Interfacial Electronics:

observing the buried physics of magnetic and superconducting nanostructures

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Science & Technology Facilities Council
ISIS

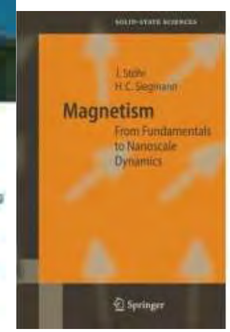
OSNS 12
September 2011

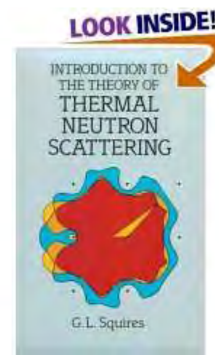
References

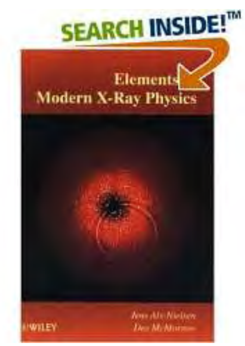
- Polarized Neutrons, W.G. Williams, Oxford (1988)
- Theory of Magnetic neutron and photon scattering, E. Balcar & S.W. Lovesey, Oxford (1988)
- Introduction to Thermal Neutron Scattering, G.L. Squires, Cambridge (1978)
- Elements of Modern X-Ray Physics, Als-Nielsen and McMorrow, Wiley & Sons (2001)
- Magnetism: from fundamentals to nanoscale dynamics, Stohr and Siegmann, Spinger (2006)
- www.ill.eu
- www.isis.stfc.ac.uk
- www.esrf.eu
- www.diamond.ac.uk

Spintronics and functional materials

The understanding of electronic behaviour in systems with reduced dimensionality and length scale is a central theme of contemporary condensed matter physics. The unique capabilities of neutron scattering make it an ideal method to study the atomic and molecular, chemical and magnetic structure of a wide class of materials. In this review we highlight recent studies where neutron techniques have been applied to emergent materials and look forward to the possibilities enabled by instrumentation on the ISIS Second Target Station.



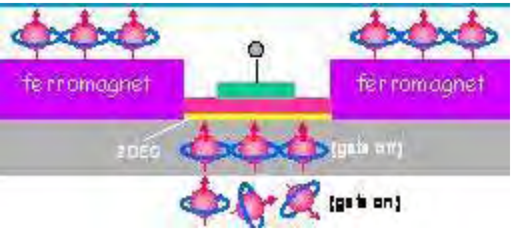


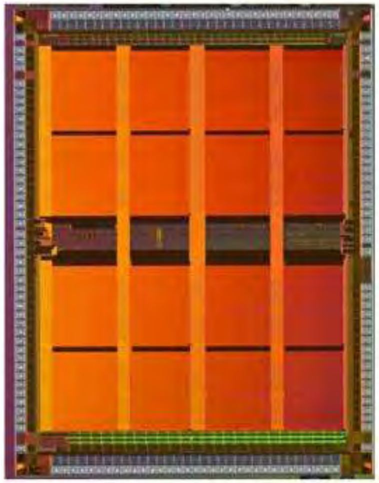


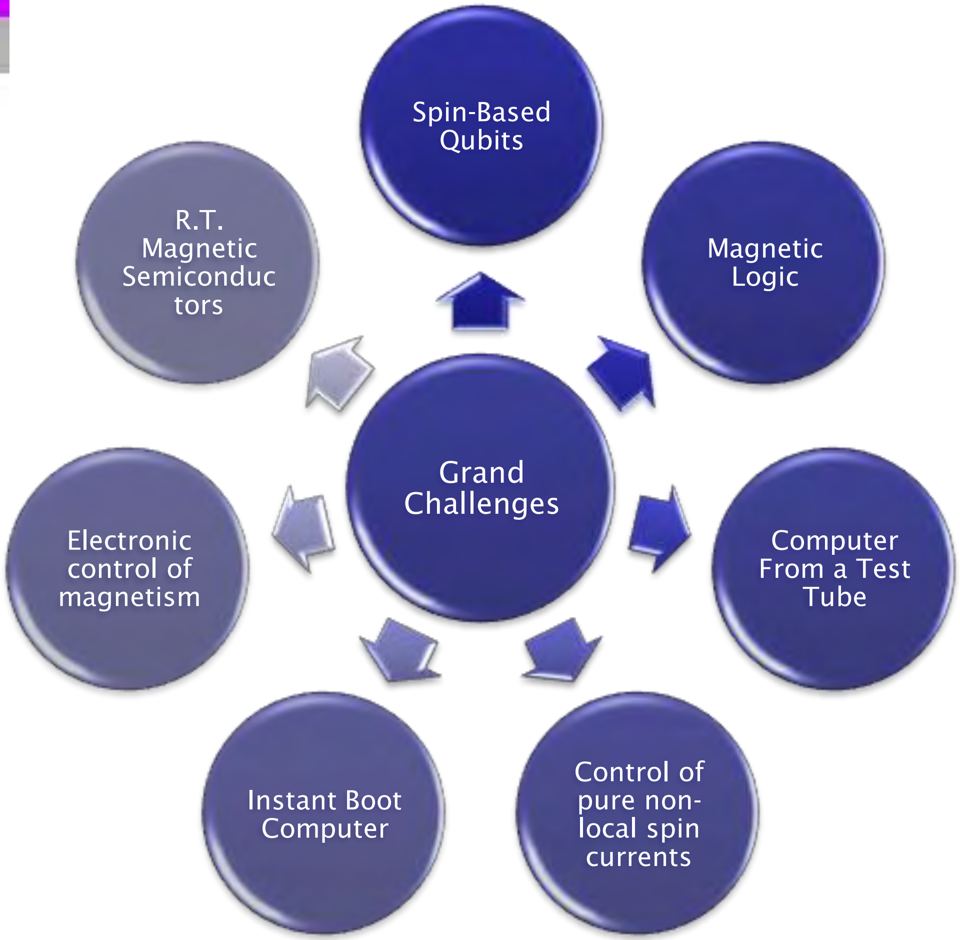
Outline

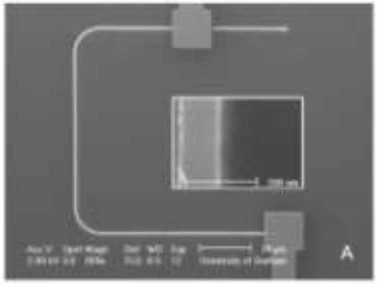
- Motivation
  - The importance of interfaces
  - Spatially resolving interfacial electronics
- Interfacial effects
  - A Magnetostructural Phase transition
  - Nanoscale Superconductivity
- Outlook
  - Bright!

Grand Challenges: Nanomagnetism





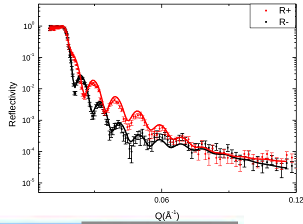




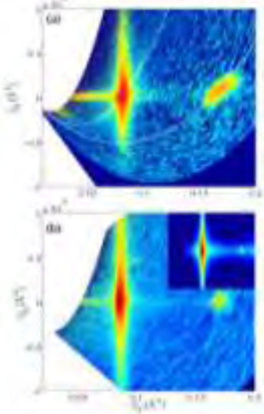
Adapted from S.D. Bader *Rev Mod Phys* **78** (2006)

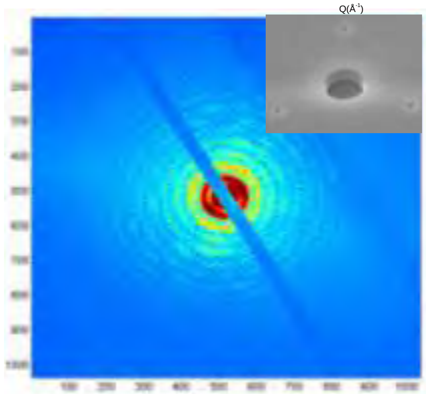
Nanoscale Electronic Phenomena Research

Heusler, DMS

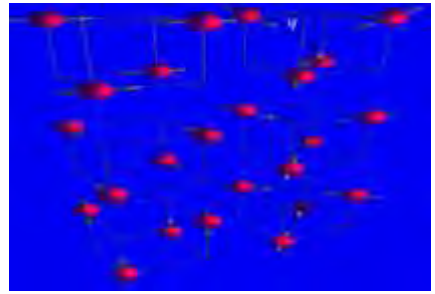


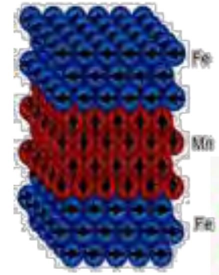
Domain Structures





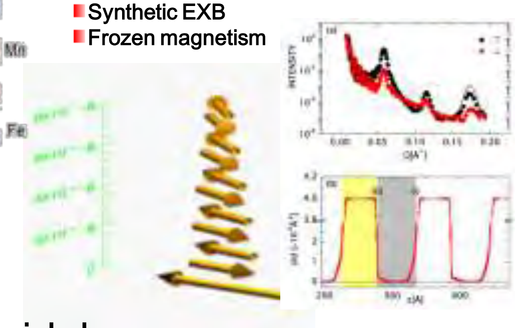
Surface Magnetism





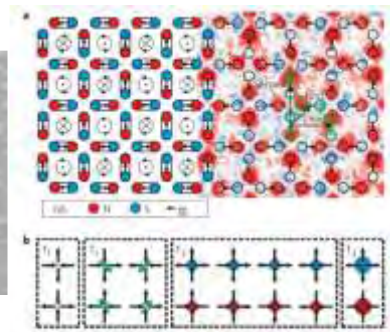
Exchange Bias

- Conventional EXB
- Synthetic EXB
- Frozen magnetism

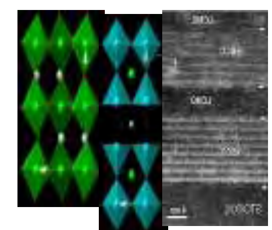


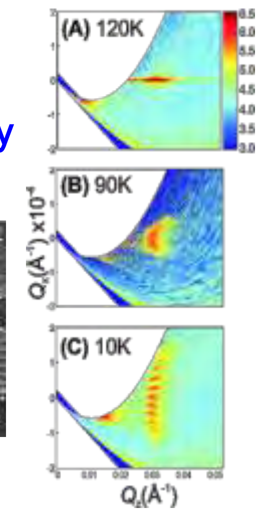
- To understand and control spin and interfacial phenomena
- Probe length scale (<1nm to >1000nm)
- Vector Magnetometry ~<0.1μ_B per f.u.

Frustration

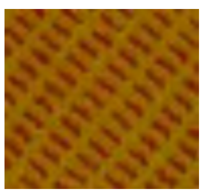


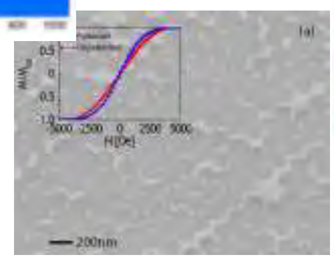
Superconductivity

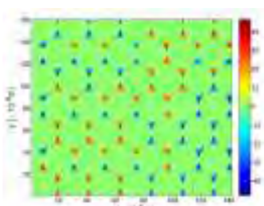


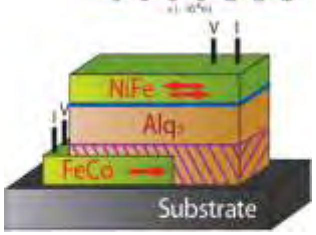


Organic Spintronics

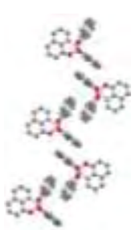


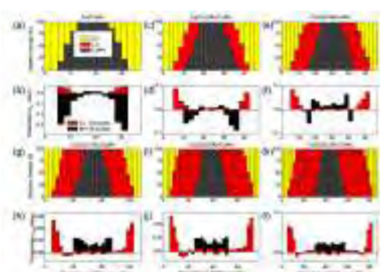


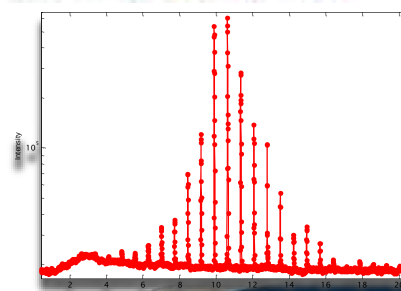


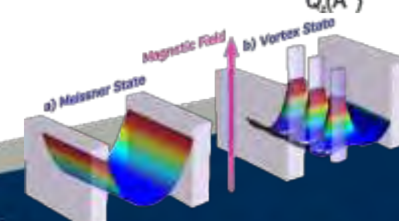


Interfacial Magnetism

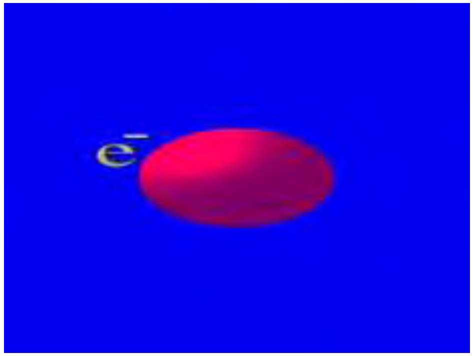


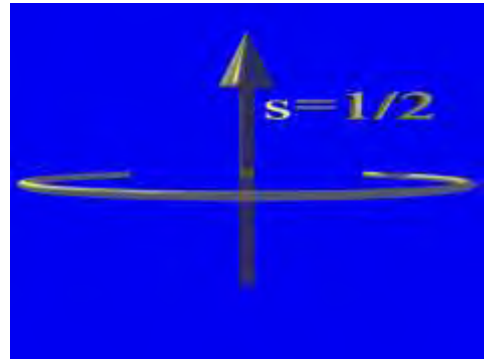


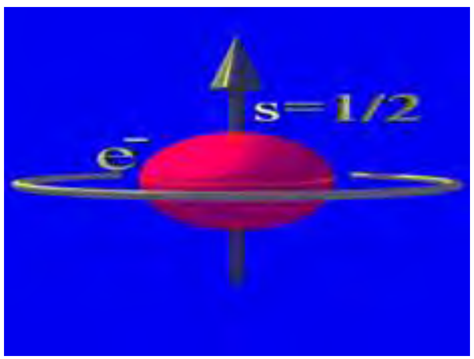




Spintronics…







- Fundamental understanding of electrons in reduced dimensions and lengthscale
- Cutting edge nanofabrication
- New physics
- Optimised functionality

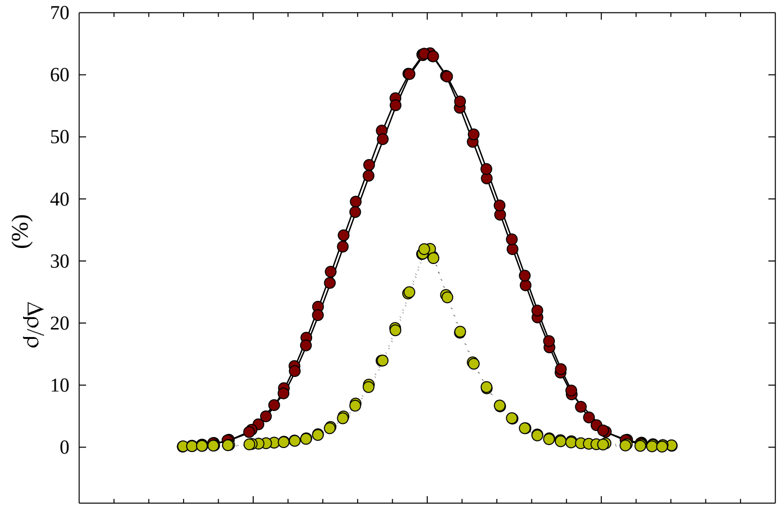
Spintronics*: Fundamentals and Applications*. I. Žutić, J. Fabian, and S. Das Sarma, Rev. Mod. Phys. 76, 323-410 (2004)

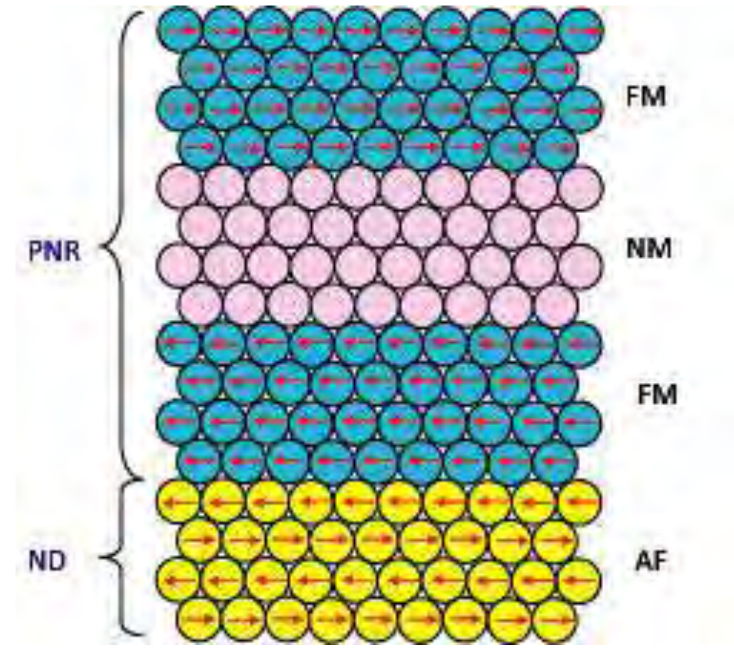
Spintronics: a spin based electronics vision for the future
S. A. Wolf, et al. Science 294, 1488 (2001);

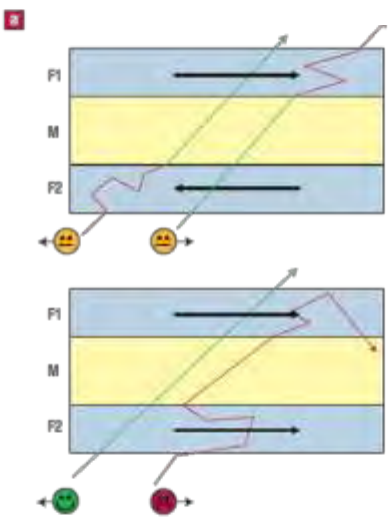
Quantum Well State

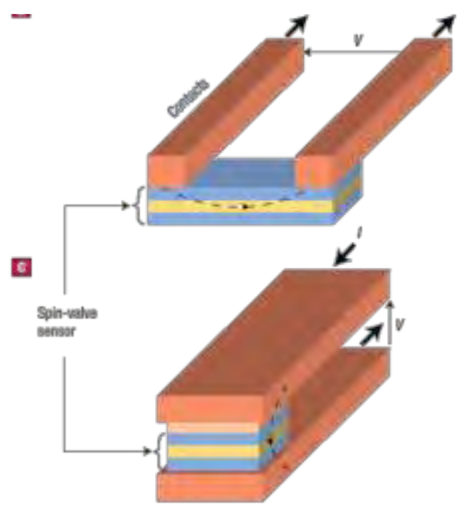
Co/Cu GMR

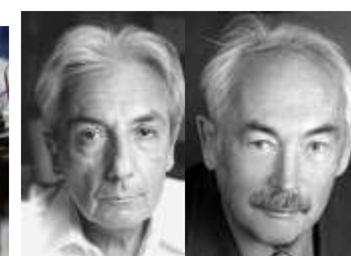
- Band matching important *e.g.* Fe/Cr









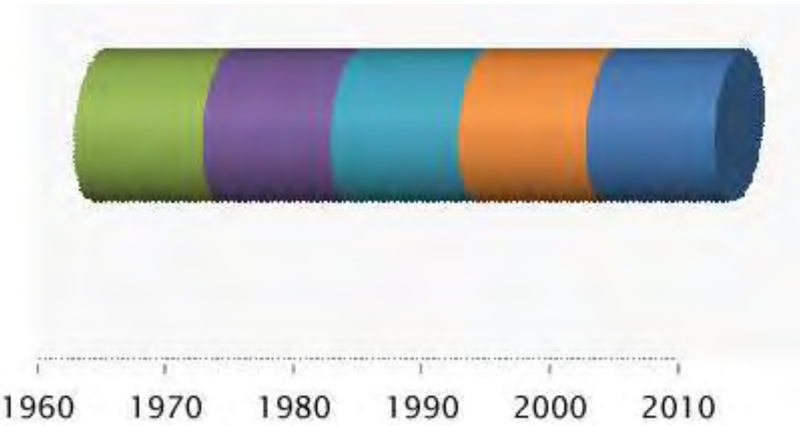


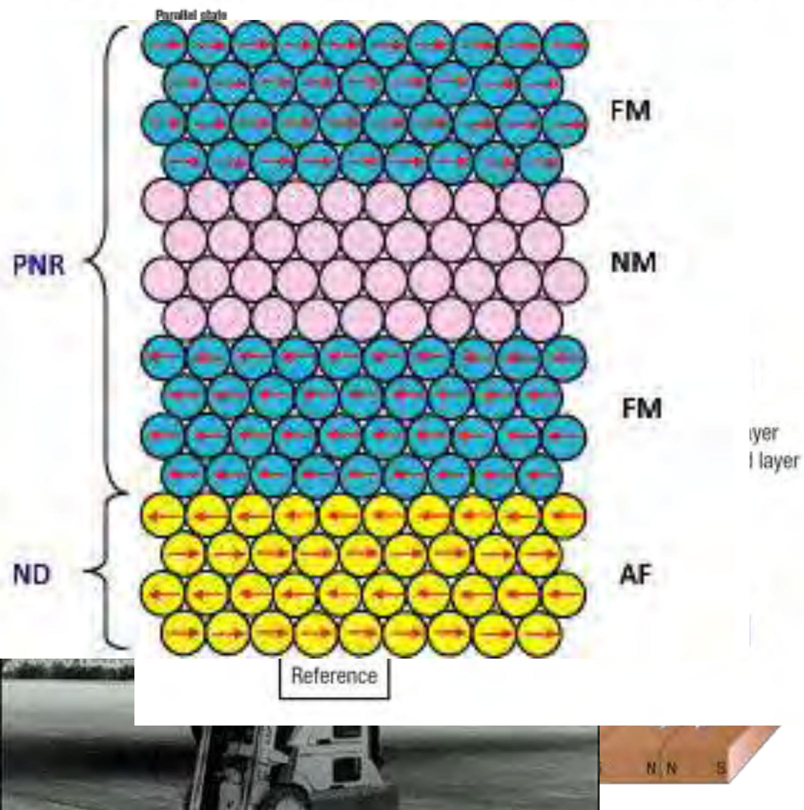
Chappert, Fert, Nguyen van Dau Nat. Matl. **6**, 813 (2007)

Spintronics is new?

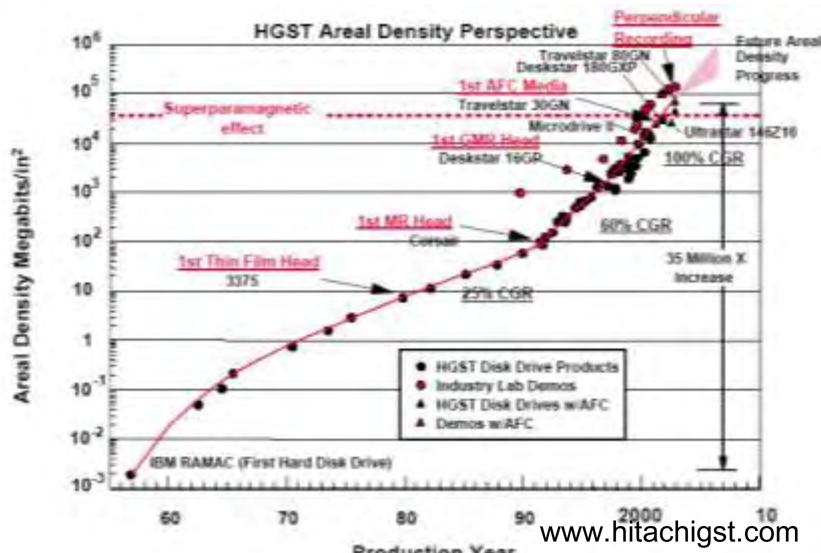
- *" … I have already communicated to the Royal Society a description of experiments by which I found that iron, when subjected to magnetic force, acquires an increase of resistance to the conduction of electricity across, the lines of magnetization…"*
- William Thomson, *"Effects of magnetization on the electrical conductivity of nickel and of iron"* Proceedings of the Royal Society of London, Vol. 8, ***1857***, pp. 546550

A history of storage/spintronics





- 1988
  - Discovery of GMR
- 1991
  - Spin Valve (IBM)
- 1994
  - MTJ
- 1997
  - SV in a HDD
- 2004
  - Epitaxial MTJ
- 2005
  - MTJ Read Heads
- 2006
  - 4Mb MRAM



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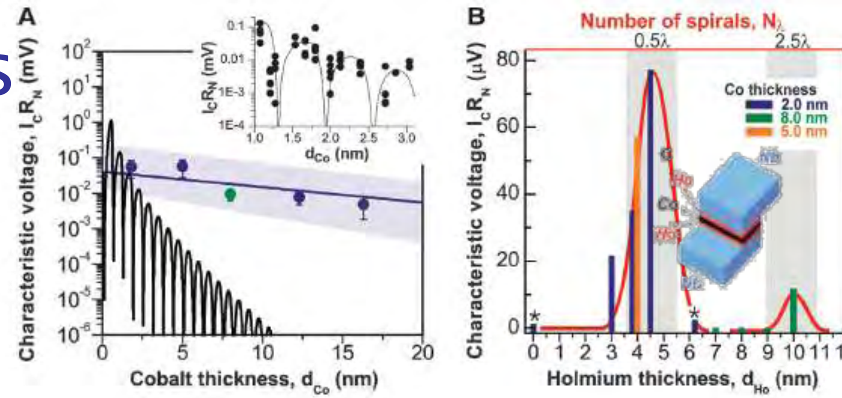
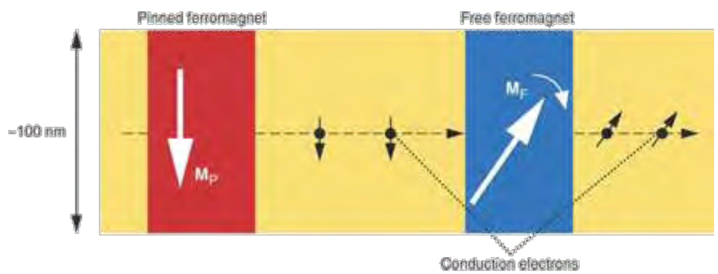
Chappert, Fert, Nguyen van Dau Nat. Matl. **6**, 813 (2007)

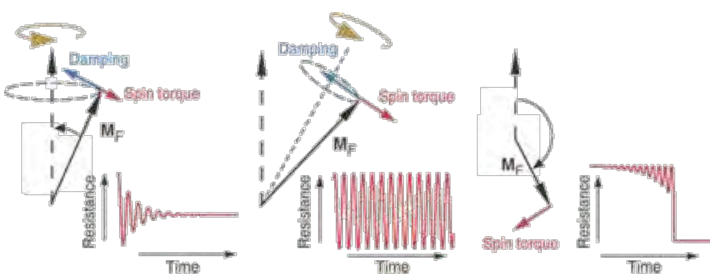
The Importance of interfaces

- Spin Transfer Torque

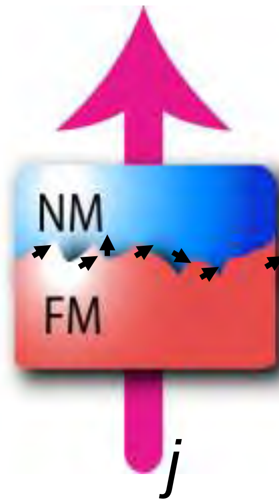


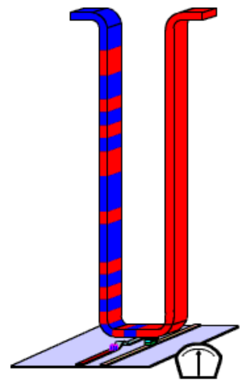
inson *et al.* Science **329** 59 (2010)



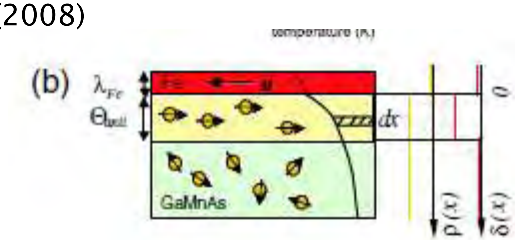


- I. N. Krivorotov et al., Science **307**, 228 (2005).

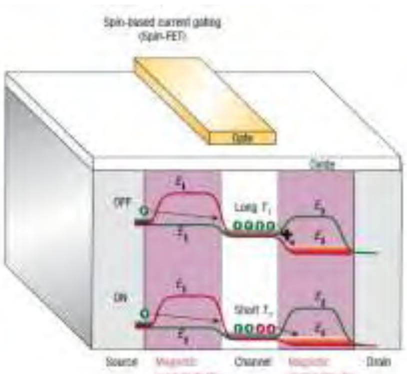


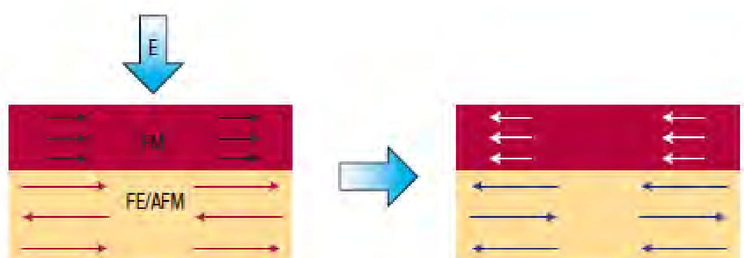


- S.S.P.Parkin et al. Science **520** 5873 (2008)



- Maccherozzi et al. Phys. Rev. Lett. **101**, 267201 (2008)

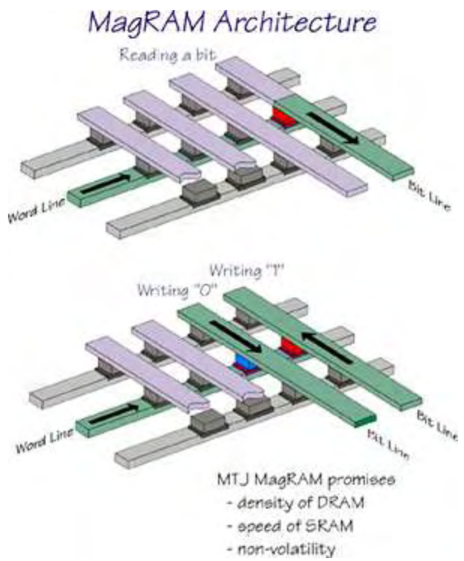


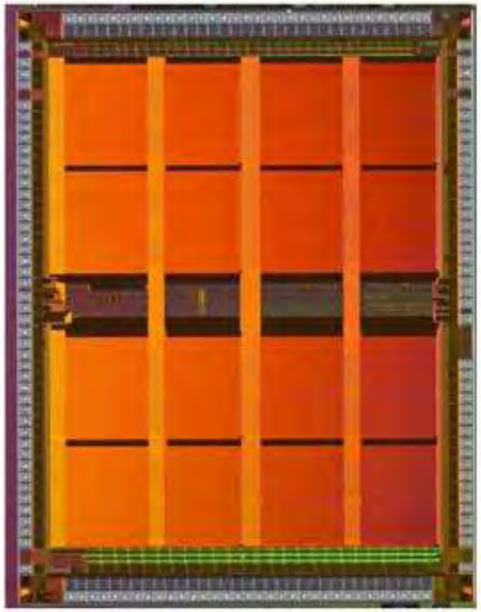


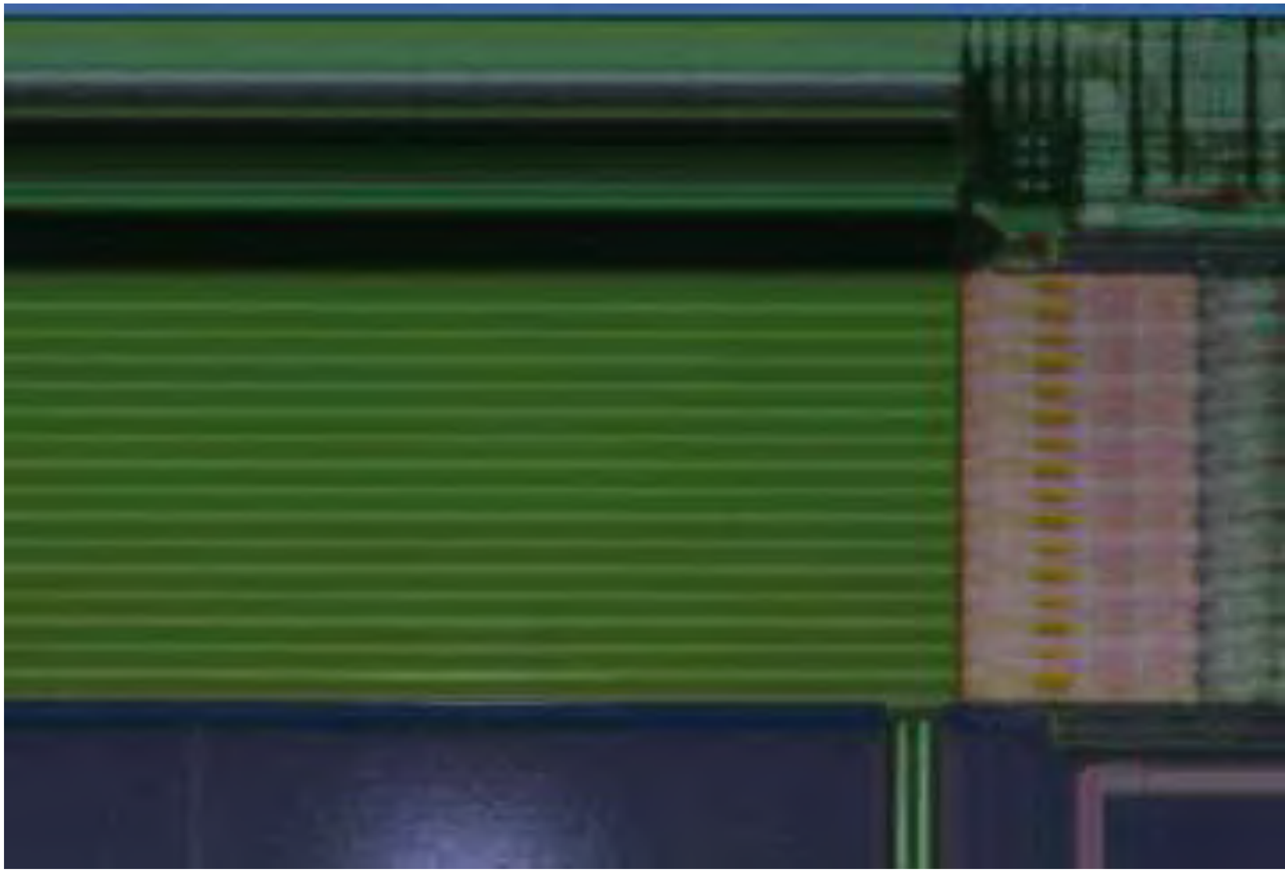
- Ramesh and Spaldin Nat. Mat. **6**, 21 (2007)

- Awschalom and Flatté Nat. Phys. **3** 153 (2007)

MRAM


MagRAM Architecture
Reading a bit
Word Line
Bit Line
Writing "1"
Writing "0"
Word Line
Bit Line
Bit Line
MTJ MagRAM promises
- density of DRAM
- speed of SRAM
- non-volatility





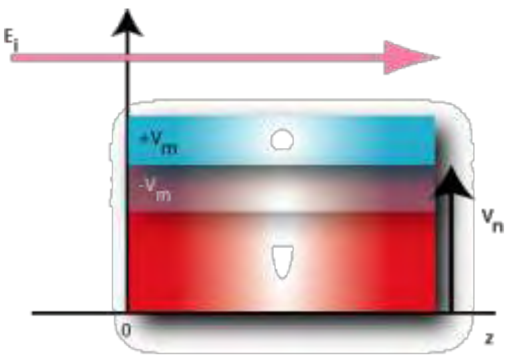
Interference effects

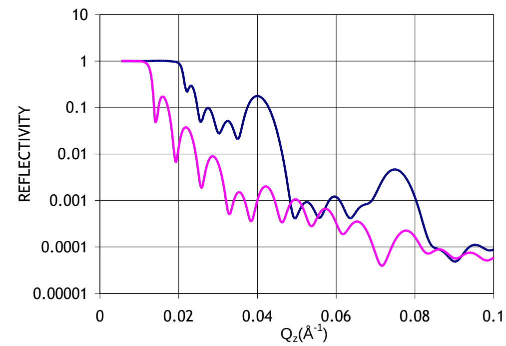
- Fresnel reflection 1815

Spin polarised Neutron Reflectivity

- Measure the reflected neutrons as a function of their perpendicular momentum and spin eigenstate

- $k^{\pm} = \sqrt{k - 4\pi N\left(b \pm cB\right)}$

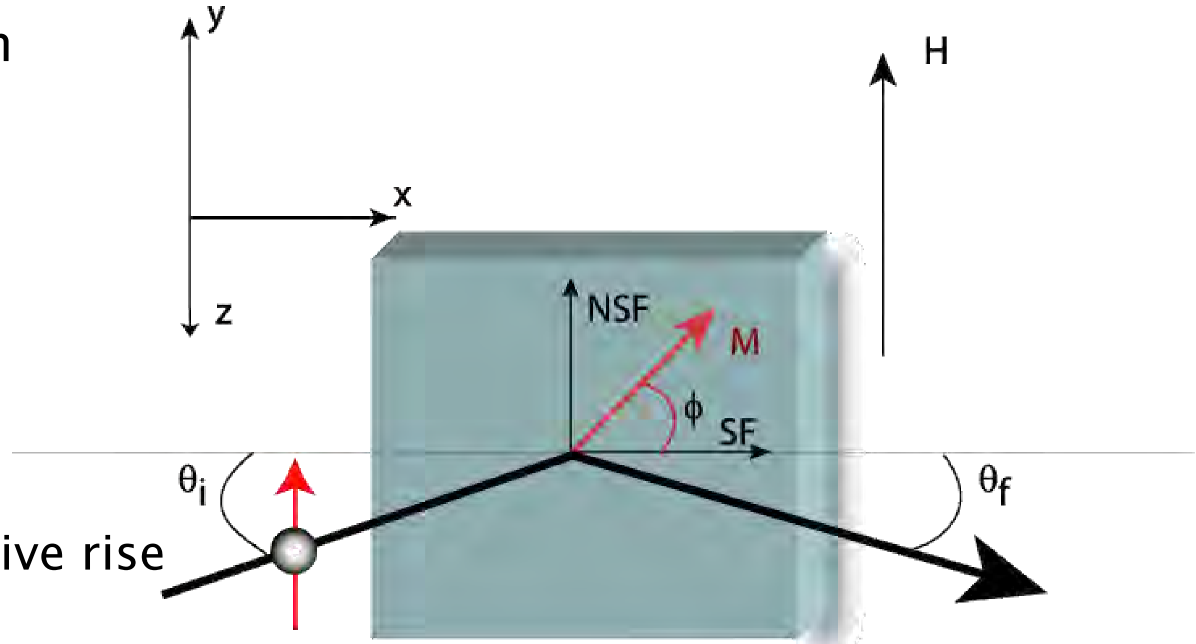




- Can observe the magnitude and orientation of atomic magnetic moments in thin films and multilayer media.
- Probe length scale (<1nm to >1000nm): covers many aspects of thin film structure and magnetism
- Complementary to:
  - VSM/SQUID
  - MOKE average magnetisation over the sample thickness
  - SEMPA, Lorentz surface domain magnetisation
  - XMCD/XRMS-element specific
- PNR gives the microscopic *in-plane vector* magnetisation *depth* profile.

Spin dependent cross-section

- In-plane orientation of magnetisation obtainable from 4 spin dependent cross-sections



- Components of the magnetisation, m give rise to
- m||H: Non Spin Flip Scattering (NSF)
- m ⊥H: Spin Flip Scattering (SF)
- Dynamical analysis gives absolute depth dependence profile

$$b = b + p \sin \phi$$

$$p_m \cos \phi = p_x$$

$$\left[\frac{-\hbar^2}{2m_n}\nabla^2 + V(r)\right]\Psi^{\uparrow,\downarrow} = E\Psi^{\uparrow,\downarrow}$$

Small Angle Scattering

- Grazing Incidence to give depth selectivity
- Difference gives the interference term

$$
\begin{aligned}
I^{+}(Q,\alpha) &= <|F^{++}|^2> + <|F^{+-}|^2> \\
&= F_N^2 + (F_M^2 - 2PF_NF_M)\sin^2\alpha
\end{aligned}
$$

$$
\begin{aligned}
I^{-}(Q,\alpha) &= <|F^{--}|^2> + <|F^{-+}|^2> \\
&= F_N^2 + (F_M^2 + 2P\epsilon F_NF_M)\sin^2\alpha
\end{aligned}
$$

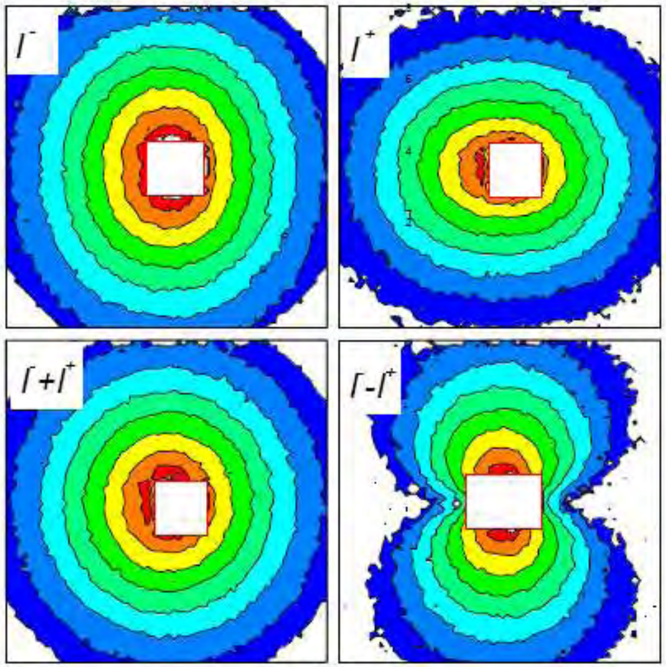


Figure 1
SANSPOL patterns in Fe_3O_4 for neutron spins antiparallel (I^-) and parallel (I^+) to the horizontal field. The arithmetic mean $[(I^-) + (I^+)]/2$ corresponds to the 2D pattern of non-polarised neutrons. The difference (I^-)-(I^+) yields the interference term [equation (1c)].

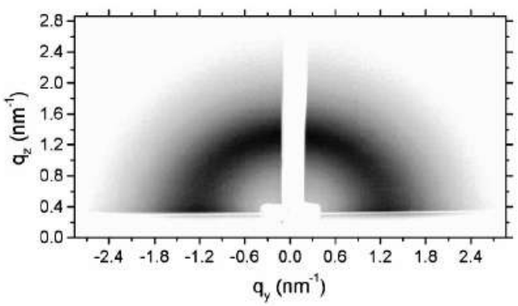


Figure 10

2D-GISAXS pattern of an *a*-C:H/Au 8.2 at.% film using an imaging plate. The interference maximum (represented by a quasi-isotropic half ring) is related to the spatial correlation between isolated gold clusters embedded in the *a*-C:H matrix. The z-direction is perpendicular to the film surface (from Babonneau *et al.*, 2001).

- A. Wiedenmann J. Appl. Cryst. (2000). 33, 428-432

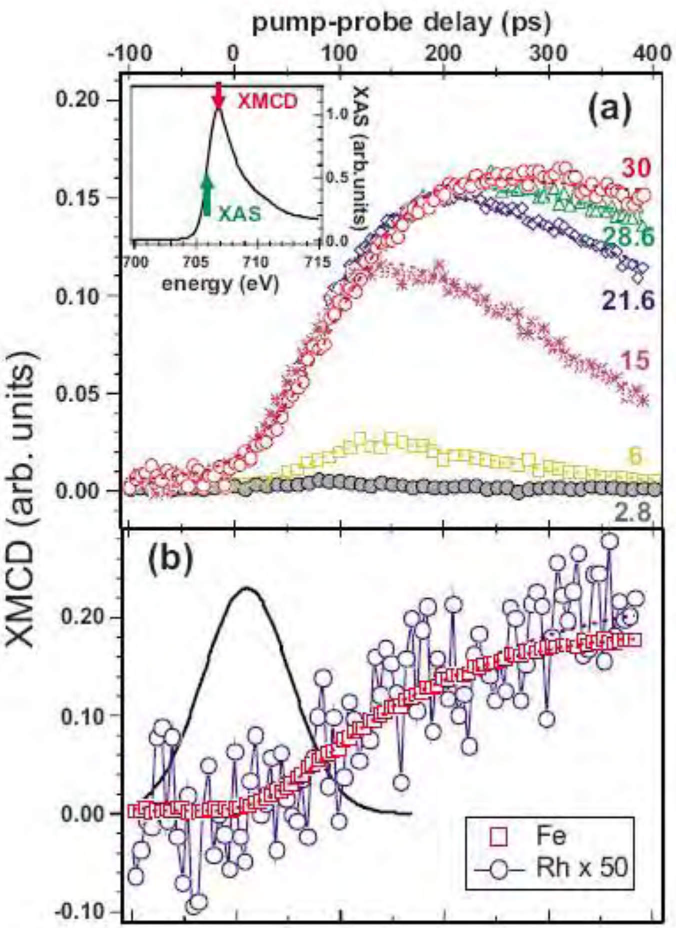
A Magnetostructural Phase Transition

FeRh epilayers

PRB **82**, 184418 (2010)

Motivation

- Tuneable Magnetostructural phase transition



pl.

K25

n-

cally

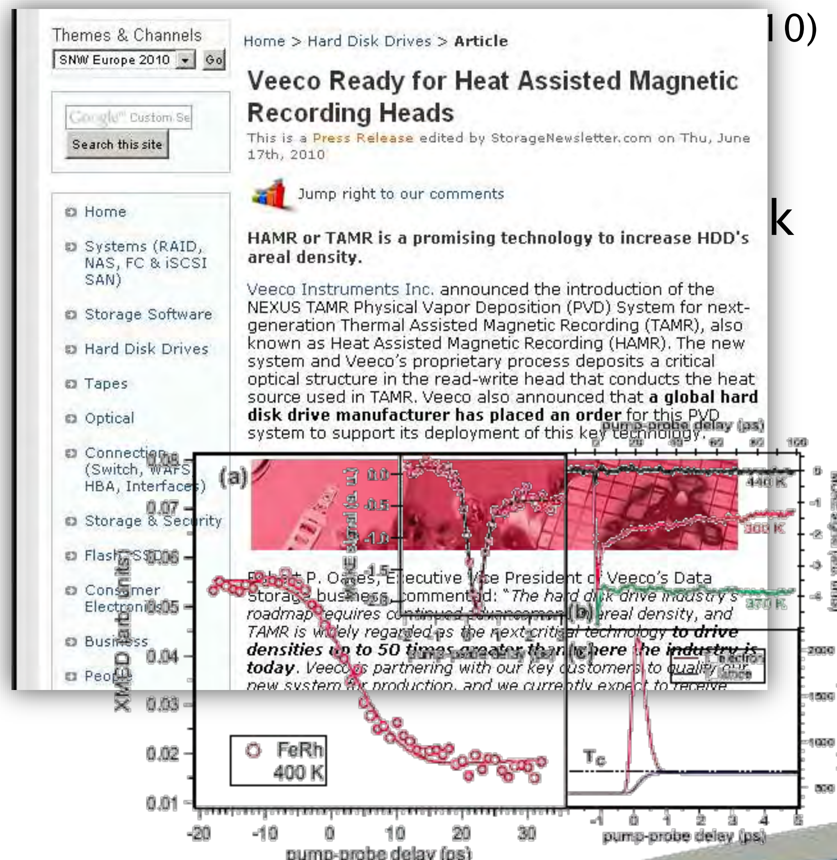
l phase

- FePt/FeRh system
  - Thiele *et al.* Appl. Phys. Lett. **82** 2859 (2003)
- Control MTJ cell coercivity:
- 50Tb in^2

- Magnetic refrigeration
  - $\Delta S \sim 15\ J\ Kg^{-1}\ K^{-1}$
- Ultra-fast switching
  - Ju *et al.* Phys. Rev. Lett. **93**, 197403 (2004)

10)

k


Themes & Channels

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Veeco Ready for Heat Assisted Magnetic Recording Heads

This is a Press Release edited by StorageNewsletter.com on Thu, June 17th, 2010

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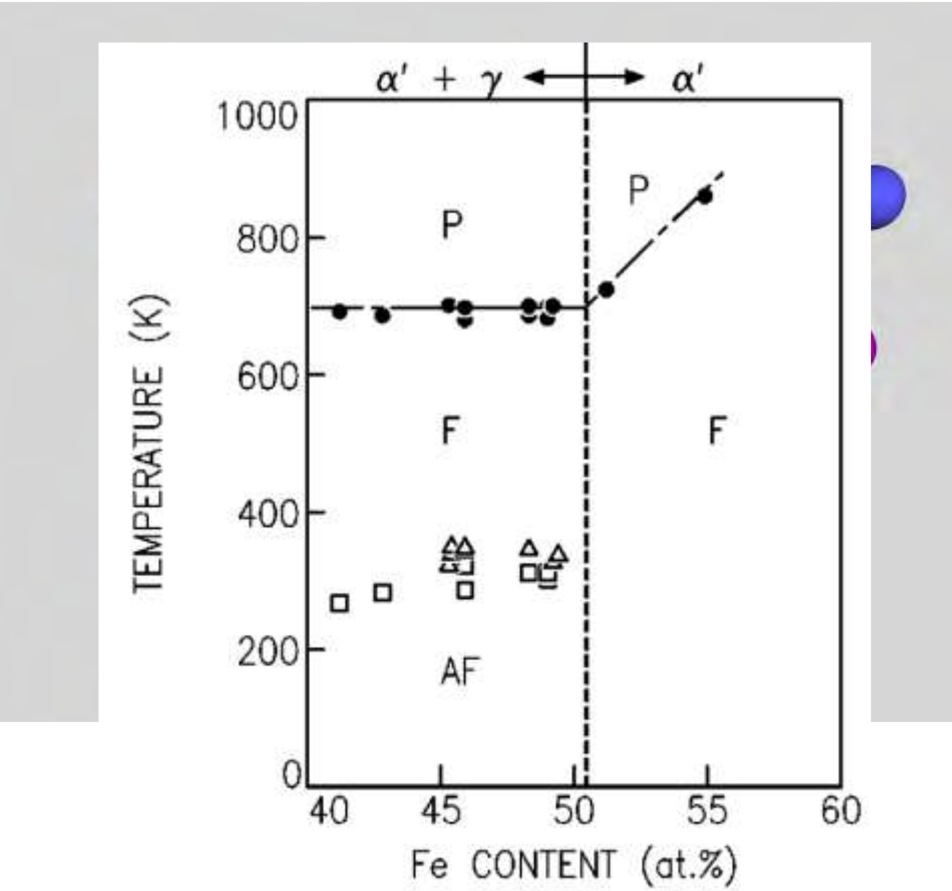
- Flash SSD
- Consumer Electronics
- Business
- People

HAMR or TAMR is a promising technology to increase HDD's areal density.

Veeco Instruments Inc. announced the introduction of the NEXUS TAMR Physical Vapor Deposition (PVD) System for next-generation Thermal Assisted Magnetic Recording (TAMR), also known as Heat Assisted Magnetic Recording (HAMR). The new system and Veeco's proprietary process deposits a critical optical structure in the read-write head that conducts the heat source used in TAMR. Veeco also announced that **a global hard disk drive manufacturer has placed an order** for this PVD system to support its deployment of this key technology.

Robert P. Oates, Executive Vice President of Veeco's Data Storage business, commented: "*The hard disk drive industry's roadmap requires continued advancement in areal density, and TAMR is widely regarded as the next critical technology* ***to drive densities up to 50 times greater than where the industry is today****. Veeco is partnering with our key customers to qualify our new system for production, and we currently expect to receive*

FeRh: Bulk Properties



- CsCl structure
  - a~2.99Å
  - α' phase
- Isostructural
- 300K: Type G AF
- Fe: ~3.3 μ_B
- Rh: no moment
- FM alignment within <111> planes
- AF alignment between <111> planes
- 350 K: AF → FM
- Fe: ~3.1 μ_B
- Rh: ~1 μ_B

- Van Driel et al., J. Appl. Phys. **85**, 1026 (1999)
- Shirane *et al*. Phys. Rev. **134**, A1547 (1964)

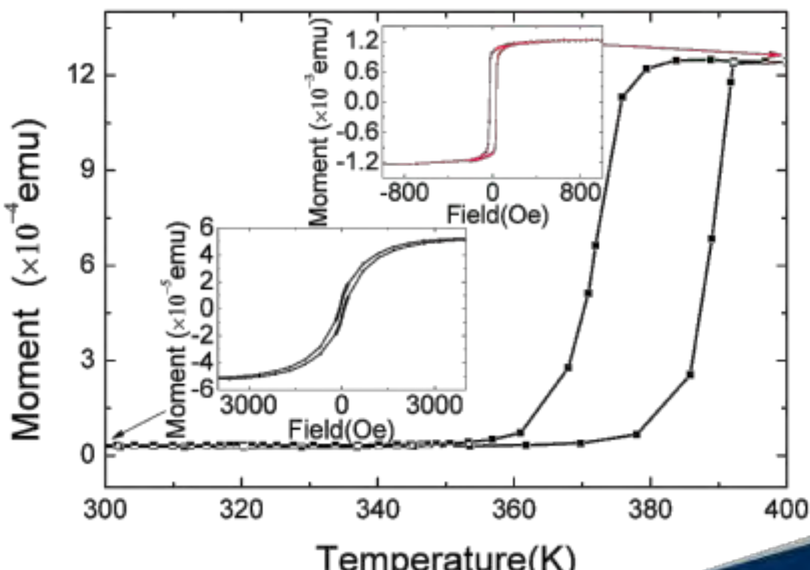
Sample Growth

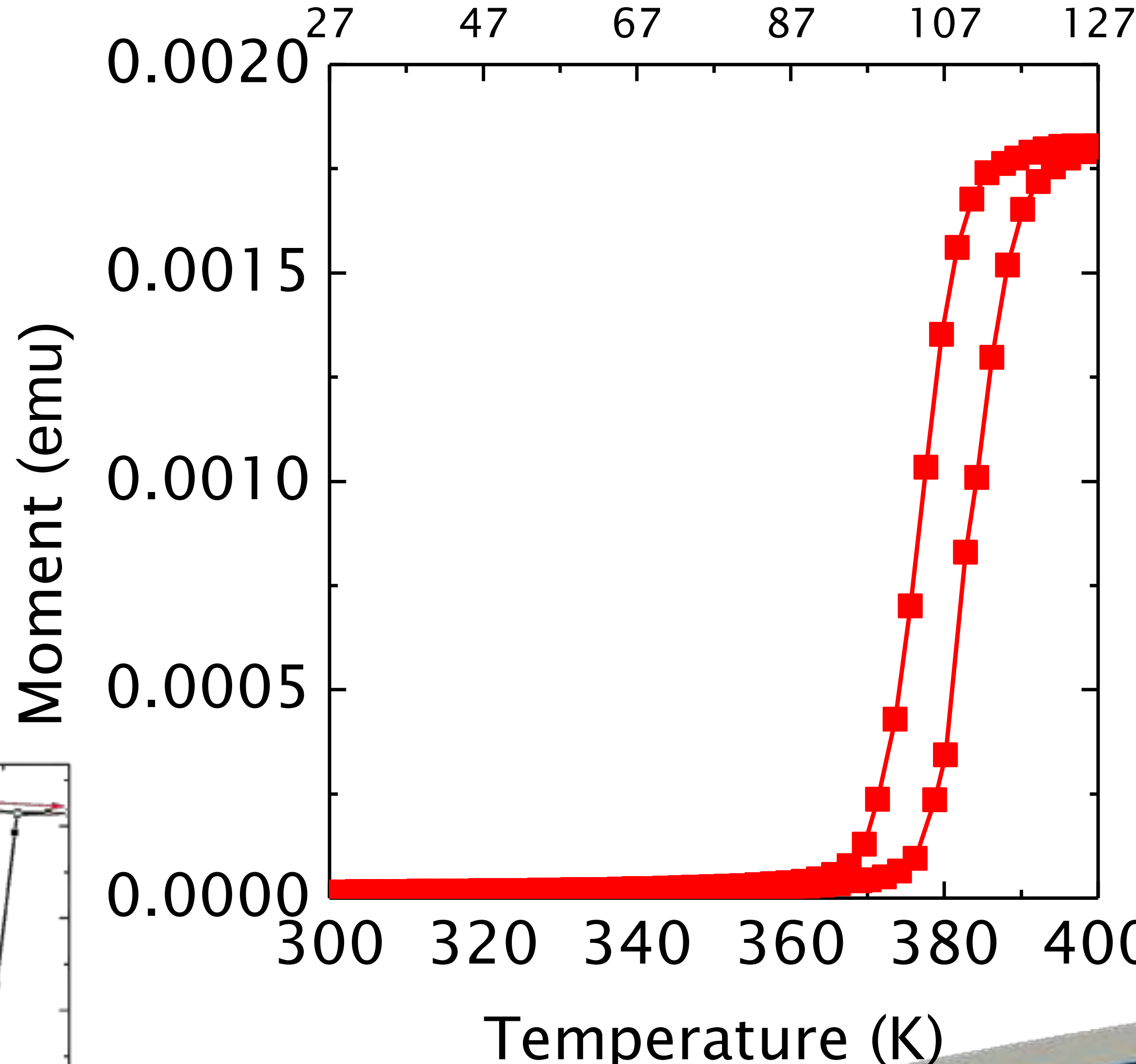
- Base pressure: ~5×10^{-10} torr
- Combination of Knudsen cells and electron beam hearths
- Substrate: MgO(001)
- Composition: 48% Fe, 52% Rh
- Deposition at 300˚C; post-growth anneal at 800˚C for 60 min.
- Cap at 300˚C with either Au, Ta or MgO
- Nominal FeRh thickness: 22, 50, & 100nm

Magnetometry

- SQUID
  - T_{AF-F}~375K
  - 10K Hysteresis
  - H=510Oe
  - Field lowers transition temperature
  - T=400K

$$H = -\sum_i D_i S_i^2 - \sum_{\langle nn,nnn \rangle} J_{ik}(r_{ik}) S_i S_k + \sum_{\langle nn \rangle} V_{nn}(r_{ik}) + \sum_{\langle nnn \rangle} V_{nnn}(r_{ik}).$$

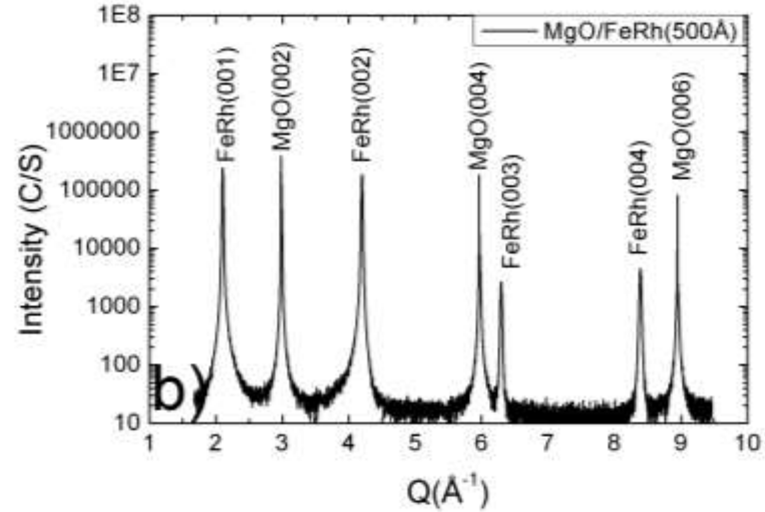


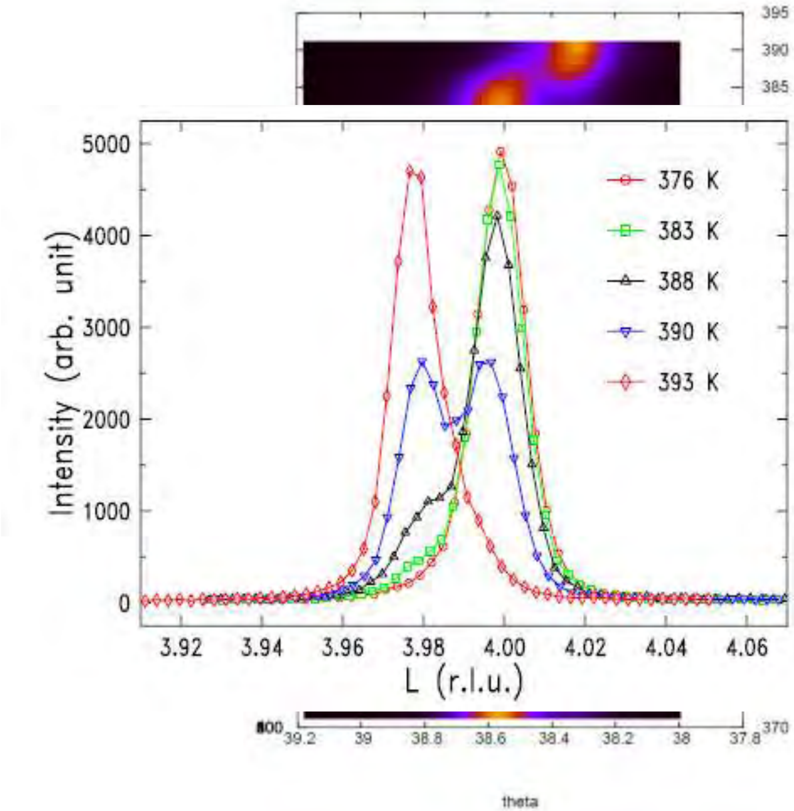


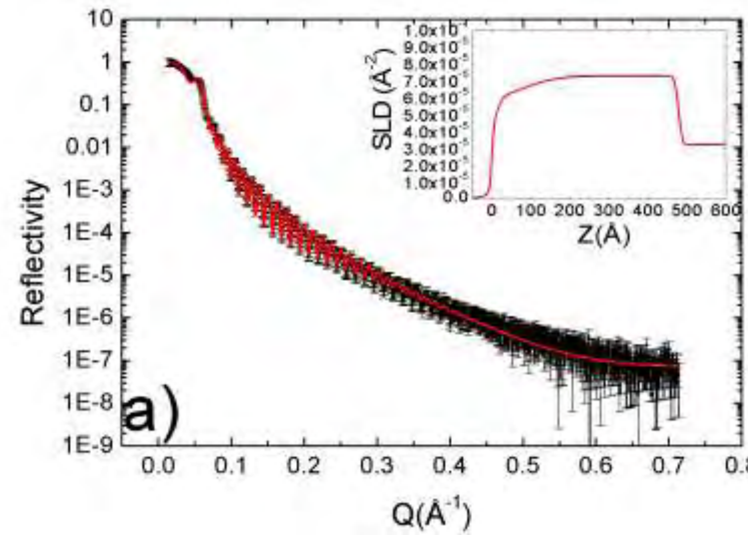
PRB **67**, 064415 (2003)

Structural

- Au/FeRh[50nm] (002)
- FeRh<001>||MgO<110>
- a= 2.998Å

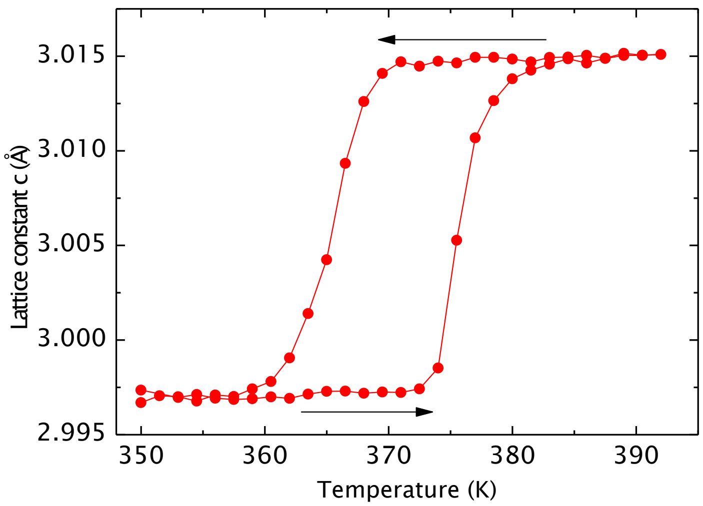


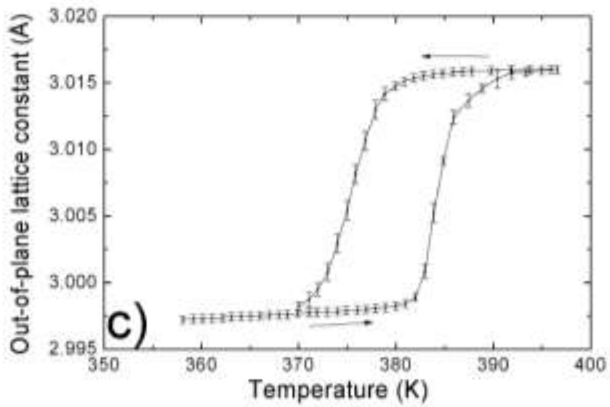


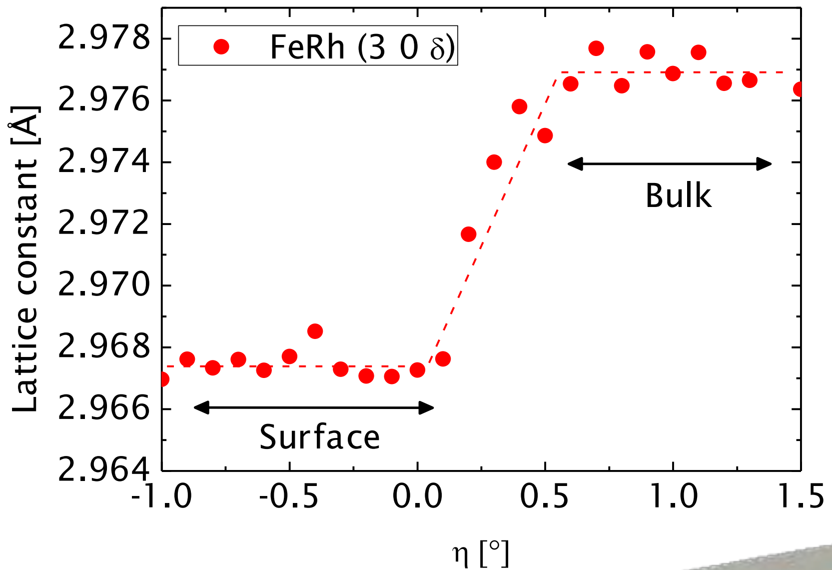


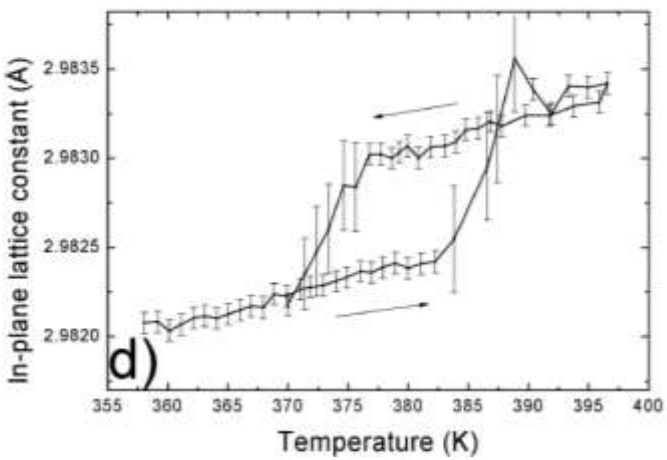
Surface Diffraction

- RT
  - Surface: 2nm
  - Bulk: 200nm



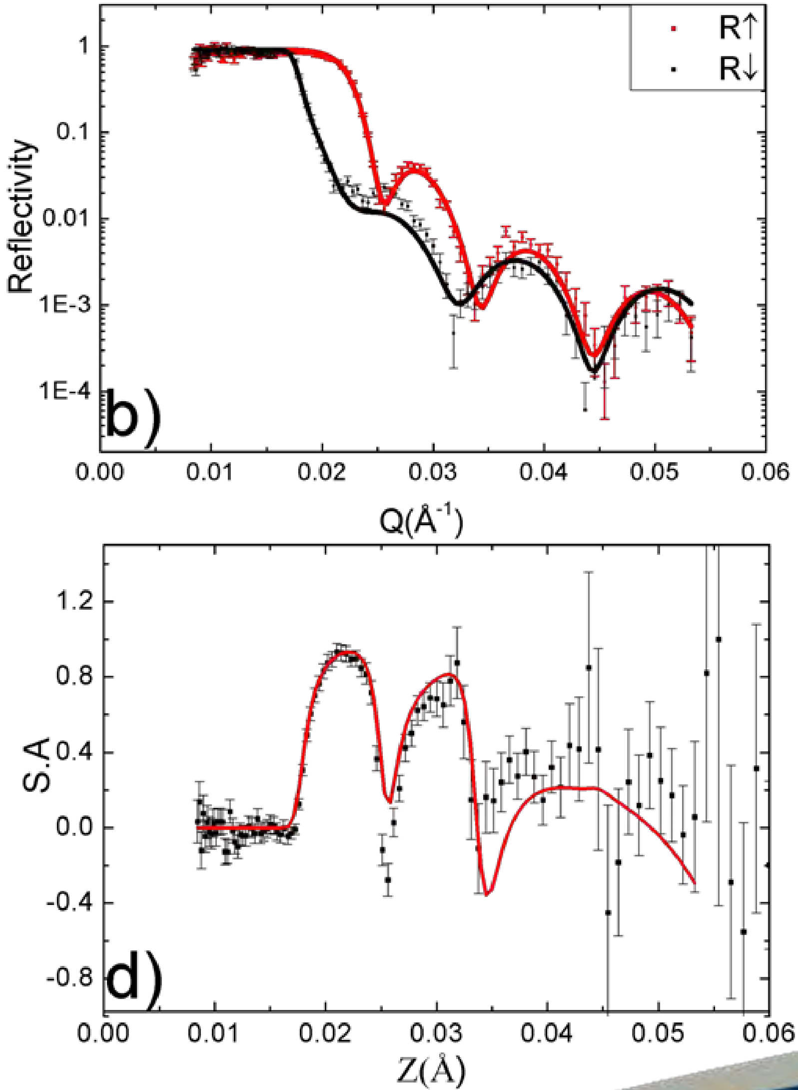






MgO[2]FeRh[50]/MgO

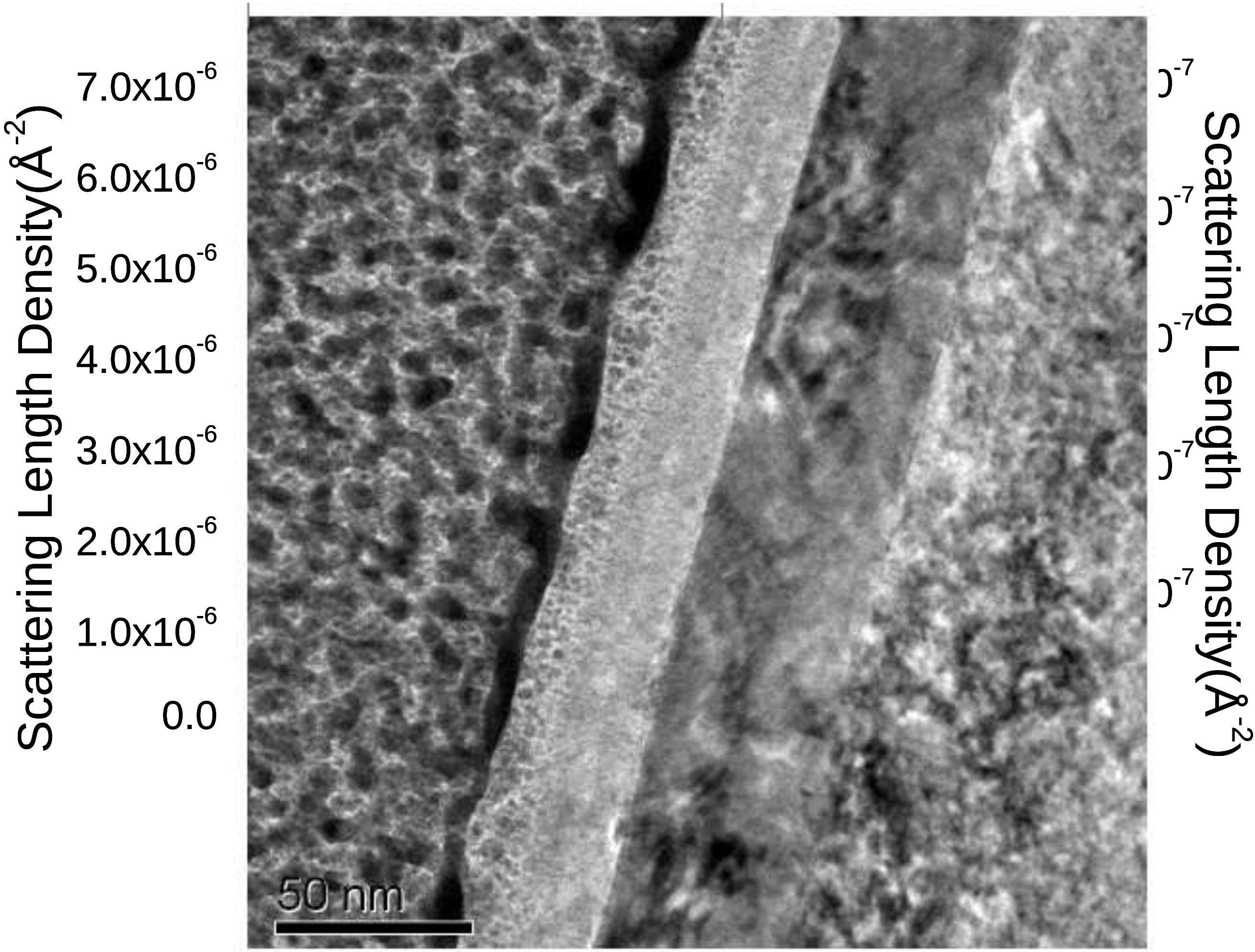
$$R = (I^+ - I^-)/(I^+ + I^-)$$

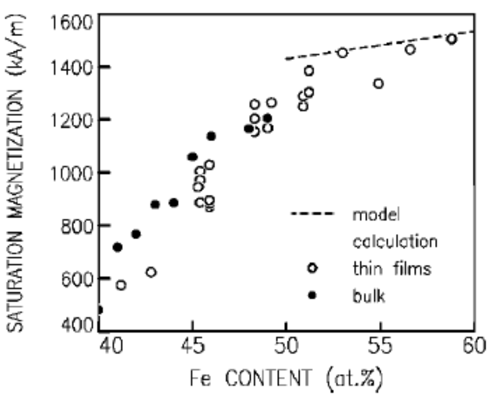


- I. Suzuki *et al*. J. Appl. Phys. **105**, 07E501 (2009)
- Fan *et al.* prb **82** 184418 (2010)

Magnetic profile

- MgO -0.5%
- Clear evidence of RT FM
  - 0.08μB
  - 1.56μB @400K
- Rh rich surface
  - Reduced moment in FM phase
  - Reduced ordering temperature

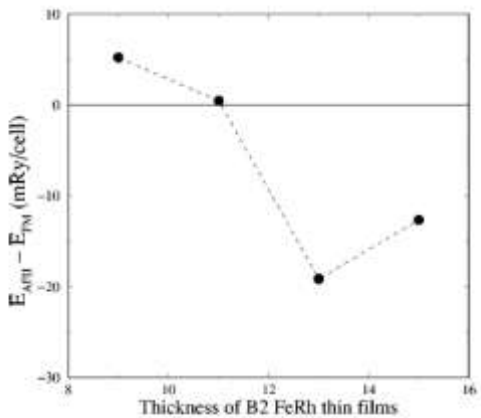


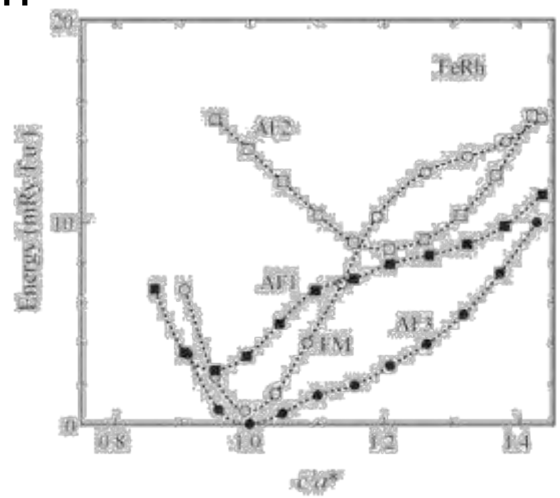


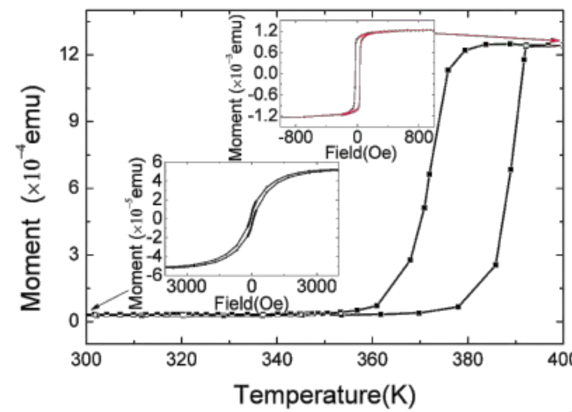
- J. Van Driel et al., J. Appl. Phys. **85**, 1026 (1999)

Origin of ferromagnetism…

- Mix of α and γ phases
  - Complex surface structure (Rh rich)
  - Favours reduction in AF-FM transition
- In-plane compression
  - Suppress the transition *viz* high pressure
  - Breaking of cubic symmetry
- Fe/Rh termination



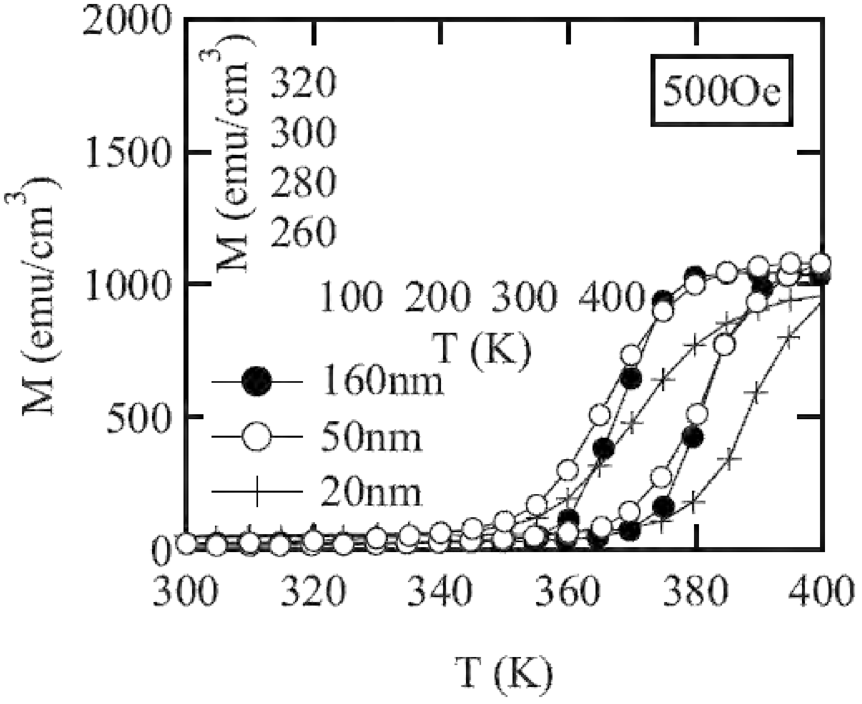


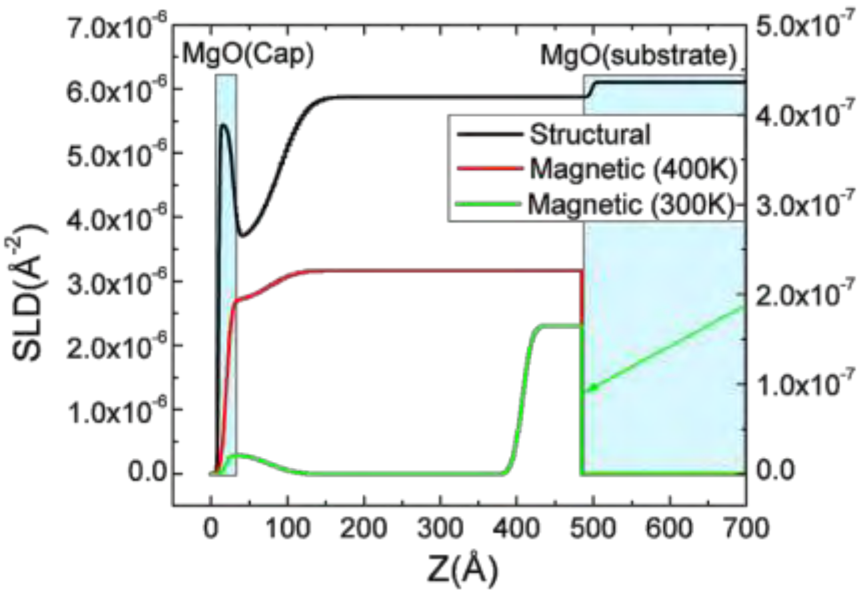


- Suzuki *et al. japl 105, 07E501 (2009)*
- Lounis *et al. prb* ***67*** *094432 (2003)*
- Yamada *et al. jac* ***415*** *31 (2006)*

Ultra-thin FeRh

- PNR gives 230×10³ Am⁻¹
- Domain distribution studies



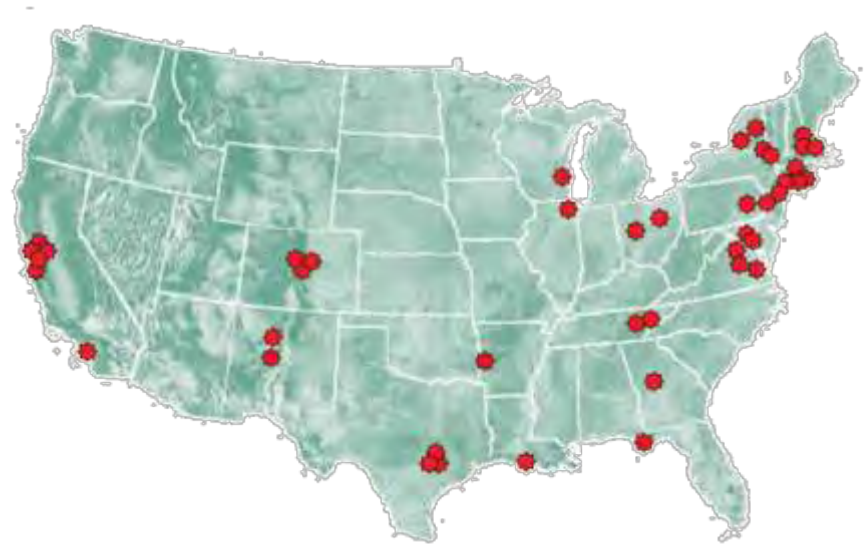


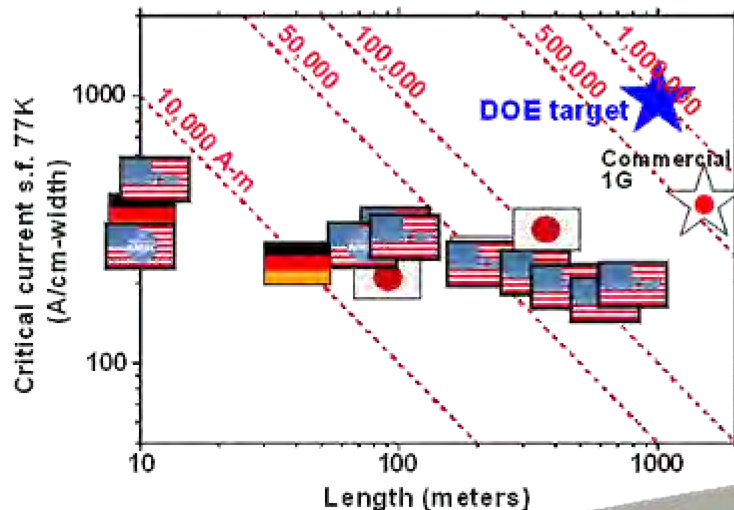
- Suzuki *et al. japl 105, 07E501 (2009)*
- Lounis *et al. prb **67** 094432 (2003)*
- Yamada *et al. jac **415** 31 (2006)*

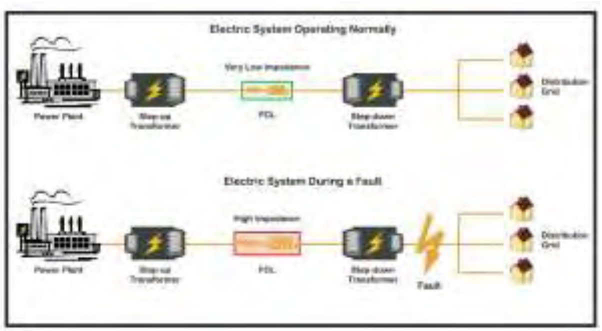
Nanoscale Superconductivity

DoE priorities

- **Superconductivity Applications**
  - Developing HTS-based electric power equipment such as transmission and distribution cables and fault current limiters
- **Second-Generation Wire Development**
  - Developing high-performance, low-cost, second-generation HTS wire at long lengths
- **Strategic Research**
  - Supporting fundamental research activities to better understand relationships between the microstructure of HTS materials and their ability to carry large electric currents over long lengths
- Applications
  - SC Generators
  - SC Energy Storage Systems
  - SC Power Cables
- Relevance of Neutron measurements
  - Proximity effects
  - Flux penetration
  - Nonlocal effects
  - FLL
  - Control of T_c
  - Importance of Interfaces

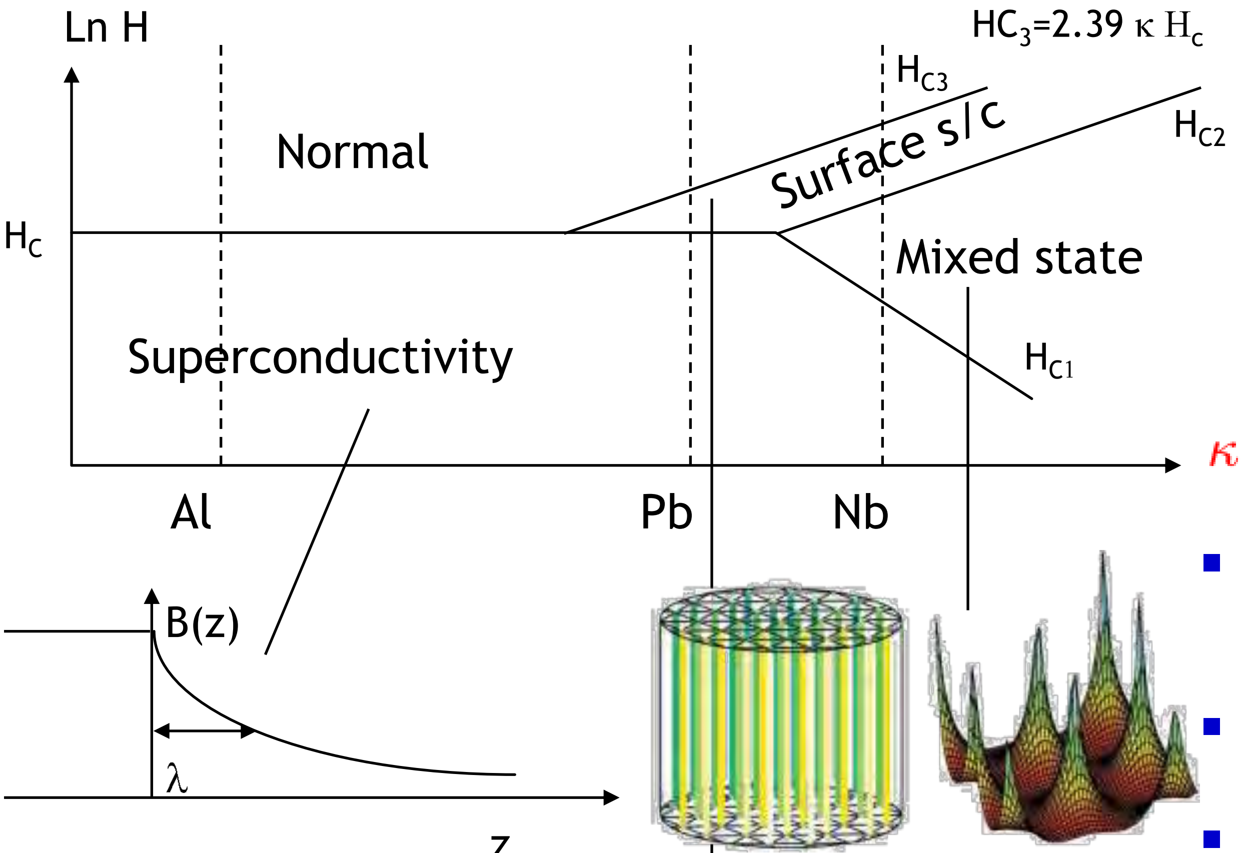


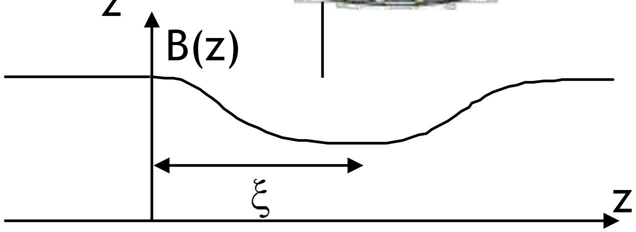


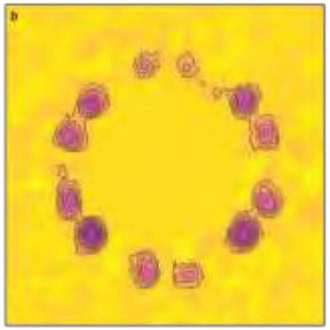


- http://www.oe.energy.gov

Flux penetration in superconductors







R.J. Cubitt *et al* Phys. Rev. Lett. **91** 047002 (2003)

$$\kappa = \frac{\lambda}{\xi}$$

- $H<H_c$ magnetic induction vanishes except within a penetration depth λ
- $H>H_c$ destroys bulk s/c and magnetic flux penetrates sample
- $H_{c3}>H> H_{c2}$ surface s/c approximately equal to the coherence length, ε
- Pb T_c=7.2K, H_c =800Oe

Flux penetration in superconductors

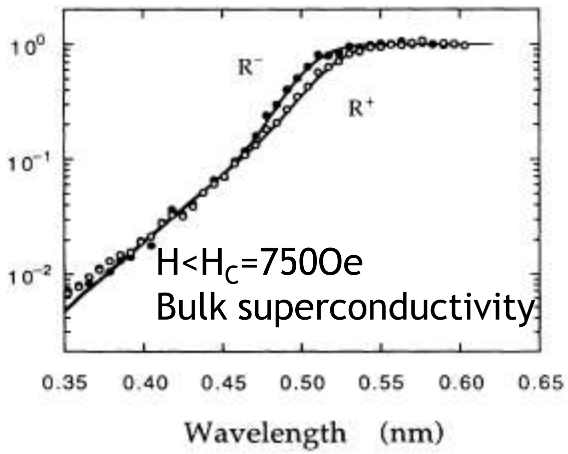


FIG. 2. The spin-dependent reflectivities R^+ and R^- measured in an applied magnetic field of 6.0×10^4 A/m (750 Oe). The continuous lines are the reflectivities calculated for the two polarization states, with the same instrumental and surface parameters as in Fig. 1, and an exponential decay of magnetic induction with a penetration depth of 39 nm.

TABLE I. Literature results for the penetration depth of lead referred to absolute zero. Only the values for the actual penetration depths, $\lambda(0)$, are given even though in some techniques the measured quantity relates more naturally to the London penetration depth, $\lambda_L(T)$, at temperatures close to T_c.

Technique	$\lambda(0)$/nm	Ref.
Absolute surface impedance	~54	28
Magnetization of thin films	39±3	29
Perpendicular field transition	~44	30
Surface impedance	~48[a]	31
Quantum interference in thin film	51-56	32
Field attenuation in thin film	45.3±8	33
Surface impedance in a field	~42	34
Absolute surface impedance	48±4	35
Inductance	~52.5	36
Polarized neutron reflectometry	39±1	This work

[a]Only $\lambda_L(0)$ is given explicitly in Ref. 31, but the results for $\lambda(T)$ obtained by a strong-coupling calculation are shown graphically in Fig. 1, and the value $\lambda(0)\approx48$ nm cited here has been taken from this graph.

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Magnetic-induction profile in a type-I superconductor by polarized-neutron reflectom

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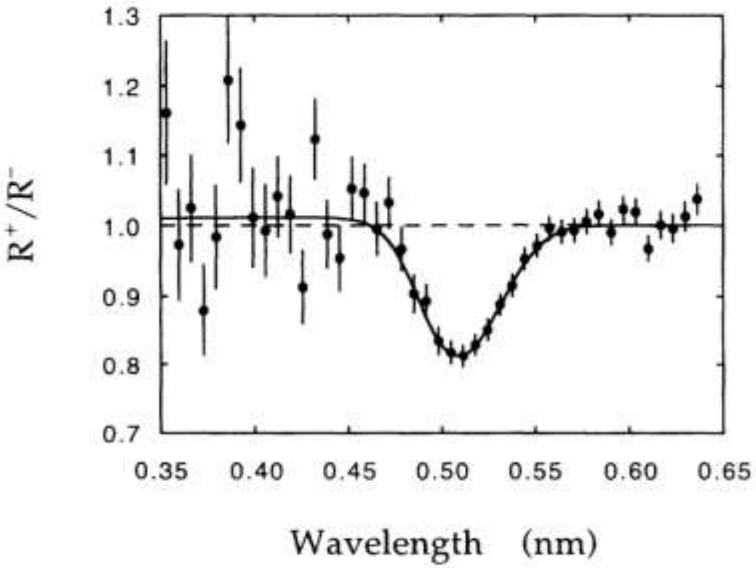
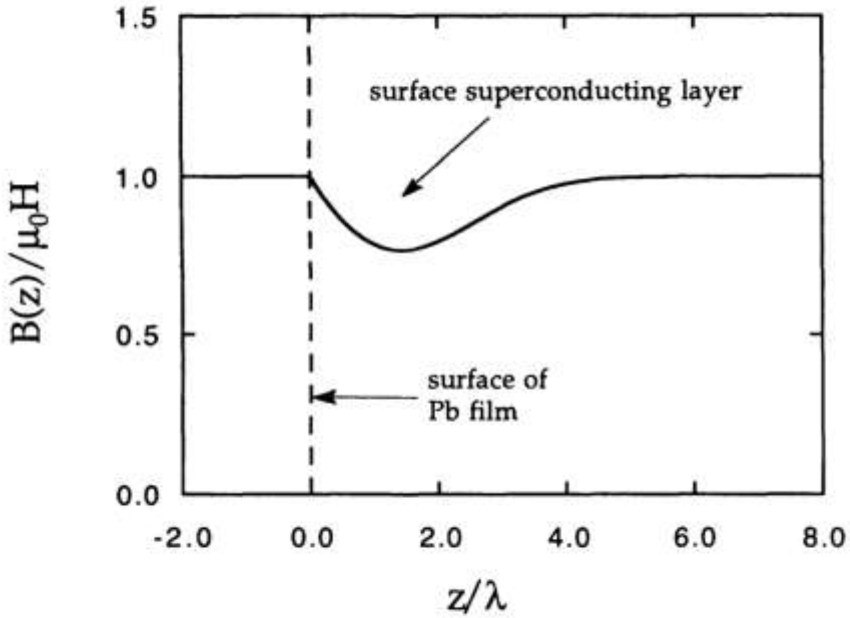
(Received 17 February 1994)

- No field dependence

$H_c<H<H_{c3}$



1.3
1.2
1.1
1.0
0.9
0.8
0.7
R⁺/R⁻
0.35
0.40
0.45
0.50
0.55
0.60
0.65
Wavelength (nm)

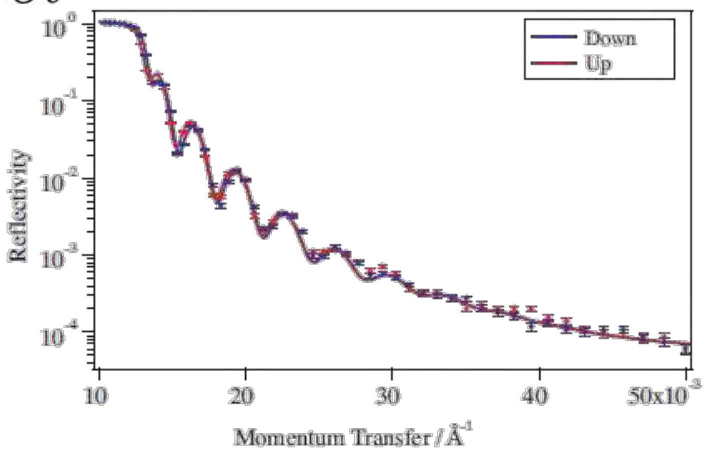


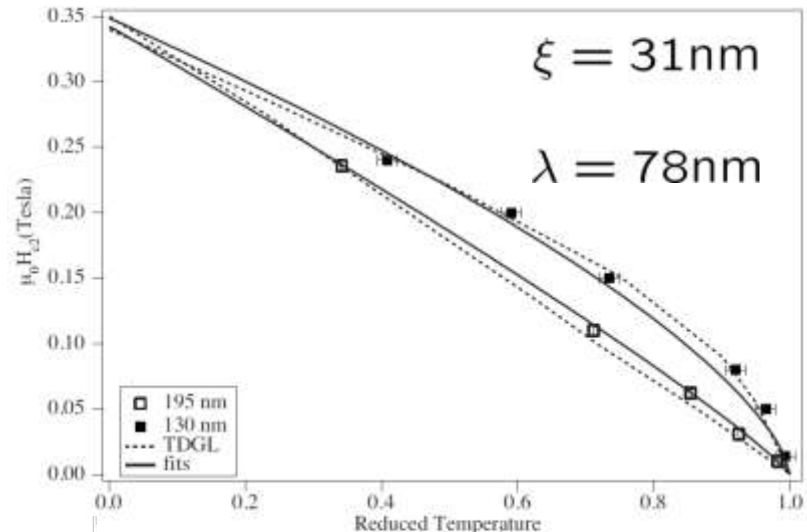
1.5
1.0
0.5
0.0
B(z)/μ₀H
surface superconducting layer
surface of
Pb film
-2.0
0.0
2.0
4.0
6.0
8.0
z/λ

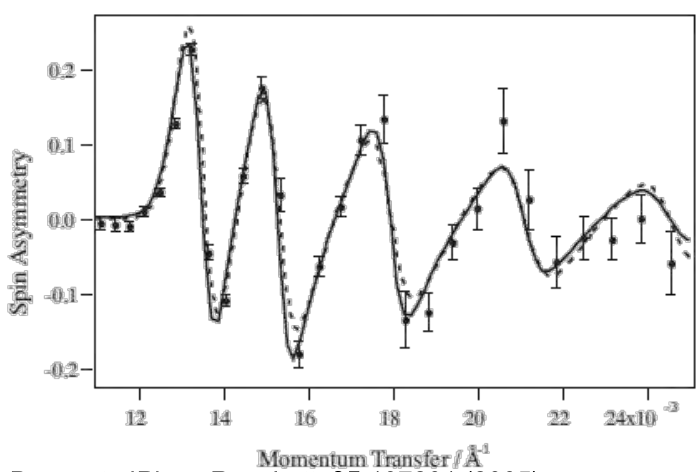
TDGL

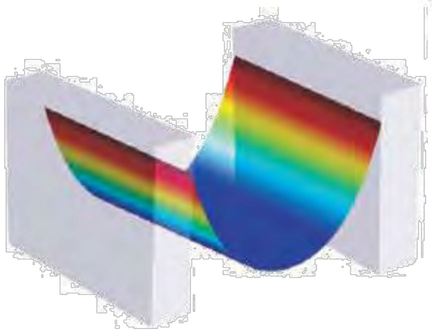
$$\frac{\partial \psi}{\partial t} = \frac{-1}{\eta}\left[(-i\nabla - \mathbf{A})^2\psi + (1-T)\left(|\psi|^2 - 1\right)\psi\right] + f$$

$$\frac{\partial \mathbf{A}}{\partial t} = (1-T)\mathcal{R}\left[\psi^\star(-\nabla - \mathbf{A})\psi\right] - \kappa^2 \nabla \times \nabla \times \mathbf{A}$$





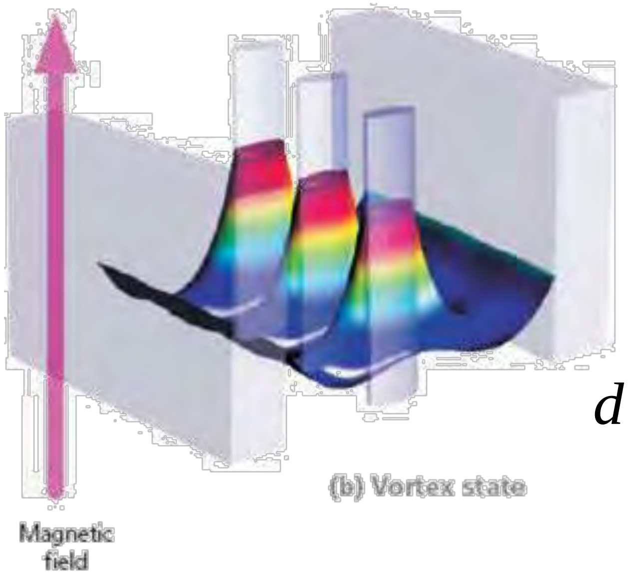




$$B(y) = \mu_0 H_E \frac{\cosh\left(\frac{2y-d}{\lambda}\right)}{\cosh\left(\frac{d}{2\lambda}\right)}$$

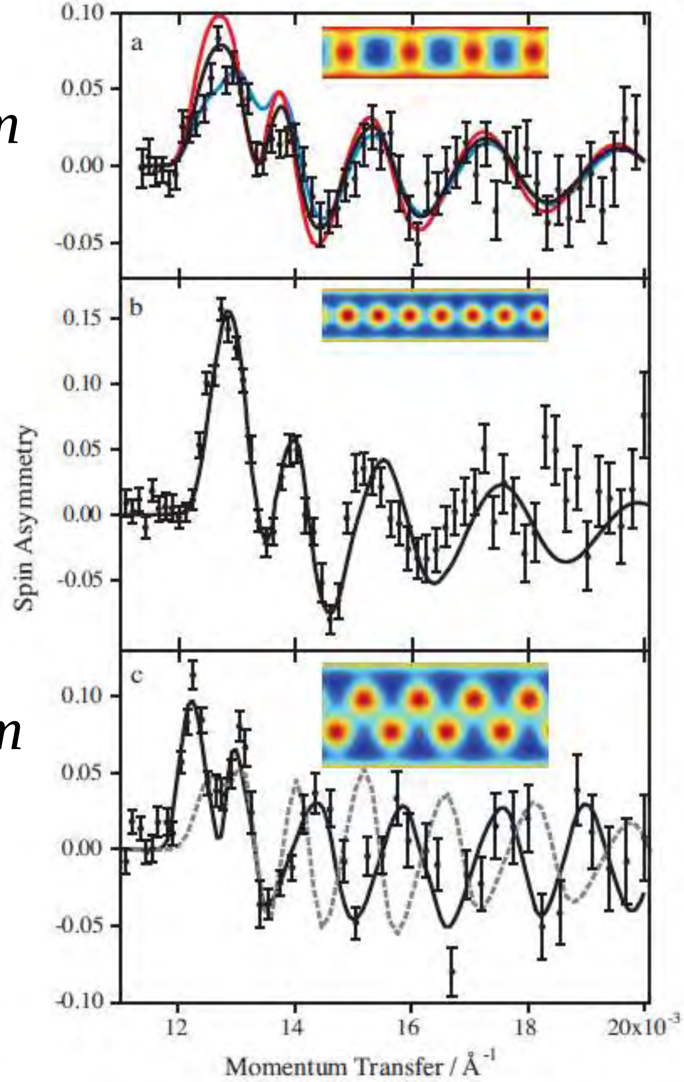
- A. Drew *et al* Phys. Rev. Lett. **95** 197201 (2005)
- A Drew *et al* Phys. Rev. B. **80** 134510 (2009)

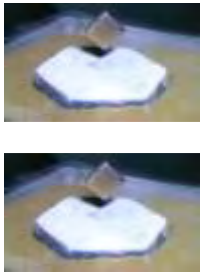
Flux distribution



$d = 195nm$

$d = 250nm$





Magnetism and high temperature superconductivity

LETTERS

Magnetism at the interface between ferromagnetic and superconducting oxides

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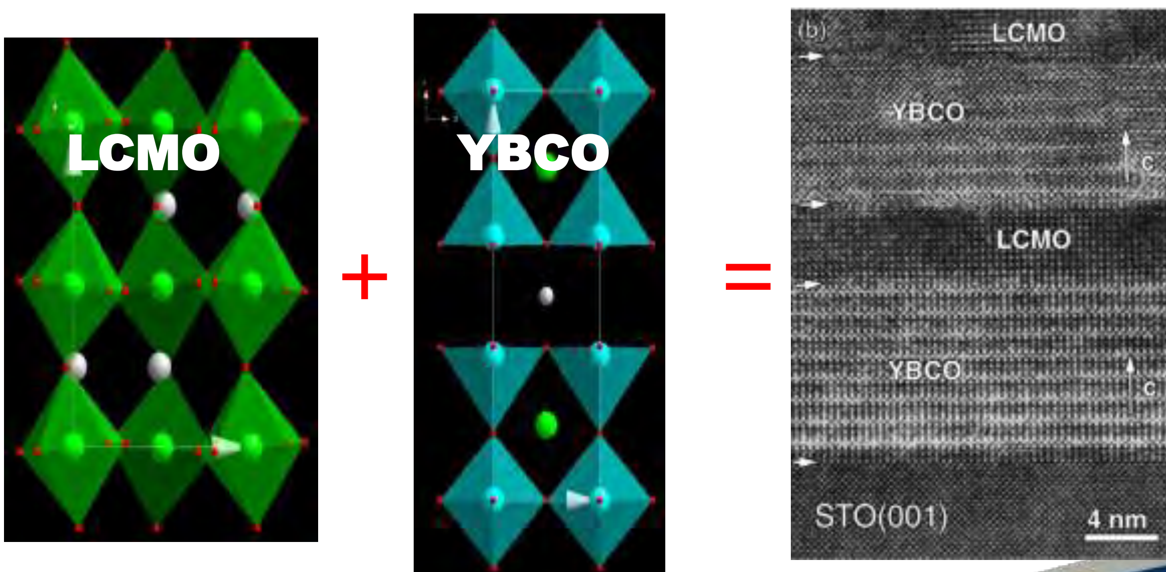
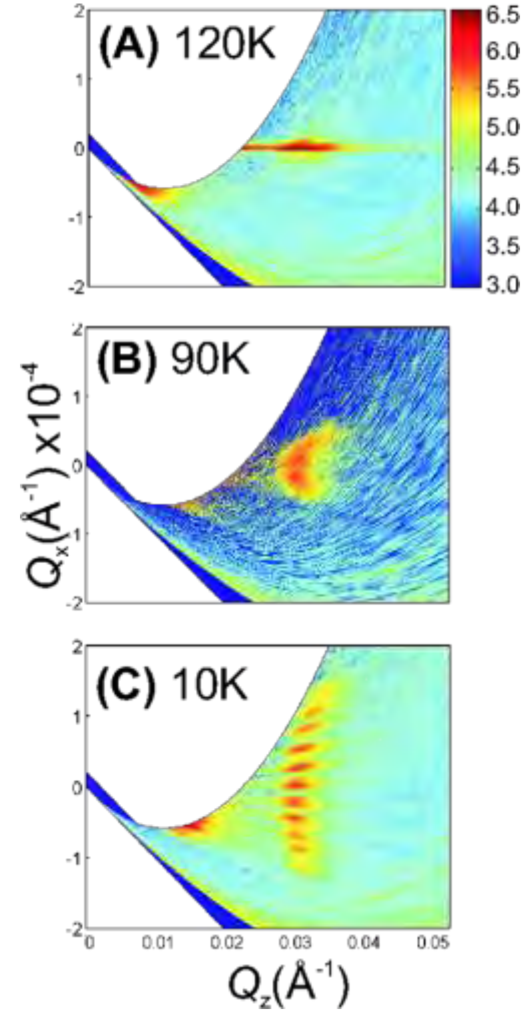
*e-mail: j.chakhalian@fkf.mpg.de

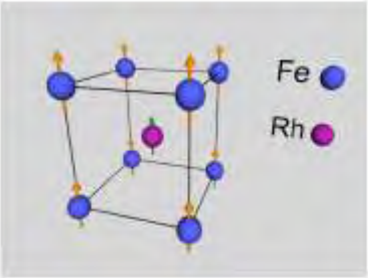
nature physics | VOL 2 | APRIL 2006 |

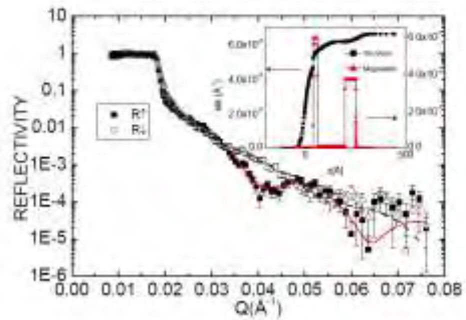


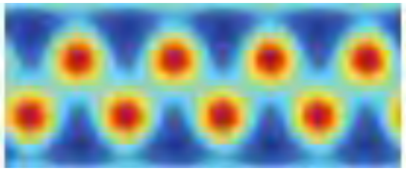


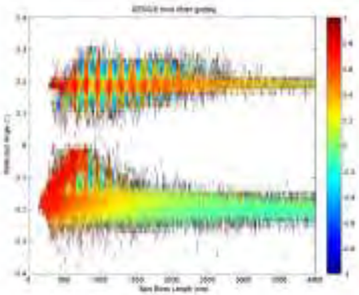
Outlook I

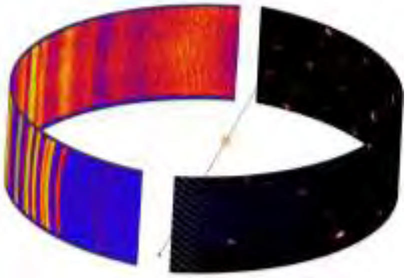
- Interfacial phenomena offer the possibility of controlling magnetism
  - Magnetostructural transitions
  - Spin Accumulation
  - Dilute magnetic semiconductors
  - Hybrid magnetic/superconducting systems
  - Multiferroics …
- Quantitative test of theory
- Interface Sensitive
- Dynamics/Kinetics
- Applicable to a wide class of nanoscale phenomena
  - Proximity effect
  - Dead layers
  - Vortex Structures (Reflectometry & SANS)











Outlook II

- Sensitive & powerful techniques to spatially resolve the magnetism and superconductivity in nanoscale systems