Sci. Rep. **20**, 251 (1994)
F. Ciccacci, Phys. Scrip. **T66**, 190 (1996)

SPIPE from Fe(001)





A. Santoni, F.J. Himpsel, Phys. Rev. **B 43**, 1305 (1991)

J. Kirschner, M. Glöbl, V. Dose, H. Scheidt: Phys. Rev. Lett. **53** (1984) , 612

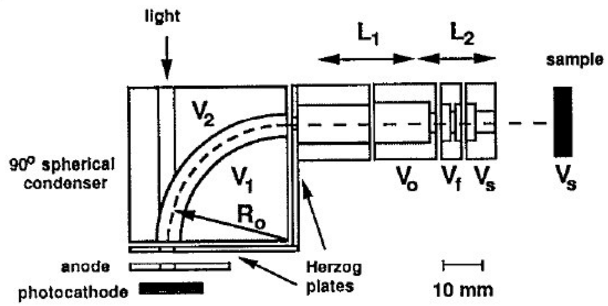
S. De Rossi, F. Ciccacci, J. Electron Spectrosc. Relat. Phenom. **76** (1995) , 177

SPIPE - Milano

3333 Rev. Sci. Instrum. 63 (6), June 1992 0034-6748/92/063333-06$02.00

Spin-polarized electron gun for electron spectroscopies

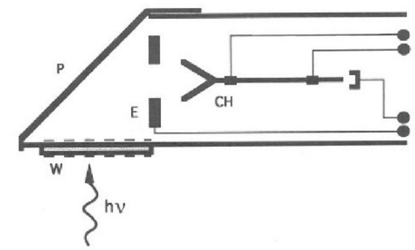
F. Ciccacci, E. Vescovo, G. Chiaia, S. De Rossi, and M. Tosca
Istituto di Fisica, Politecnico di Milano, piazza Leonardo da Vinci 32, I-20133 Milano, Italy

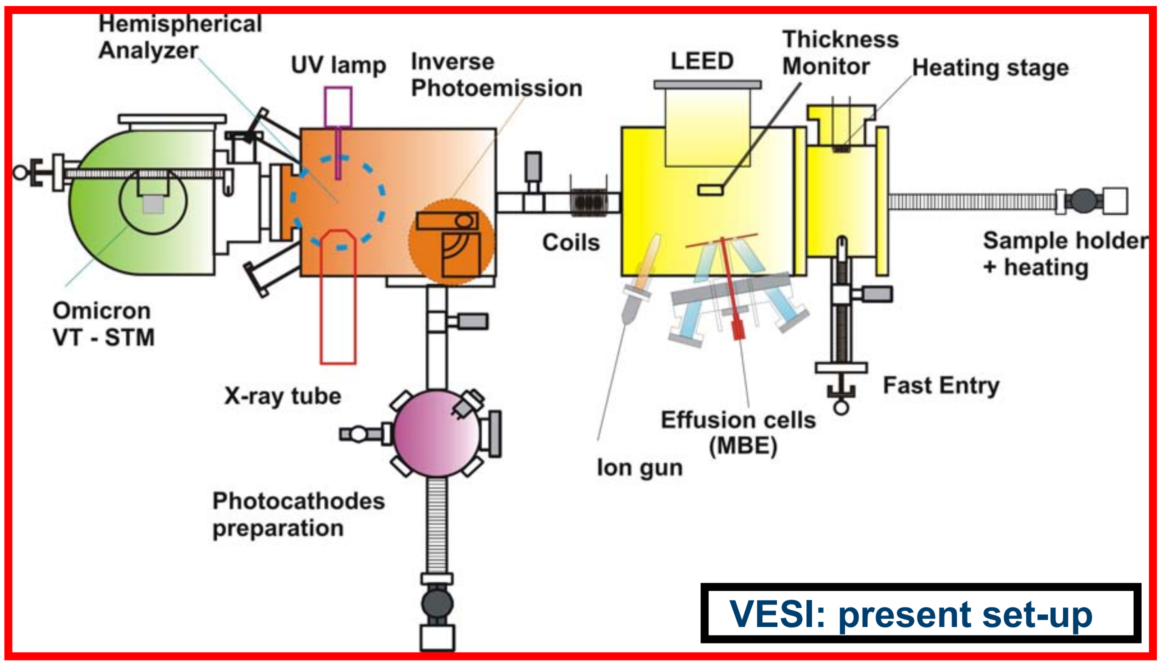


Meas. Sci. Technol. 4 (1993) 234–236. Printed in the UK

High-sensitivity bandpass UV photon detector for inverse photoemission

M Finazzi, A Bastianon, G Chiaia and F Ciccacci
Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci 32, I-20133 Milano, Italy





SPIPE - Milano

first publication

PHYSICAL REVIEW B VOLUME 48, NUMBER 15 15 OCTOBER 199

Thin Fe films grown on Ag(100) studied by angle- and spin-resolved inverse-photoemission spectroscopy

G. Chiaia, S. De Rossi, L. Mazzolari, and F. Ciccacci
Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci 32, I-20133 Milano, Italy

(Received 12 February 1993; revised manuscript received 4 May 1993)

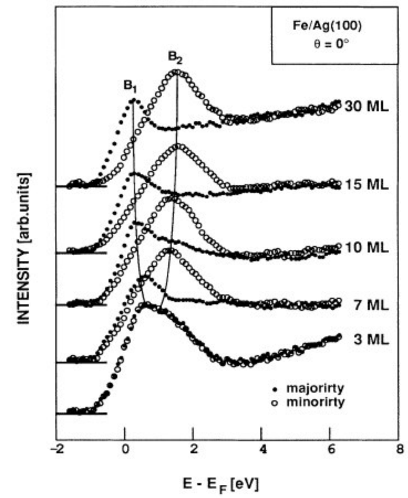


FIG. 7. Spin-resolved spectra normalized to a 100% polarized incident beam from Fe films grown on Ag(100), taken at normal incidence. The majority and minority B_1 and B_2 structures appear in two different spin channels.

thin magnetic films
evolution of electronic and magnetic structure: Fe on Ag(001), Au(001), and Cu(001)
antiferromagnetic films: Cr/Ag(001) and Cr/Fe(001)
metastable films: hcp Co on Fe(001)
thin oxide films: NiO on Ag(001) and Fe(001)
half-metals: LaMnSrO and LaMnSrO/SnTiO interfaces
Fe homoepitaxial growth

clean surfaces - adsorbates
“negative” exchange splitting of image states in Fe(001)
adsorbate-induced enhancement of spin dependent effects at Fe(001)-p(1x1)O

magnetic coupling in multilayers
oscillatory exchange coupling: Fe/Cr/Fe(001)
exchange bias: Fe/NiO/Fe(001)

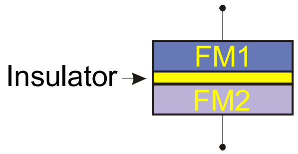
non-magnetic films on ferromagentic substrate
spin dependent quantum well states: Ag on Fe(001)
interface states: Pt on Fe(001)
electron mean free path: V on Fe(001)
localized f-states: Ce on Fe(001)

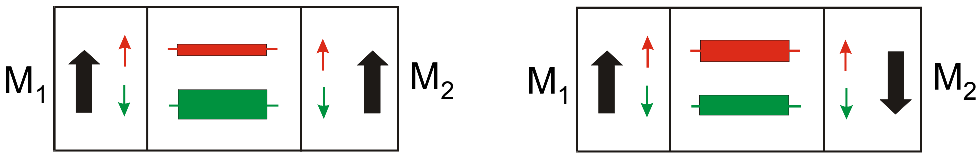
ferromagnet / semiconductor interfaces
Fe/GaAs(001), Fe/Ge(001), Fe/ZnSe(001)

organic-inorganic semiconductor interfaces

Magnetic Tunneling Junctions
STO/LSMO/STO, Fe/MgO/Fe(001)

MTJ: Magnetic Tunnel Junctions



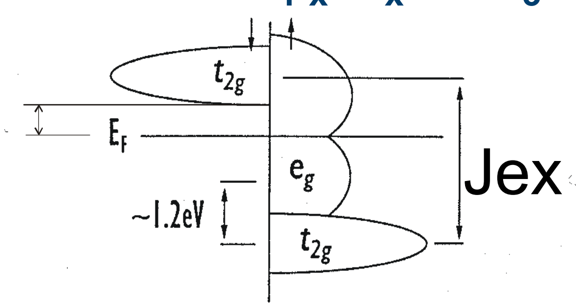


$$TMR = \frac{R_{AP} - R_P}{R_P} = 2\frac{P_1 \cdot P_2}{1 - P_1 \cdot P_2}$$

Rp < Rap

Important to find materials with high spin polarization at the Fermi level

Half metals: $La_{1-x}Sr_xMnO_3$



J.-H. Park et al. Nature, 392, 794 (1998)

A. Chattopadhyay et al., Phys. Rev. B, 61, 10738 (2000)

MTJ: LSMO/STO/LSMO

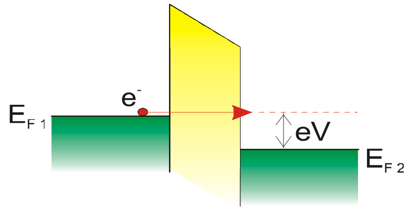
(epitaxially grown by PLD)

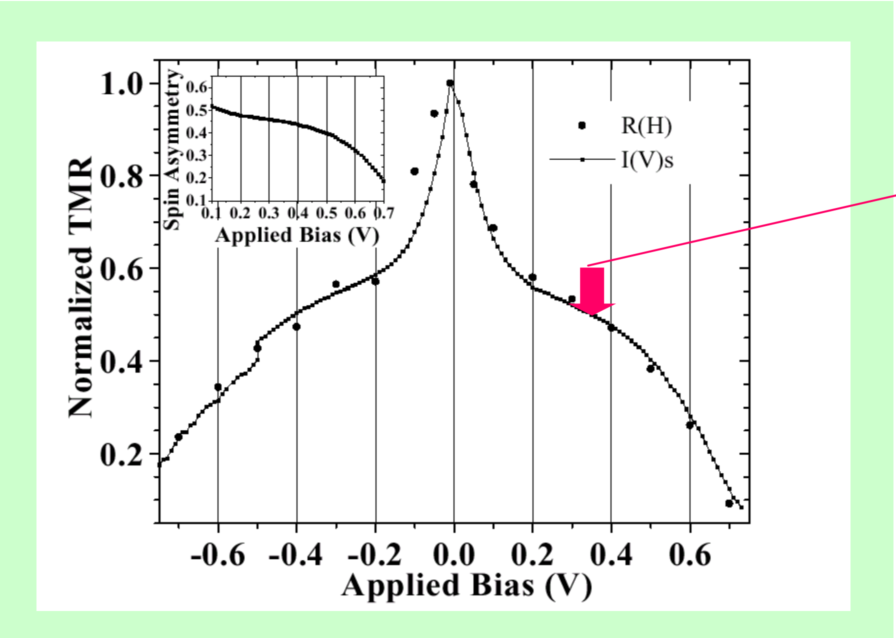
TMR ≈ 1900% ⟺ $P \approx 95\%$

J.M. De Teresa, A. Barthélémy, A. Fert, J.P. Contour, F. Montaigne, P. Seneor, Science 286, 507 (1999)

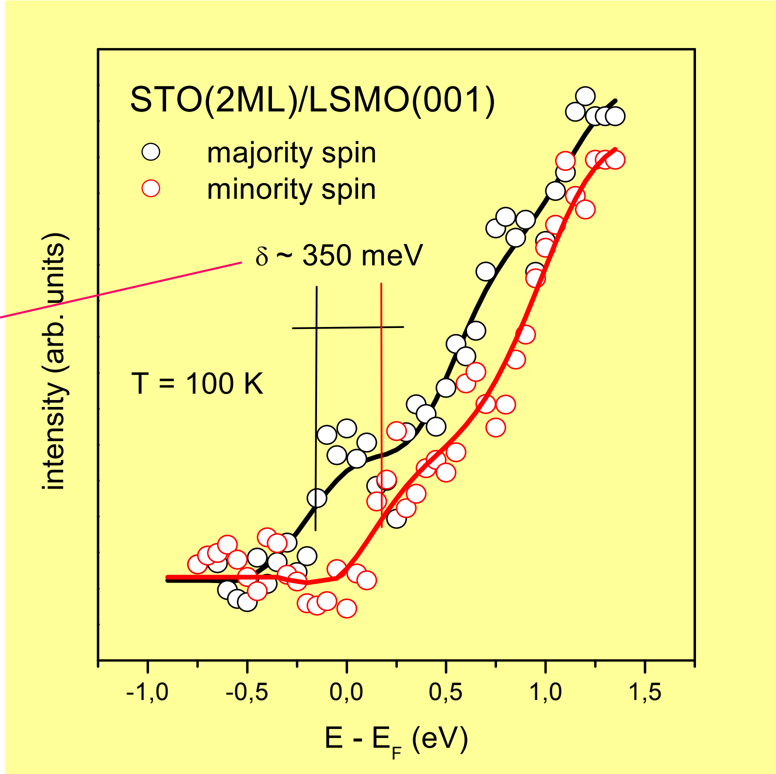
MJT: LSMO/STO/LSMO

Bias dependence of TMR (Paris)





Spin resolved inverse photoemission (Milano)

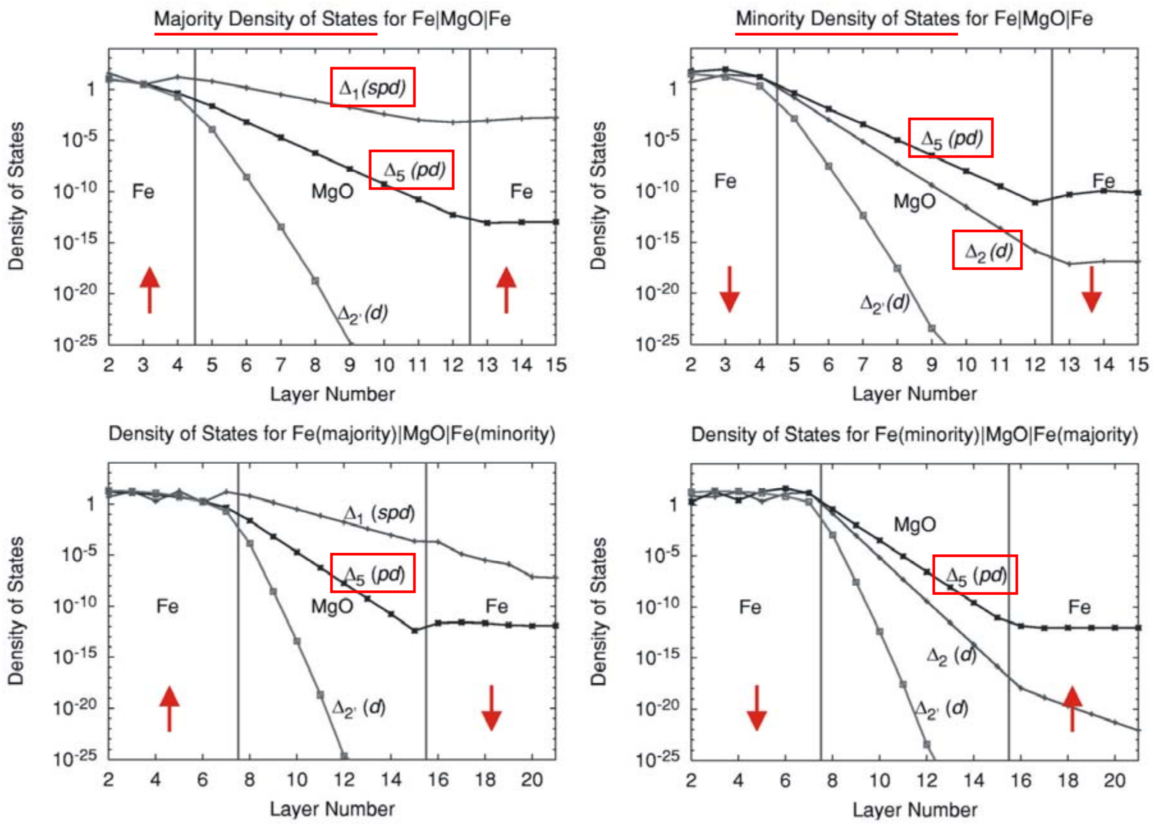


TMR *versus* empty state density at FM/insulating interface

M. Bowen, A. Barthèlèmy, M. Bibes, E. Jacquet, J.P. Contour, A. Fert, F. Ciccacci, L. Duò, R. Bertacco

Phys. Rev. Lett. 95, 137203 (2005)

MJT: Fe/MgO/Fe(001)



W. H. Butler *et al*, PRB **63** 054416 (2001)

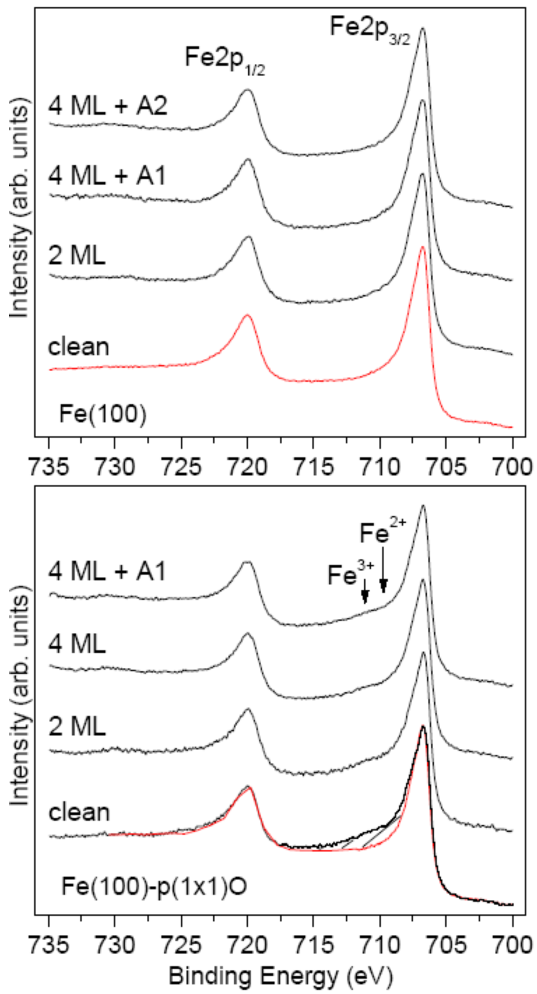
symmetry filtering effect

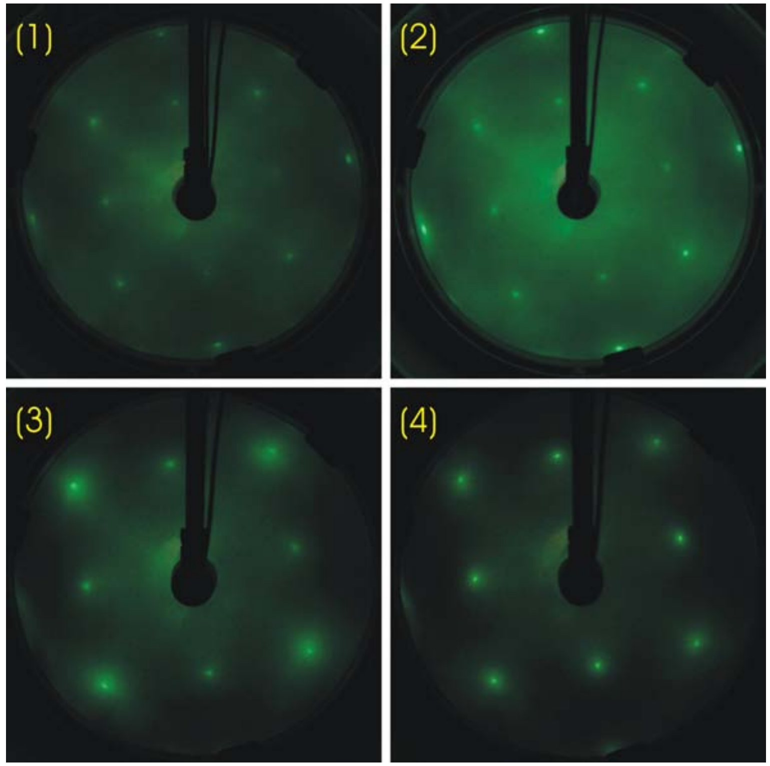
TMR ~1000% (theory)   200-300% (experimental)

S. Yuasa *et al*, *Nature Materials*, **3** 868 (2004)

role of Fe oxidation at interface

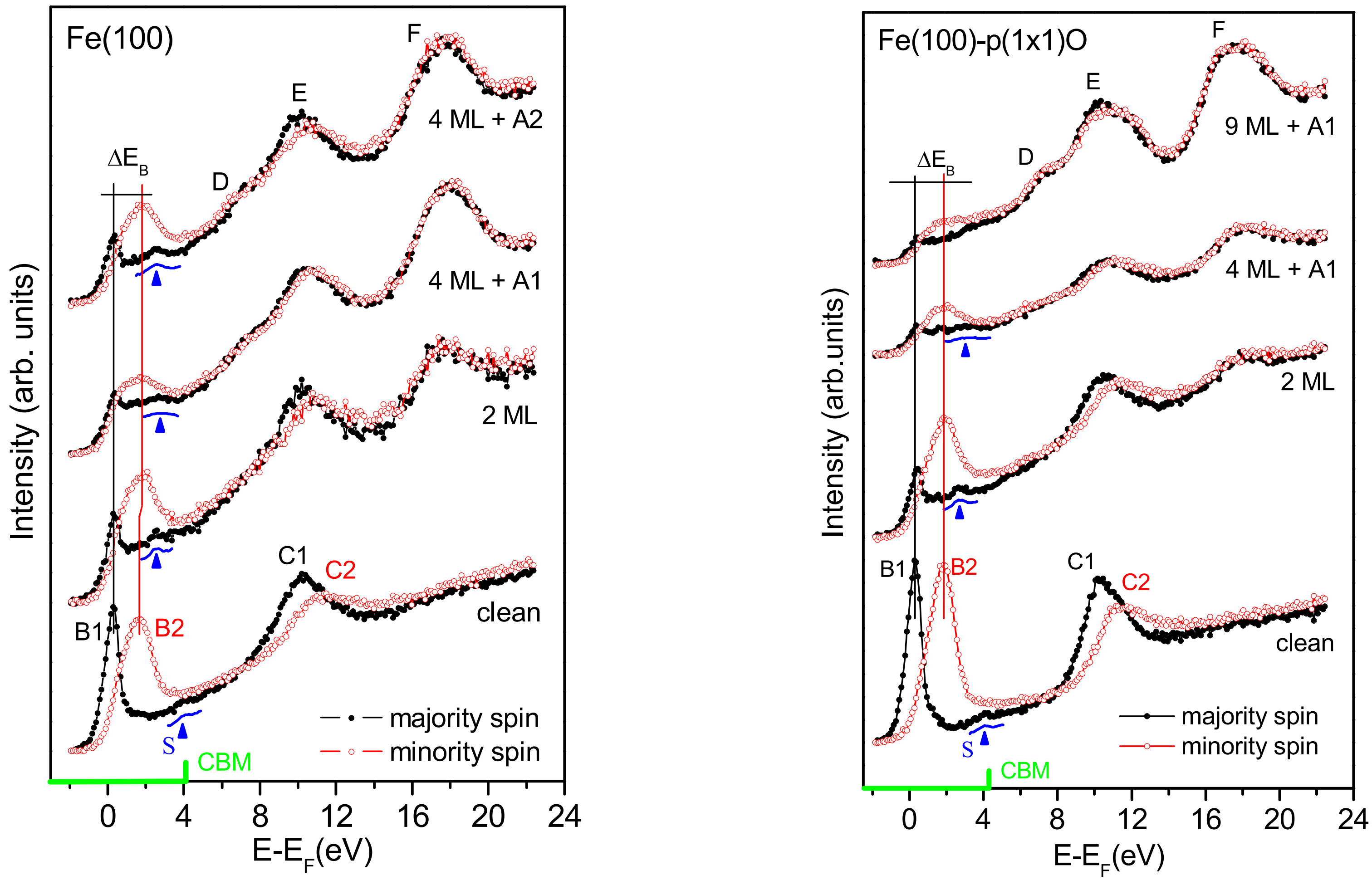
MgO/Fe(001) *vs* MgO/Fe(001)-p(1x1)O – XPS, LEED





A. Cattoni, D. Petti, M. Cantoni, R. Bertacco, F. Ciccacci (2009)

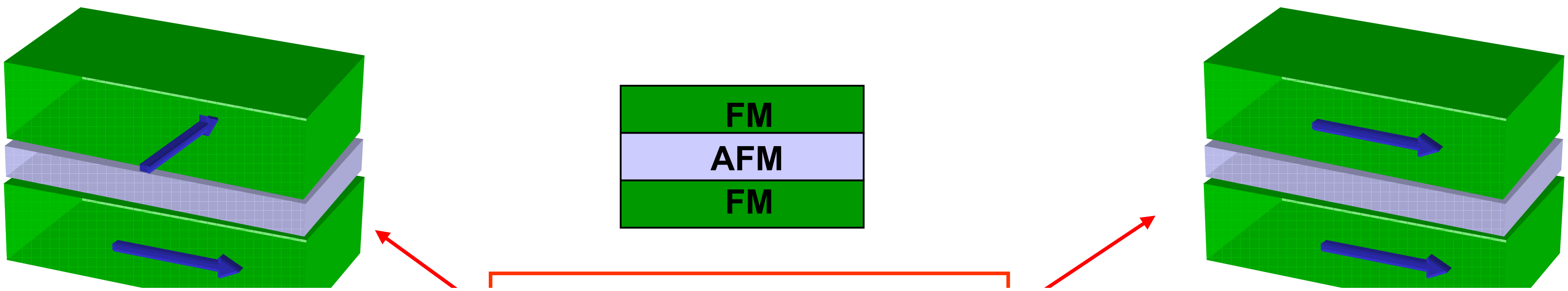
MgO/Fe(001) versus MgO/Fe(001)-p(1x1)O - SPIPE



…. the Fe(001)-p(1x1)O surface is a good candidate for the realization of good interfaces in Fe/MgO/Fe MTJs…

A. Cattoni, D. Petti, M. Cantoni, R. Bertacco, F. Ciccacci (2009)

FM/AFM interfaces and multilayers



Surface Science Reports 64 (2009) 139–167

Contents lists available at ScienceDirect

Surface Science Reports

journal homepage: www.elsevier.com/locate/surfrep

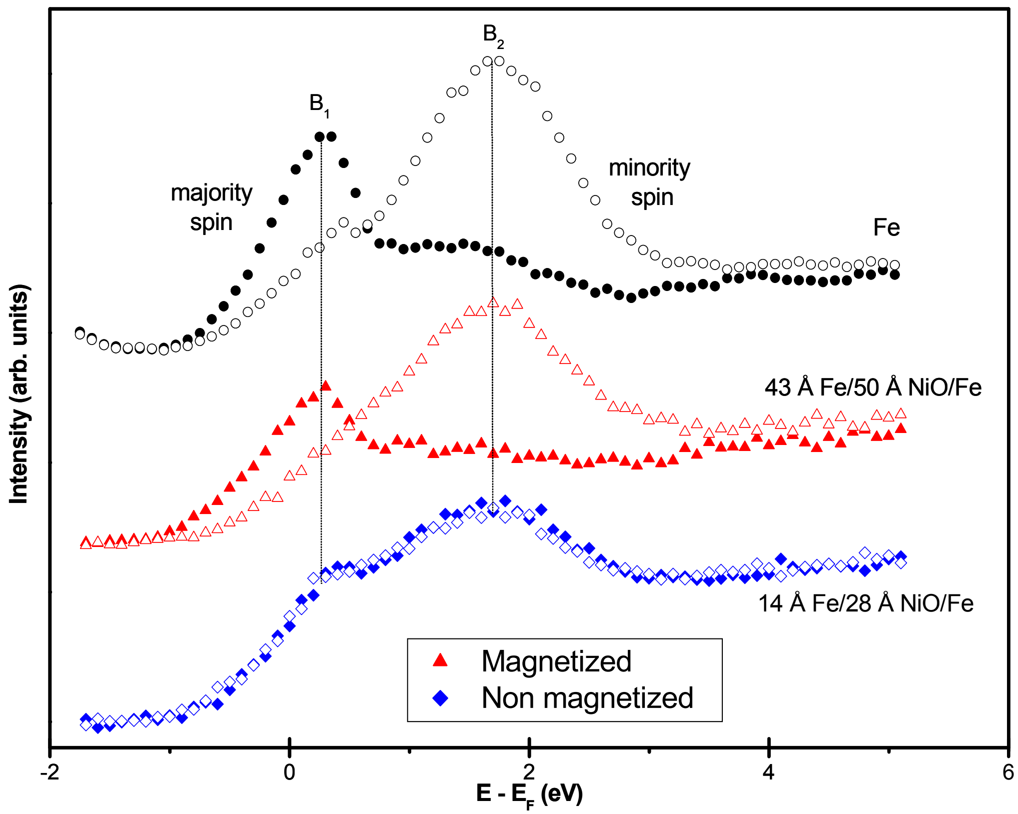
ELSEVIER

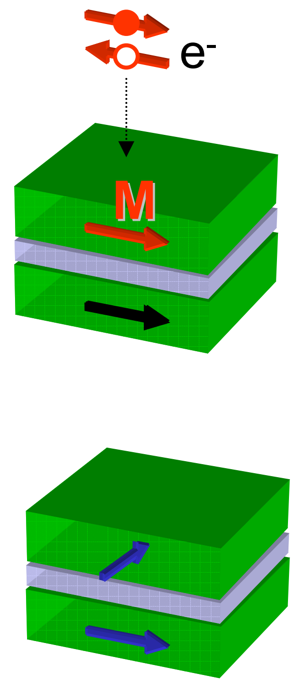
Magnetic properties of interfaces and multilayers based on thin antiferromagnetic oxide films

Marco Finazzi*, Lamberto Duò, Franco Ciccacci

L-NESS, Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

Fe/NiO/Fe: SPIPE results





PHYSICAL REVIEW B **72**, 174402 (2005)

Magnetization reversal properties of Fe/NiO/Fe(001) trilayers

A. Brambilla,* P. Biagioni, M. Portalupi, M. Zani, M. Finazzi, and L. Duò
INFM, Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo Da Vinci 32, 20133 Milano, Italy

P. Vavassori
INFM, S[3], Dipartimento di Fisica, Università di Ferrara, Via Paradiso 12, 44100 Ferrara, Italy

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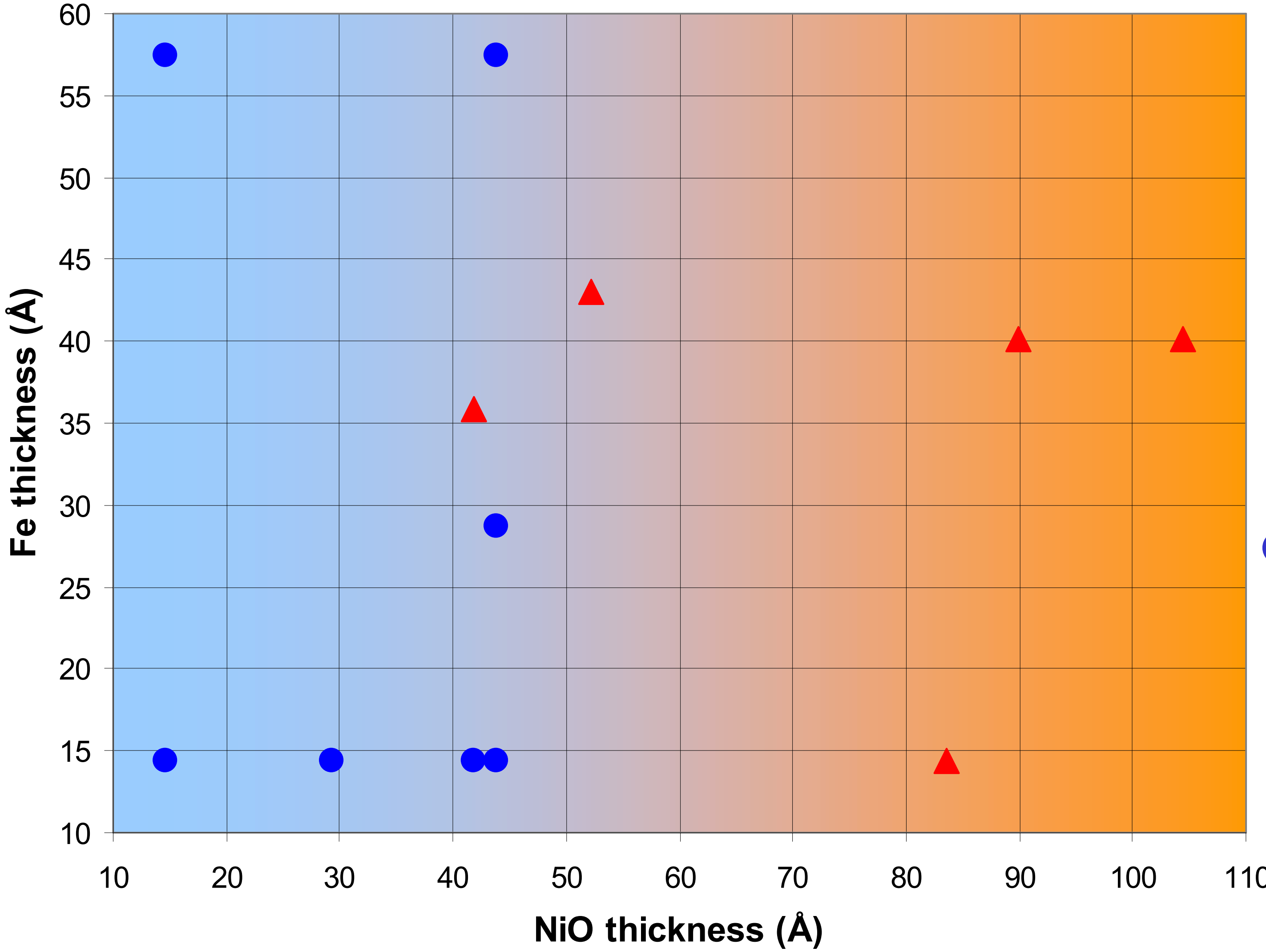
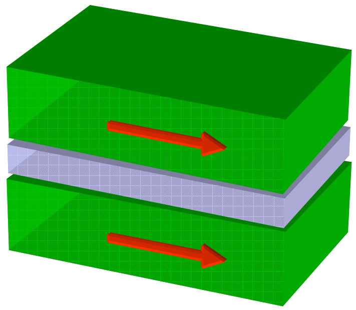
(Received 5 August 2004; revised manuscript received 4 August 2005; published 1 November 2005)

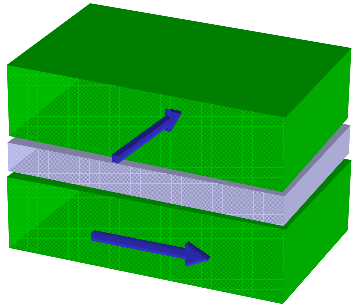
Fe/NiO/Fe: SPIPE results



= Polarized

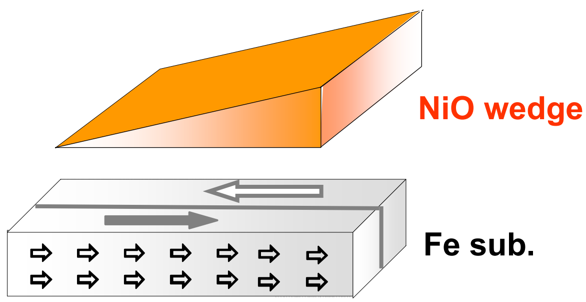


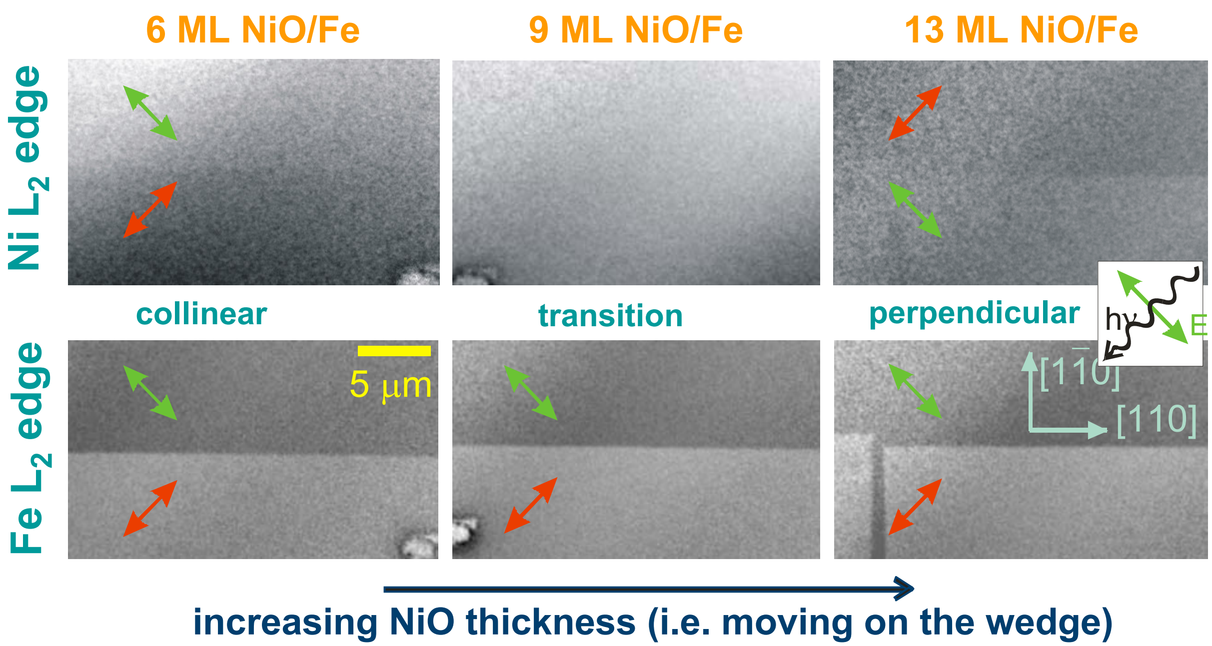
= Non polarized



transition regime $t_{AFM} \approx 40$ Å

NiO/Fe: XPEEM contrast (ALS-Berkely)





M. Finazzi *et al.*, Phys. Rev. Lett. **97**, 97202 (2006); L. Duò *et al.*, Surf. Sci. **600**, 4160 (2006)

Reverse interface: Fe/NiO(001) perpendicular coupling at any Fe coverage

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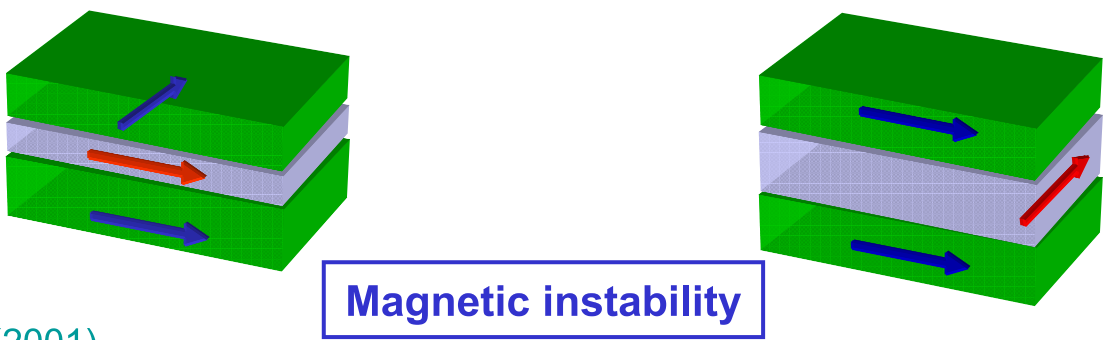

Fe/CoO/Fe magnetic nanodomains

PHYSICAL REVIEW B **79**, 172401 (2009)

Frustration-driven micromagnetic structure in Fe/CoO/Fe thin film layered systems

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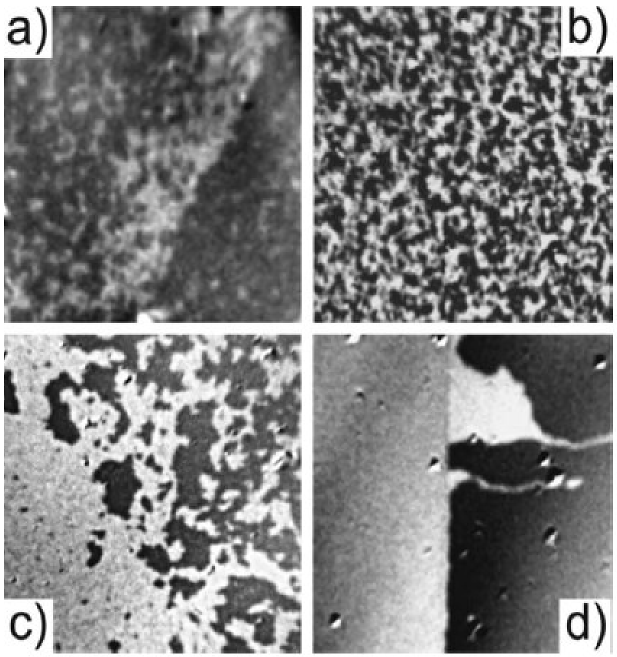

FIG. 1. Room-temperature XMCD asymmetry images from the top Fe layer in the Fe/CoO/Fe system. The CoO thickness is from panels (a) to (d): 1 nm, 2 nm, 4 nm, and 5 nm, respectively. The field of view is 10 $\mu m \times 10$ μm for each image.

In conclusion, we have provided experimental evidences of the stabilization of very small in-plane magnetic domains on top of Fe/CoO/Fe trilayer systems and compared such observations with analogous results previously obtained on Fe/NiO/Fe systems, also in consideration of the dramatically different values of the magnetocrystalline anisotropy reported for the two systems. The observed domain structure cannot be explained in the framework of conventional magnetic domain theories, while it is clearly connected with magnetic instabilities generated by frustrations at the FM/AFM interfaces. Such instabilities are also expected to be connected to the different coupling regimes between the magnetization directions in the FM layers which have in fact been observed by MOKE for different CoO thicknesses.

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