Investigations on the potential use of silicon substrate as support for magnetic iron nanostructured films

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Short Outline

Introduction:

- Why magnetic systems?
- Why magnetic systems on Si?
- What about Fe on Si ?
- Looking for a buffer layer...

Lecture 1: Can magnetic Fe films be epitaxially grown on a Si substrate by using Cu or β-$FeSi_2$ buffer layers?

Lecture 2: A careful study of the magnetic and structural properties of ultrathin Fe films deposited on Cu/Si(111)

Magnetic films and multilayers:

- giant magnetoresistence
- magnetic memories
- microwave devices

Systems characterized by the change of

- value of magnetic moment
- magnetization axis
  - vs thickness
  - choosing appropriate combination of materials

WHY

magnetic systems on Si substrate ?

- Silicon is cheaper and easier to prepare than any metallic single crystal substrate
- In view of their potential integration with Si technology

BUT

Si does not provide a close lattice match to any of the elemental magnetic metals

↓

It is not easy to achieve epitaxial growth

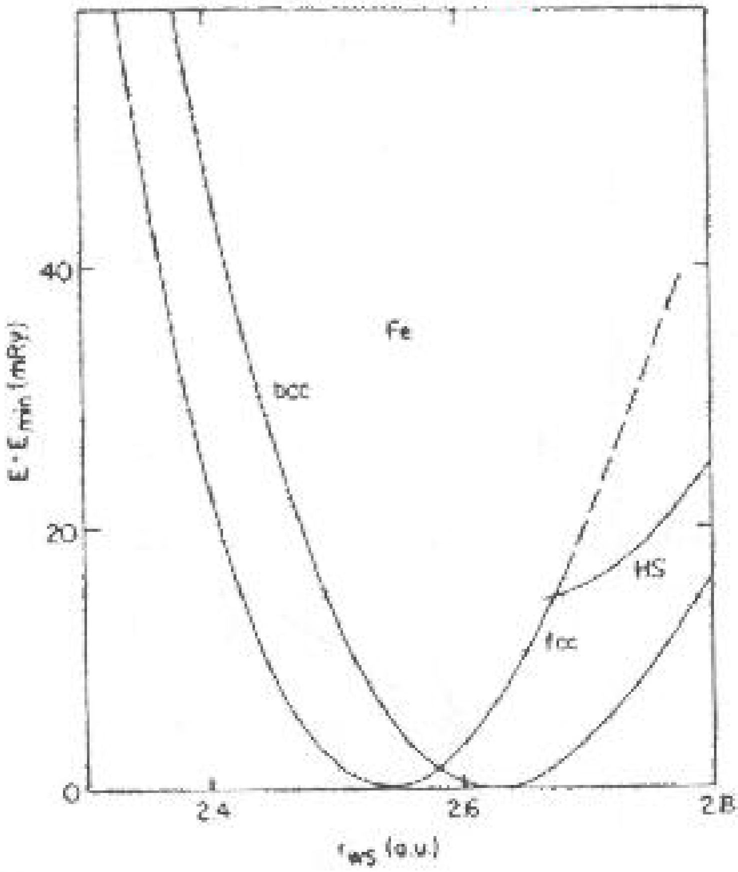
↓

Serious limitations of the device performances

Iron

is a natural candidate
to obtain such magnetic
systems

Theoretical prediction :



Total energy vs r_{WS}

by V. L. Moruzzi, P. M. Marcus, K. Schwarz, P. Mohn, 5)

- **bcc phase (α-Fe)**
  - magnetic for all the r_{WS} values

  - the most stable: r_{WS} = 2.63 a.u.

- **fcc phase (γ-Fe)**
  - different stable and metastable phases
  - NM, HS, LS

as a function of r_{WS}

Experimental observation :

The iron fcc phase is stable :

- **in bulk**

  only for 1184 K < T < 1665 K

- **as small precipitates in a Cu matrix**

  at room temperature

- **in ultra thin films**

  epitaxially grown on substrates as Cu(001), Cu(111), Cu_3Au(001), Ni(001), fcc Co(001)

RT deposited Fe on Si substrates

- *No* LEED patterns
- Formation of intermixed phases
  (various silicides FeSi, $FeSi_2$, Fe_3Si and non-stoichiometric alloys have been suggested to form at the Fe/Si interface)

↓

No good quality epitaxial Fe films

Moreover

The stoichiometry of Fe-Si alloy affects

- the magnetic behaviour

  ferromagnetic silicides:
  $Fe(Fe_xSi_{1-x})$ with $0.15 \leq x \leq 0.5$

- the value of Fe magnetic moment (*m*)

  ***m* decreases with iron content**

- defects presence

  it increases with Si content

Therefore

- to avoid Fe-Si interdiffusion
- to grow good quality iron epitaxial films

buffer layer

- Deposition of Cu on Si(001) and Si(111)
- Formation of β-$FeSi_2$ on Si(001)

Why a copper buffer layer ?

Iron films epitaxially grow
on Cu(111) and Cu(001) single crystals

Iron ultrathin films

- mostly fcc arranged (but also fct in Cu(001) substrate case)
- showed an out-of-plane magnetization

Cu(111) → Superparamagnetic ?

Cu(001) → HS ferromagnetic & sometimes AF

Iron thin and thick films

- bcc arranged
- ferromagnetic behaviour
- in-plane magnetization

What about Fe/Cu/Si ?

- Can we epitaxially grow high quality Fe/Cu/Si ultrathin films?
- Are their magnetic properties similar to those of ultrathin iron films grown on Cu syngle srystals?
- Which are the morphological, structural and electronic properties of these films?
- Does a correlation exist between the magnetic and structural or morphological properties of these films?

Methodology and experimental techniques

- Growth in UHV system: $p \sim 1x10^{-10}$ torr
- Fe deposited on the sample kept at RT

LEED :

- to check the quality of the Si substrate reconstruction
- to monitor morphology and structural changes after the buffer layer formation and each Fe deposition

Auger spectra :

- to check the atomic purity of substrates & overlayers

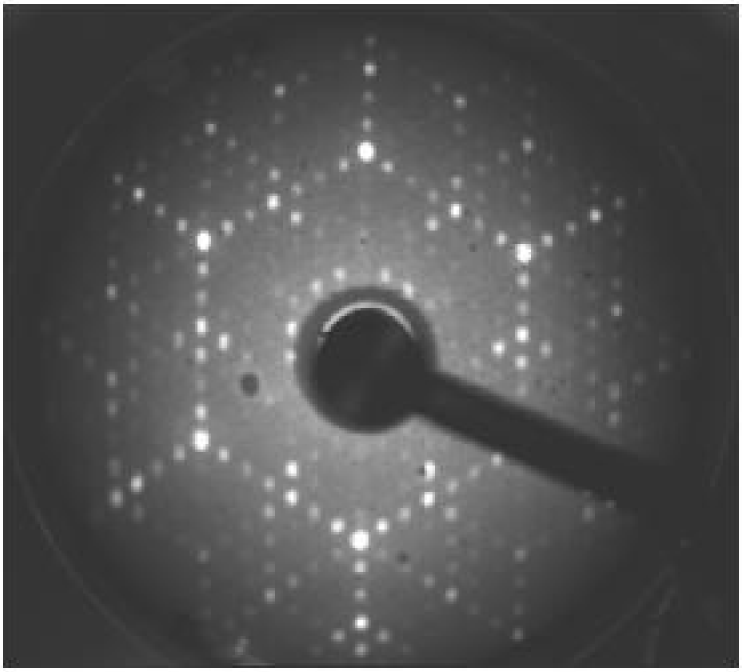
- **Auger electron diffraction**
- **XAS e UPS**
- **SMOKE**
- **STM and MFM**

Polar angular
Auger electron diffraction patterns:

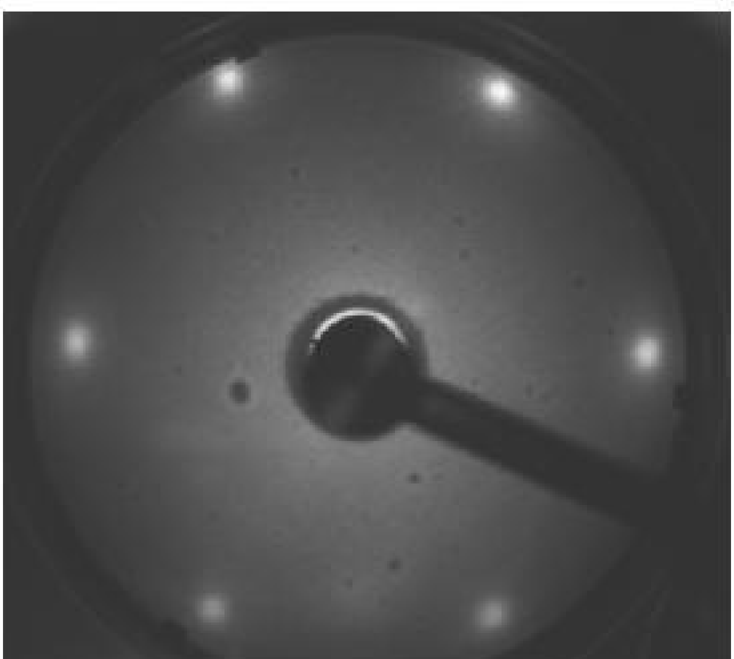
- sample rotation in front of the CMA
- azimuthal plane identified by LEED images
- peak-to-peak intensity of Fe $L_{2,3VV}$ and/or Cu $L_{2,3VV}$
- Auger spectra
  - collected in first derivative mode
  - measured vs polar angle
- primary electron beam of 1500 eV

Si(111) substrate

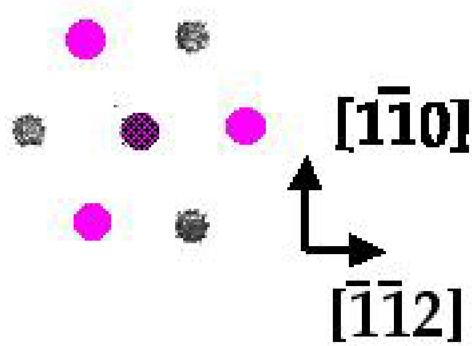
LEED images E_p = 70 eV

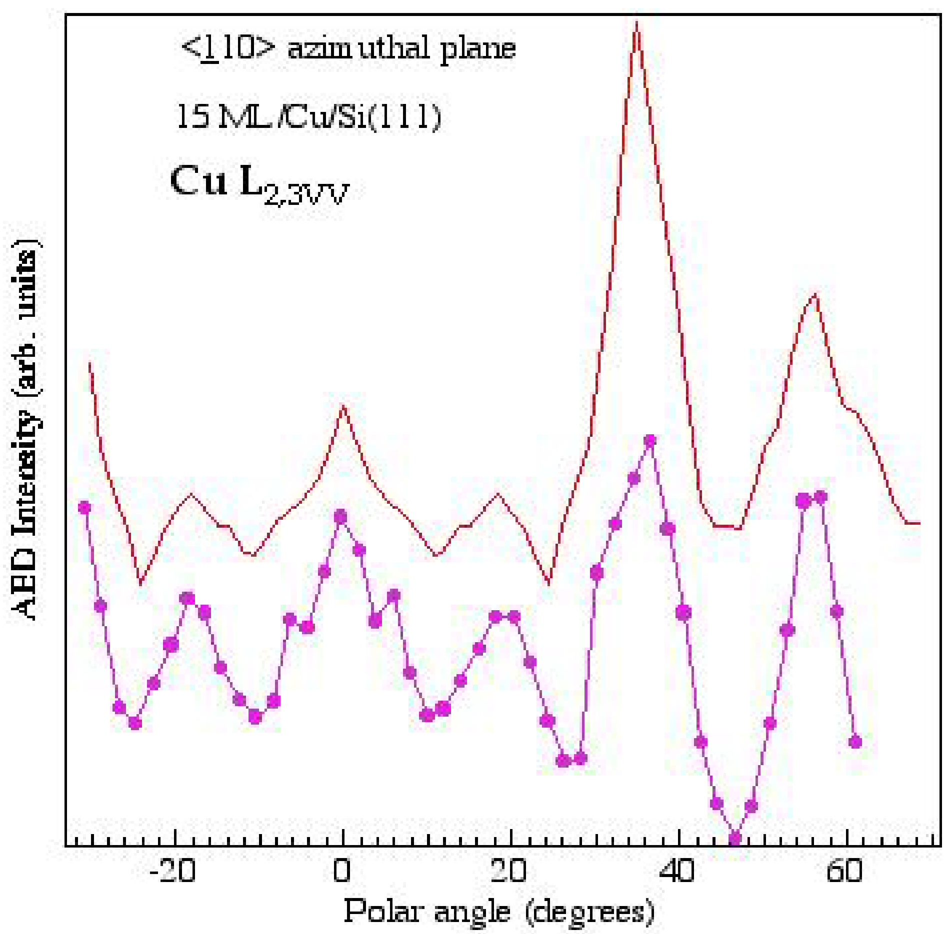


Si(111)7x
7

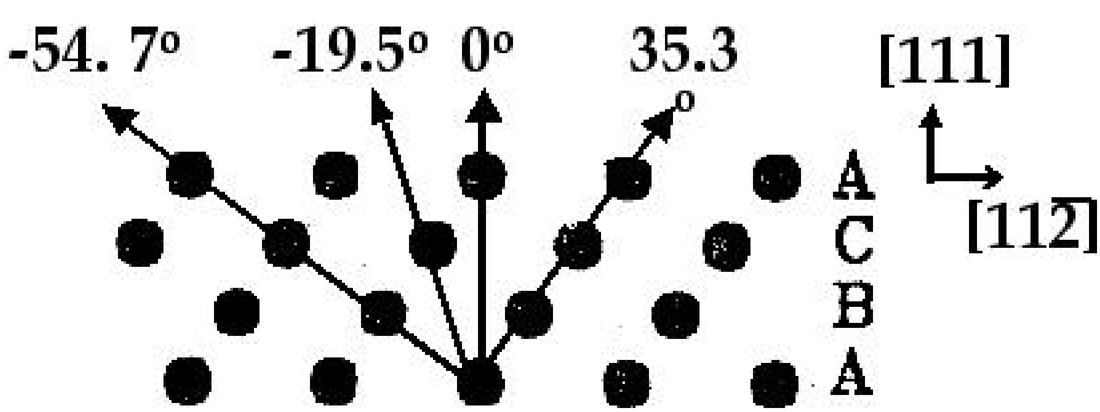


15 ML Cu
on Si(111)7x7



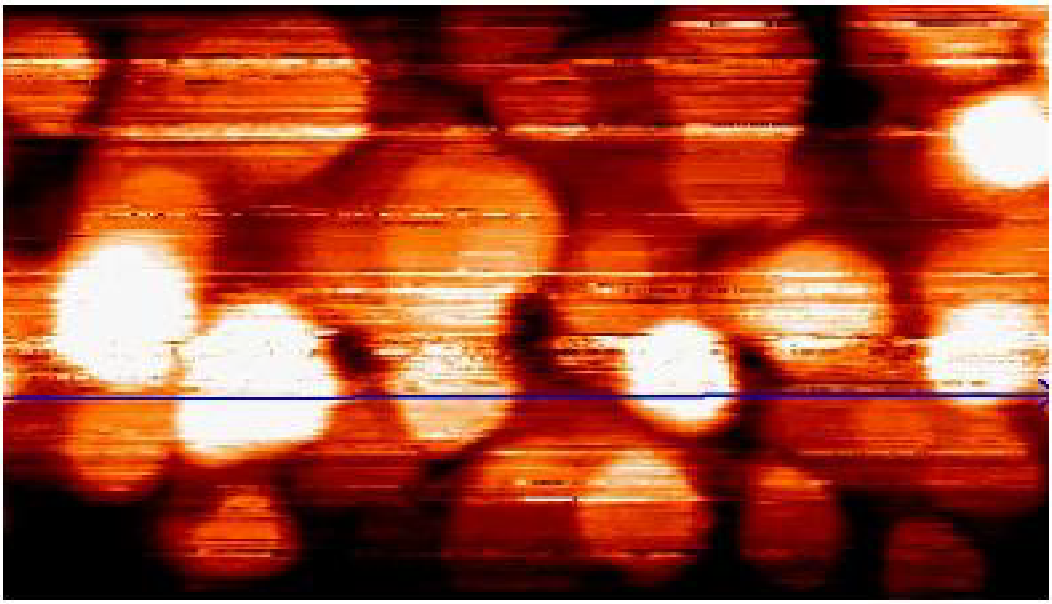


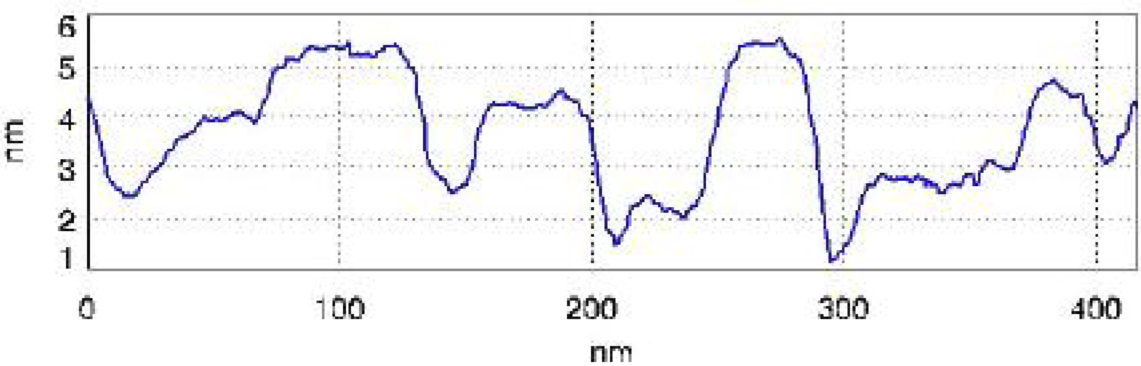
<110> azimuthal plane
15 ML/Cu/Si(111)
Cu L2,3VV
AED Intensity (arb. units)
-20
0
20
40
60
Polar angle (degrees)



-54. 7º
-19.5º
0º
35.3º
[111]
[112]
A
C
B
A

STM
15 ML Cu/Si(111)

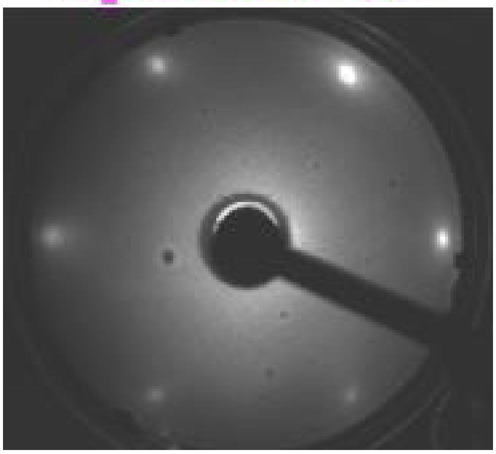
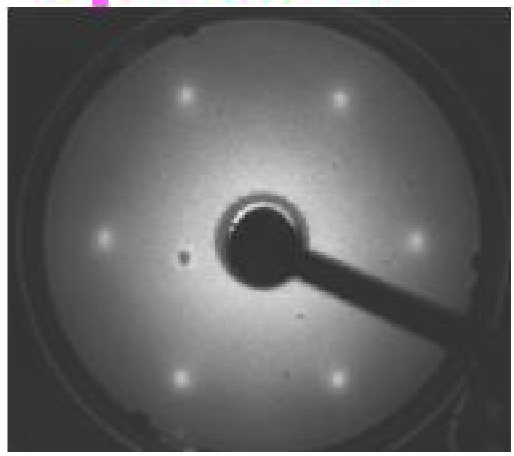




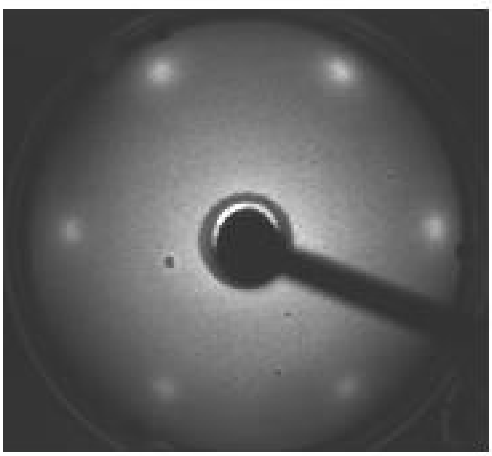
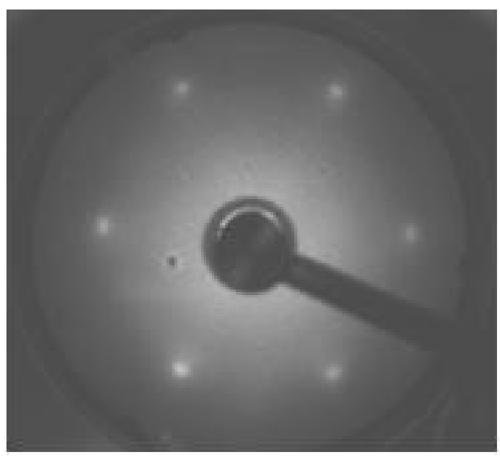
Cu flat nanostructures
average size ≈ 30-40 nm

LEED images for Fe/Cu/Si(111)

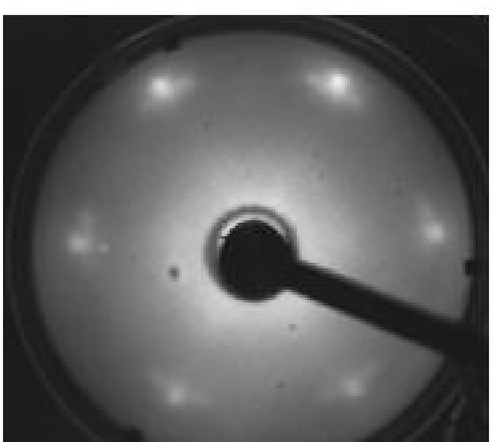
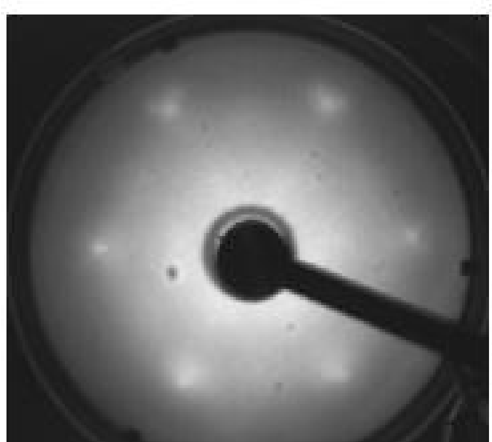
Ep = 70 eV | **Ep = 90 eV**

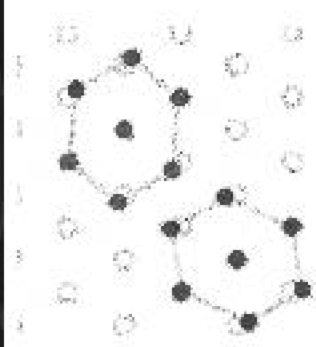
Fe 1ML

Fe 2ML

Fe 3ML

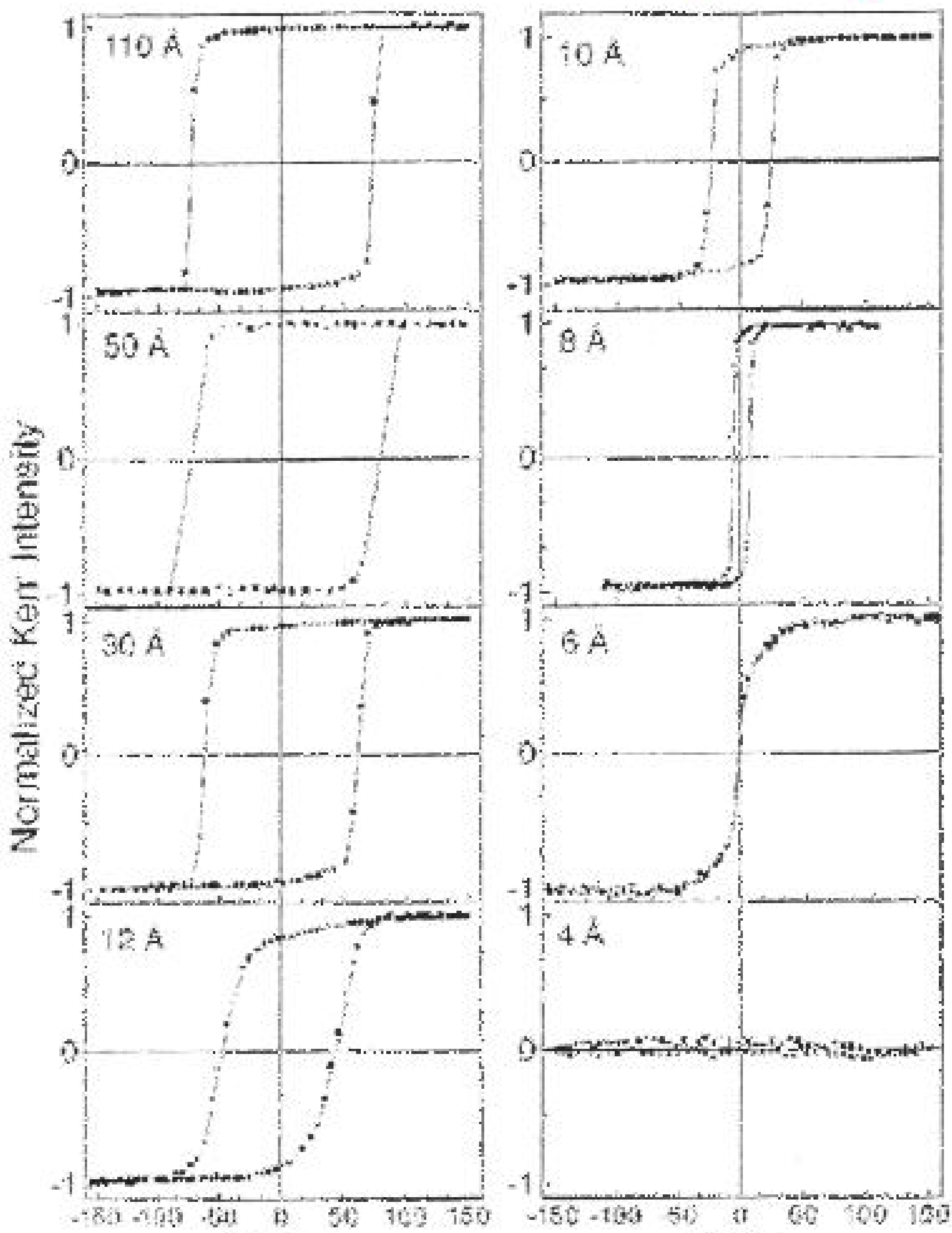


LEED analysis for Fe/Cu/Si(111)

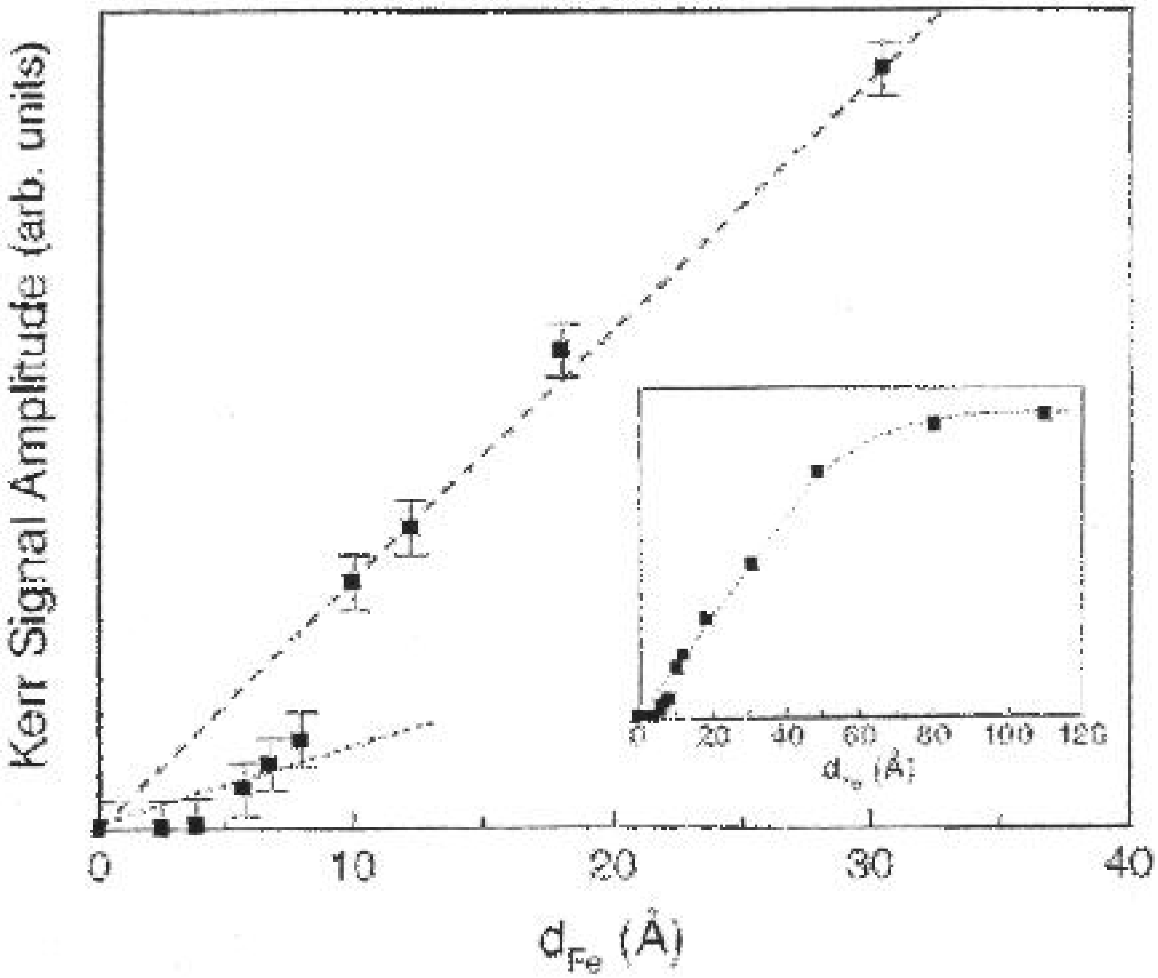
For Fe coverages higher than 3 ML the LEED patterns do not change with the exception of

- the disappearence of the p(1x1) spots since the electrons can no more reach the fcc(111) hexagonal net
- a broadening (for thicker and thicker films) of the satellite spots since the growth of rotationally related bcc Fe(110) domains introduces structural disorder in the film

RT Longitudinal SMOKE on Cu/Fe/Cu/Si(111)



No RT Polar SMOKE loops have been measured



- Two ranges of Fe thickness (lower and higher than 10 Å) can be identified
- The linear behaviour of the saturation magnetization above 10 Å (≈5 ML), i.e. slightly above the fcc→bcc structural transition detected by LEED, can be interpreted as a constant value of the magnetic moment per atom in that Fe thickness range.

Resonant magnetic scattering of polarized x-rays

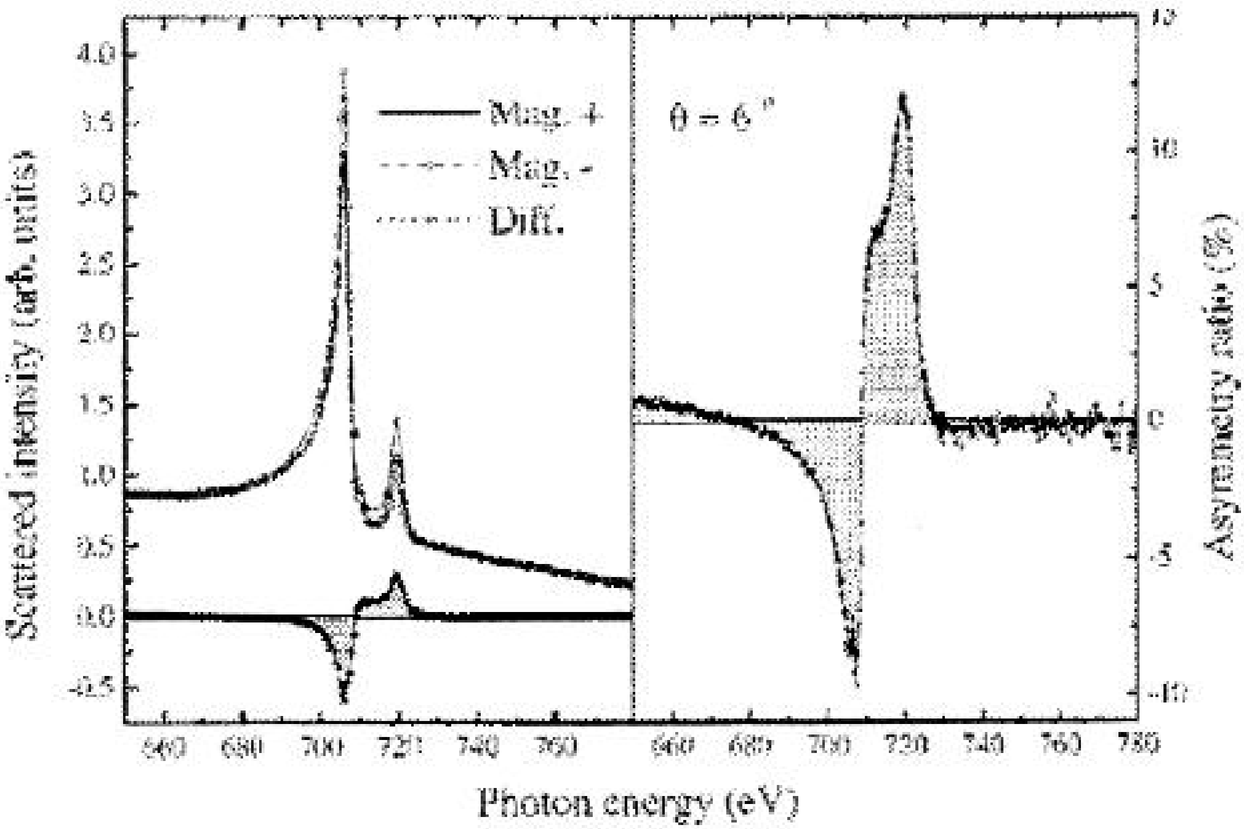
- Reflectivity curves at the Fe *2p* edge vs both photon energy and angle for the two orientation of the magnetic field are recorded

- Data are analysed by using the computer code ONDA which describes the scattering process from stratified media using the dynamical theory, directly solving the Maxwell's equations for a dielectric tensor constructed from the experimental absorption curves.

  The dielectric tensor contains explicit information on electronic and magnetic properties of the system

A large set of experimental data can be analysed to obtain information on the local magnetic moment per atom.

Resonant magnetic scattering at the 2p edge for Cu/Fe_x/Cu/Si(111)

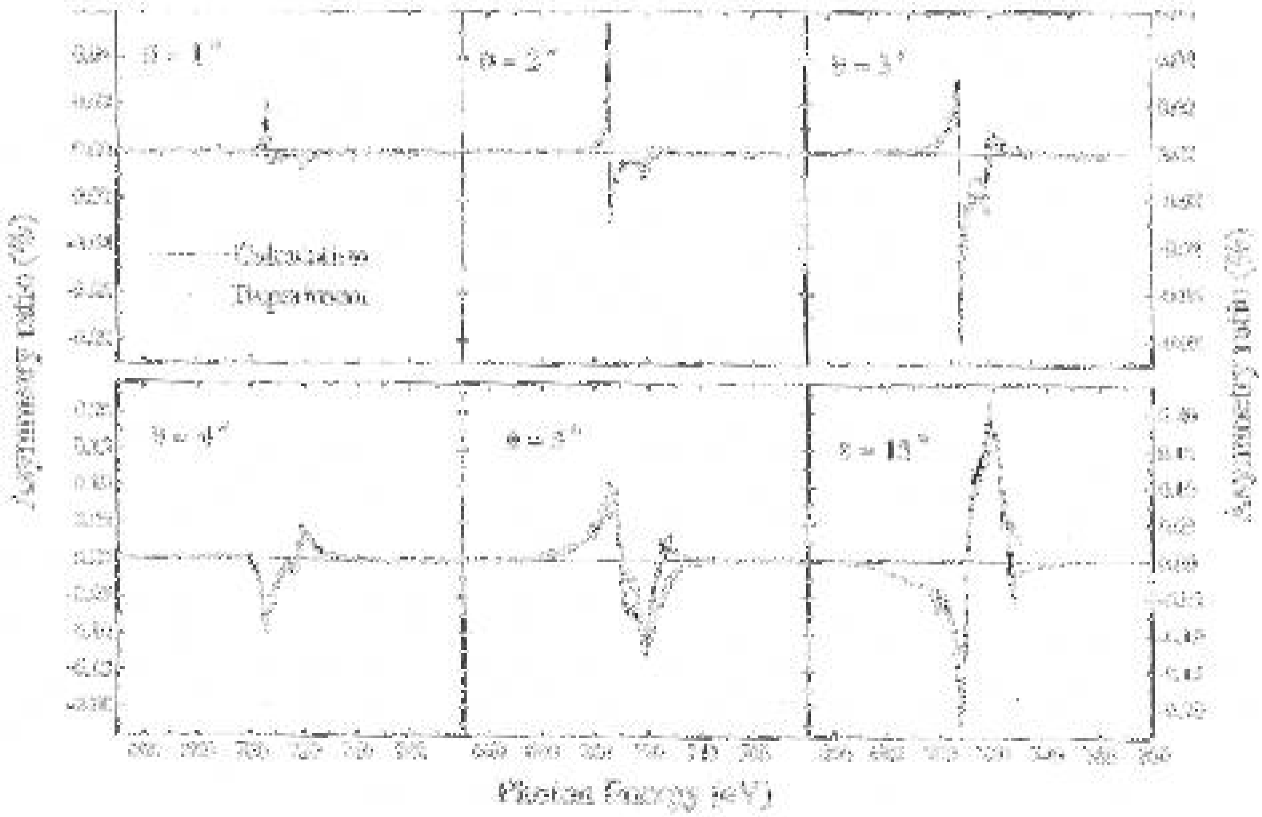


x = 20 Å

Asymmetry ratio **:** difference between the two curves for opposite magnetization divided by their sum

RT , in–plane H field

Comparison between experimental and calculated curves vs photon energy and for several scattering angles



- the non resonant optical constants of Cu and Si are taken from tabulated curves
- for Fe a previous experimental determination has been used

$m = 2.2\ \mu_B$ /atom

In summary:

- Cu epitaxial buffer layer can be grown on Si(111)7x7 reconstructed substrate

- Epitaxial Fe films can be successfully deposited on Cu/Si(111)

- For Fe thickness higher than 6 Å
  - fcc->bcc structural transition
  - in-plane magnetization

- For Fe thickness higher than 10 Å
  $m = 2.2\ \mu_B$ /atom

In the Cu/Si(001) case:

- **no** LEED patterns have been found
- X-ray Photoelectron Diffraction measurements suggested that Cu epitaxy does not occur on Si(001) even at the early stage of the interface formation *(J. Vac. Sci. Technol. B10 (1992) 2082)*.

The Fe/β-$FeSi_2$ /Si(001) growth :

- After the Si(001)2x1 reconstruction
- 20 Å of iron have been deposited at RT
- 500ºC annealing for 5′

↓

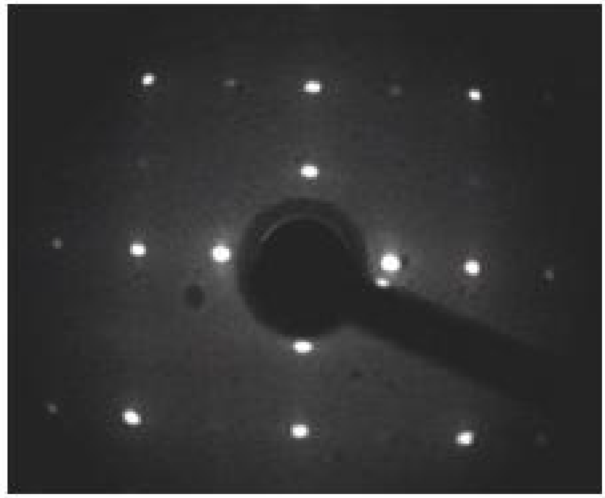
β-$FeSi_2$ /Si(001)

Then different Fe amounts have been deposited at RT

LEED analysis

$E_p = 65\ eV$

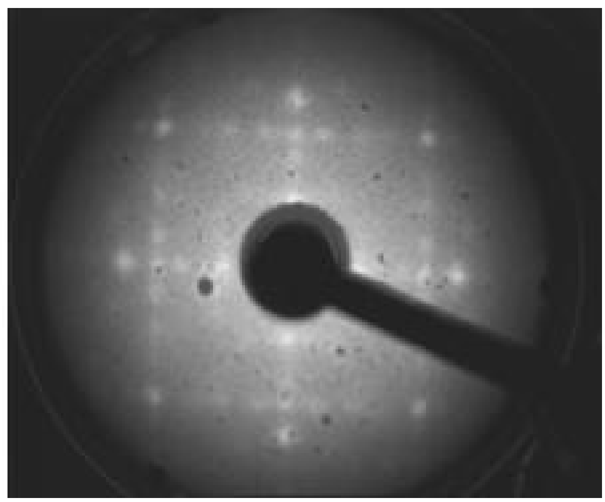
Si(001)-2x1
double domain reconstruction



A

β-$FeSi_2$/Si(001)
grown as two epitaxial domains on the silicon surface:

- β-$FeSi_2$[010] //Si[110]
- β-$FeSi_2$[010]//Si[100]



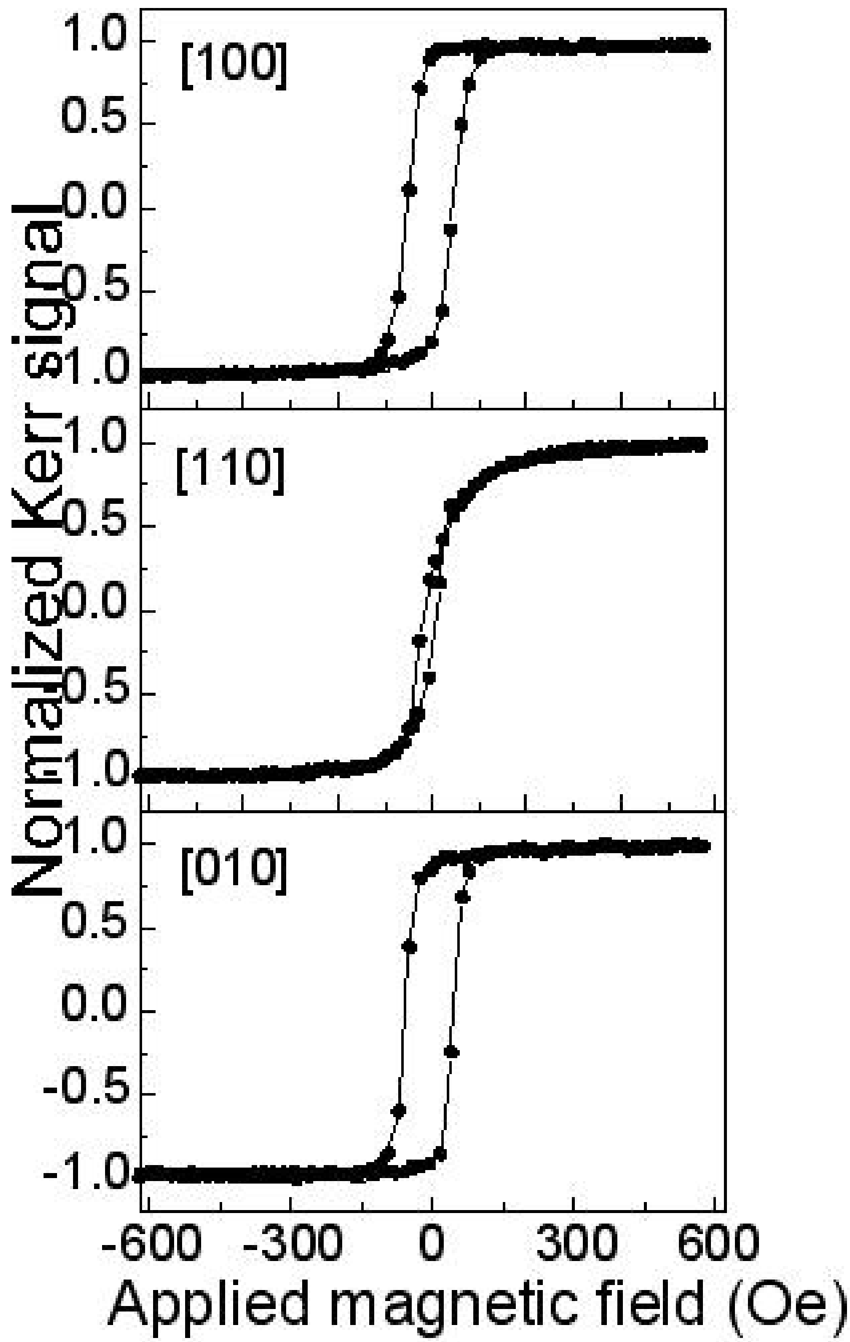
B

20 Å Fe/$FeSi_2$/Si(001)
the image points out the presence of three Fe domains rotated one each other.

C

A similar pattern is observed also for Fe thicker films, though with a more diffuse background

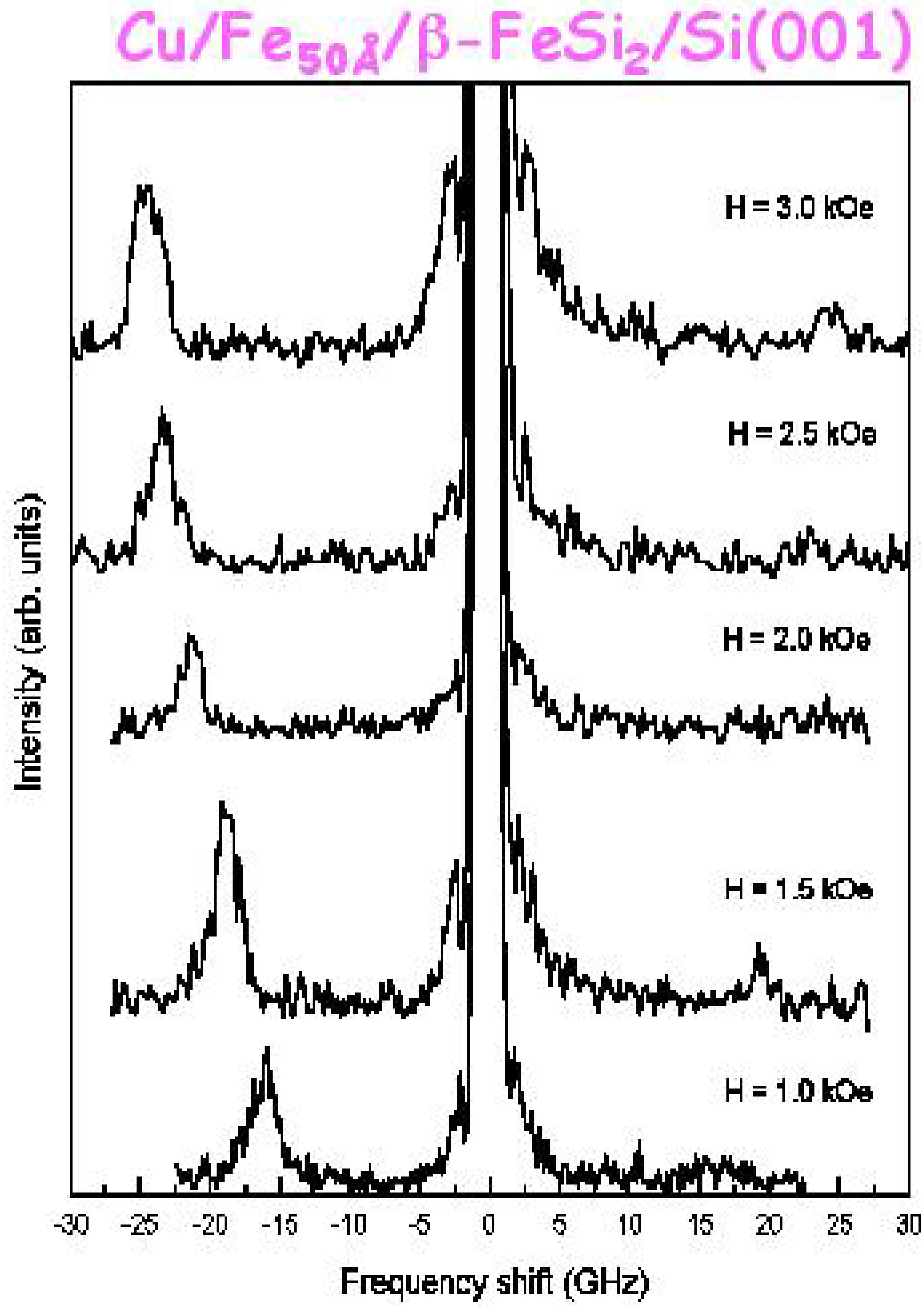
SMOKE 50 Å Cu/Fe/$FeSi_2$/Si(001)



In-plane magnetization :

- [100] and [010] easy magnetization axes
- [110] hard magnetization axis

BLS spectra vs in-plane H field intensity

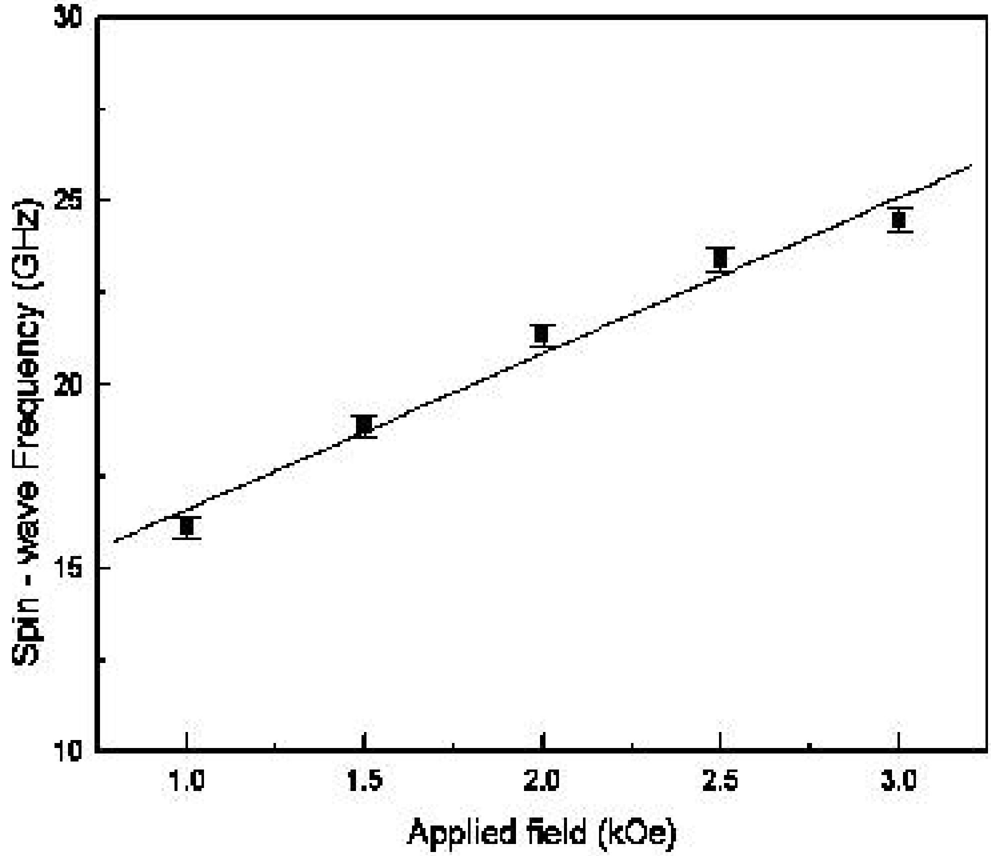


The increasing of the H field intensity raises the absolute value of surface magnon frequency in the anti-Stokes branch

in-plane magnetization vector

Magnon frequency vs H field intensity

Experimental data ■ ( ) result to be in a good accordance with a linear dependence (solid line) that intercepts the frequency axis.



- The linearity of the best-fitting curve
  ➡ *good epitaxial quality for the Fe film*

- The presence of an offset in the best fitting curve
  ➡ *in-plane magnetization*

In summary

- High quality epitaxial iron films can be grown on β-$FeSi_2$/Si(001) substrate

- Fe films are ferromagnetic at room temperature and present an in-plane magnetization with fourfold anisotropy induced by the Si(001) substrate

Conclusions

- Cu/Si(111) and β-$FeSi_2$/Si(001) have been successfully used to obtain good quality epitaxial magnetic Fe films on silicon substrate
- Thin Fe films are ferromagnetic at room temperature and present an in-plane magnetization