Fabricated Magnetic Structures

YURI SUZUKI

LECTURE 1

Synthesis and Fabrication of Magnetic Films and Structures

BOULDER SUMMER SCHOOL

Lectures on Fabricated Magnetic Structures

- Introduction
- Synthesis and fabrication techniques for magnetic structures
  - Spin Polarized Thin Film Material
  - Thin Film Synthesis and Lithography
  - Synthesis of Magnetic Particles
- Magnetic behavior in small magnetic structures
- Magnetic Junction Devices

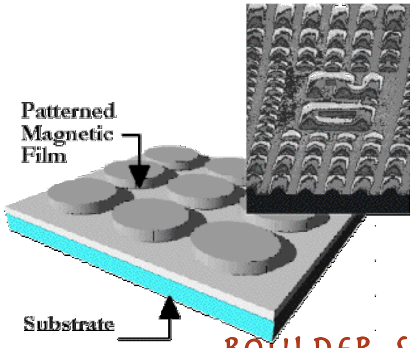
Novel Magnetic Materials

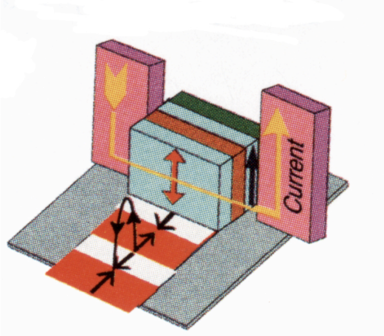
Novel magnetic materials have enabled the development of

- denser conventional media
- new class of magnetic readheads
- new class of nonvolatile RAM (Magnetic RAM)

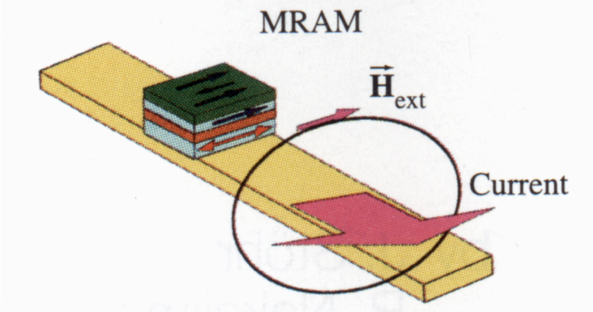
Magnetic media at 10Gb/in^2

Future patterned media



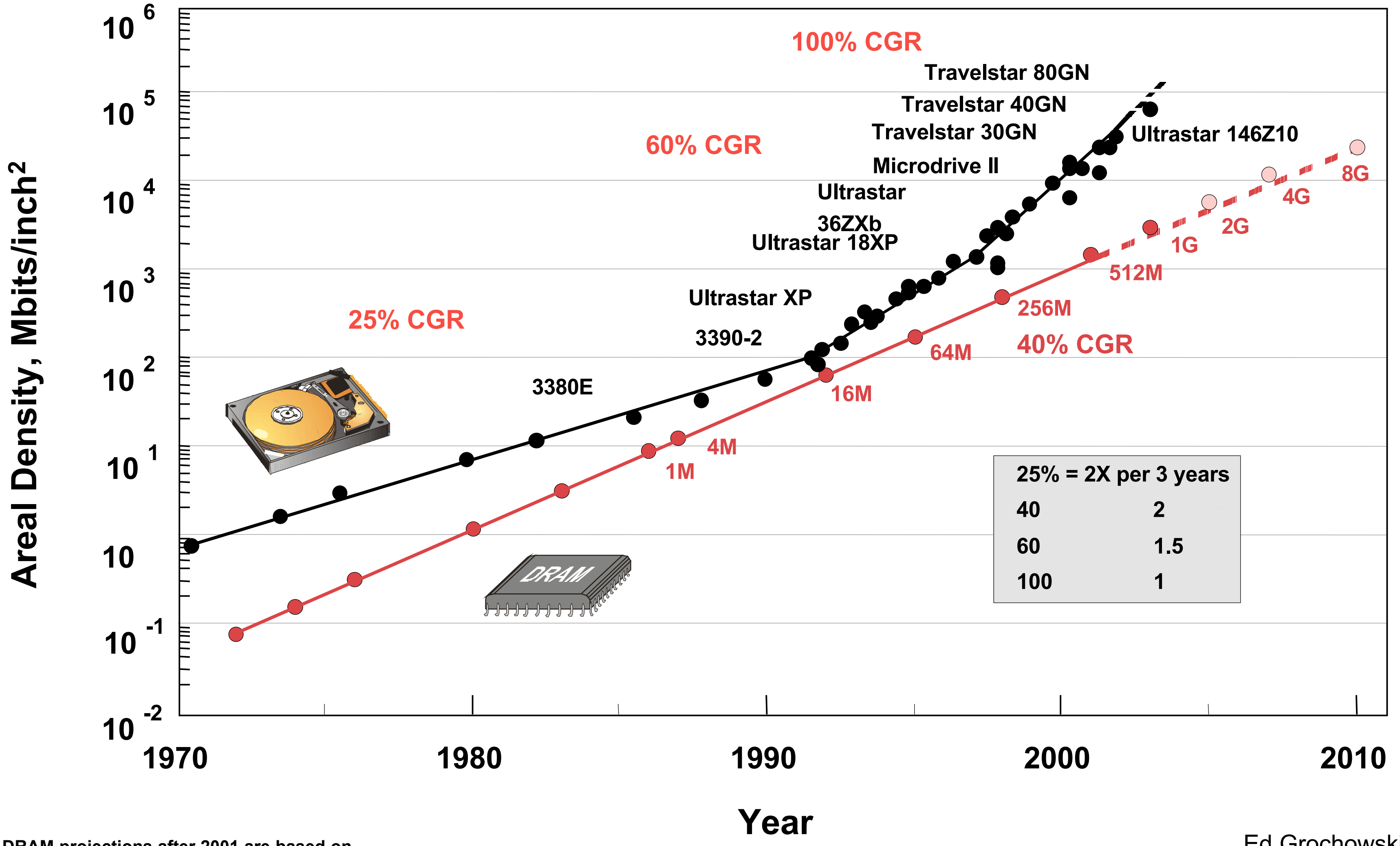


Spin valve readheads



Magnetic RAM based on magnetic tunnel junctions

Areal Density of Magnetic HDD and DRAM

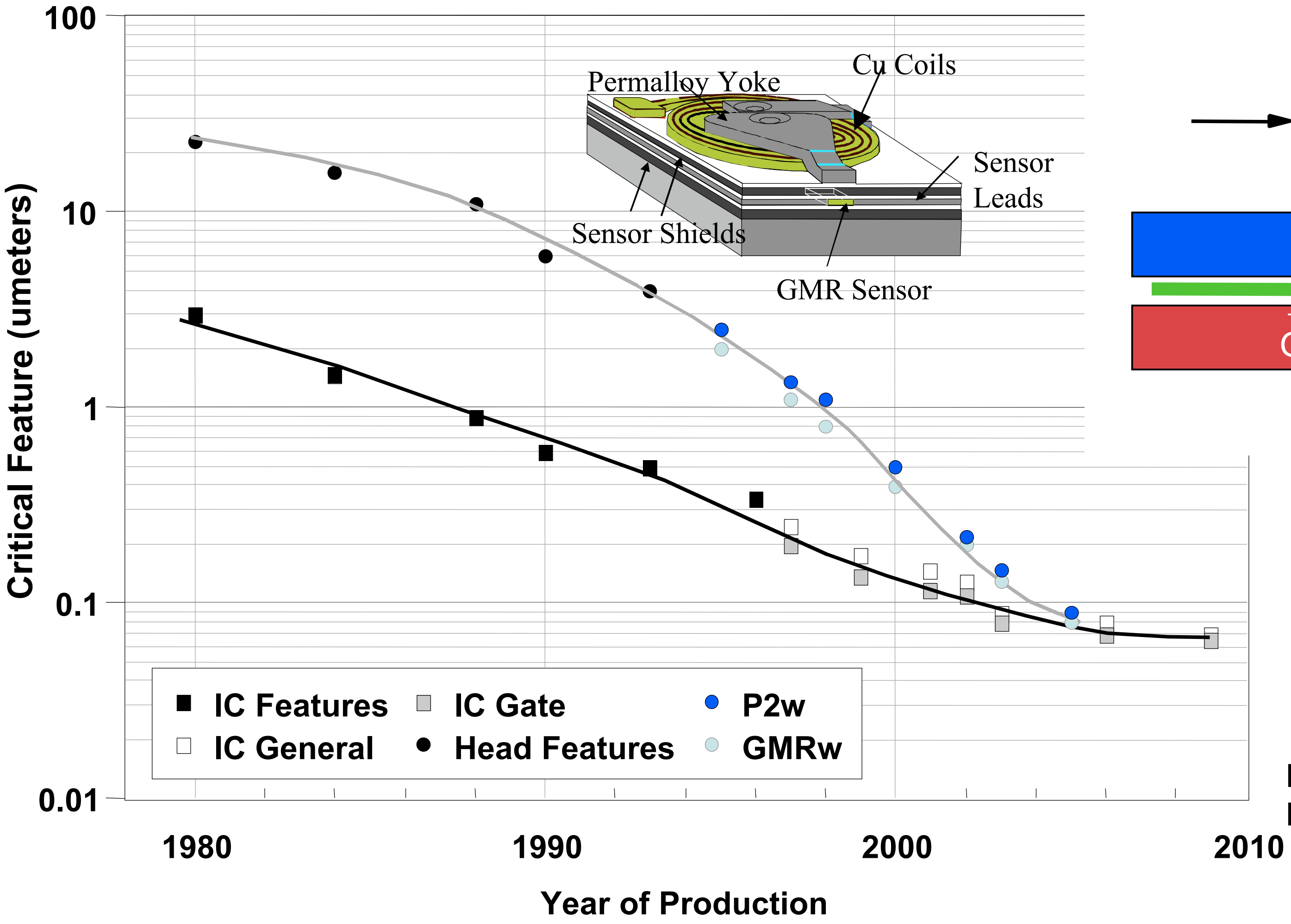


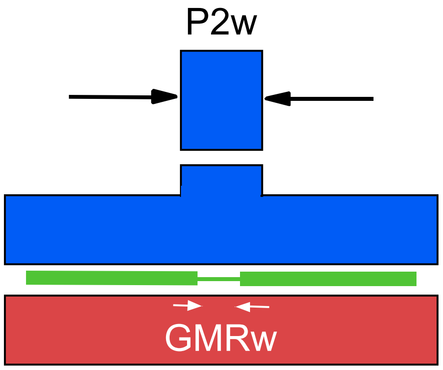
DRAM projections after 2001 are based on
industry capacities and constant chip area

Ed Grochowski
HGST

AREAL2002Eh.PRZ

Lithographic Critical Feature Roadmap for GMR Heads and Semiconductor IC





Robert Fontana
HGST

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Spin Polarization

- Materials whose population of spin up and down electrons at the fermi level are uneven have a net spin polarization
- Examples:

Spin polarization

$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

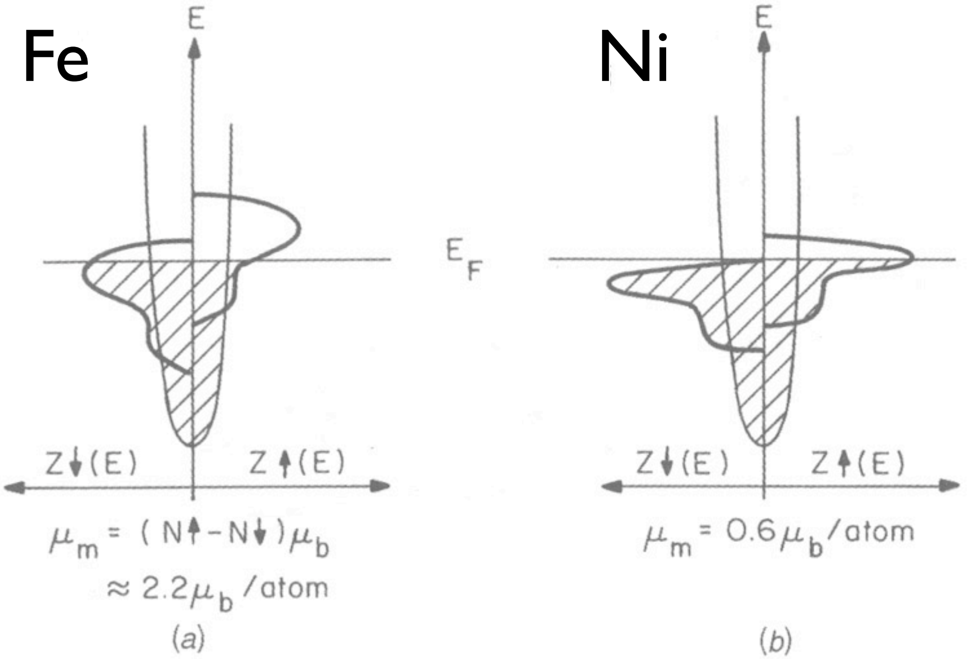
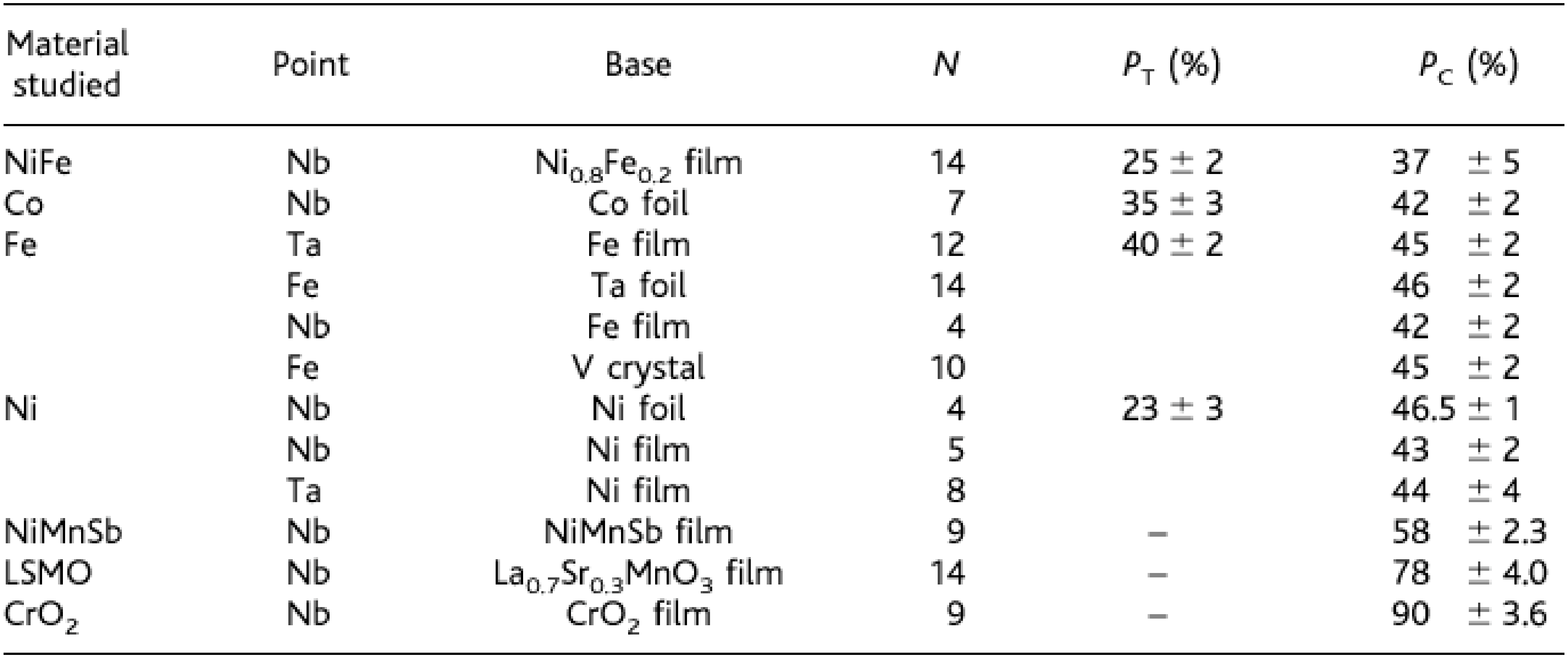


Figure 5.4 Density of states compared for Fe and Ni. The Ni *d* band is narrower in energy and the Fermi level is closer to the top of the Ni *d* band.

O'Handley

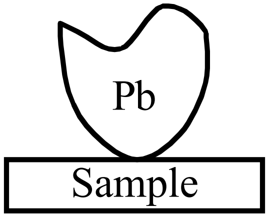
Spin Polarized Thin Film Materials



Material studied	Point	Base	N	P_T (%)	P_C (%)
NiFe	Nb	$Ni_{0.8}Fe_{0.2}$ film	14	25 ± 2	37 ± 5
Co	Nb	Co foil	7	35 ± 3	42 ± 2
Fe	Ta	Fe film	12	40 ± 2	45 ± 2
	Fe	Ta foil	14		46 ± 2
	Nb	Fe film	4		42 ± 2
	Fe	V crystal	10		45 ± 2
Ni	Nb	Ni foil	4	23 ± 3	46.5 ± 1
	Nb	Ni film	5		43 ± 2
	Ta	Ni film	8		44 ± 4
NiMnSb	Nb	NiMnSb film	9	–	58 ± 2.3
LSMO	Nb	$La_{0.7}Sr_{0.3}MnO_3$ film	14	–	78 ± 4.0
CrO_2	Nb	CrO_2 film	9	–	90 ± 3.6

Soulen *et al*., Science 282, 85 (1998).

Spin polarization as measured by Andreev reflection



Half Metallic Materials

Materials where the electrons available for conduction at the Fermi level are completely spin polarized……

CrO_2

- theoretically predicted to have 100% spin polarization
- T_c=390K (bulk)

Fe_3O_4

- theoretically predicted to have -100% spin polarization
- T_c=858K (bulk)

$La_{0.7}Sr_{0.3}MnO_3$

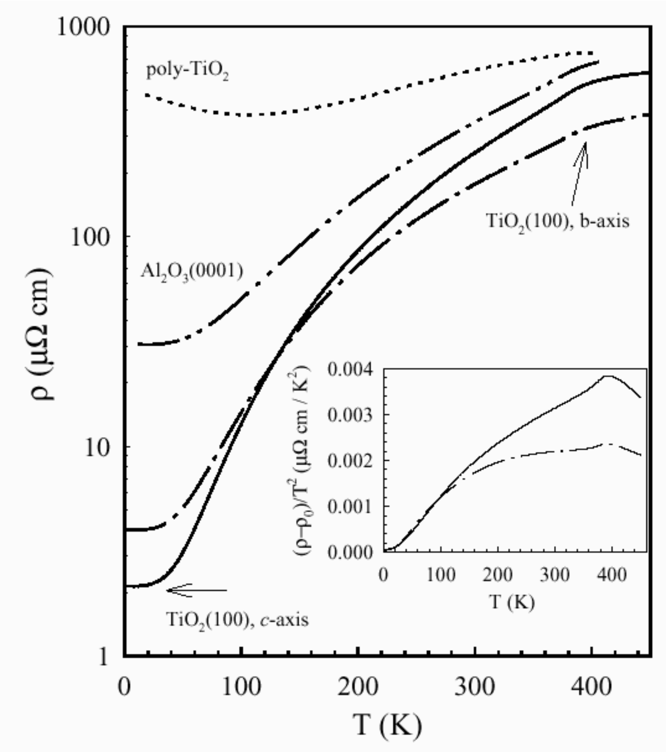
- double exchange ferromagnet
- +100% spin polarization
- T_c=360K (bulk)

Sr_2FeMoO_6

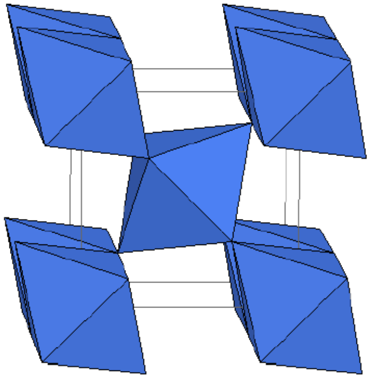
- theoretically predicted to have 100% spin polarization
- T_c~420K (Tomioka et al. PRB **61** 422 (00))

CrO_2

- Half metallicity
- High conductivity

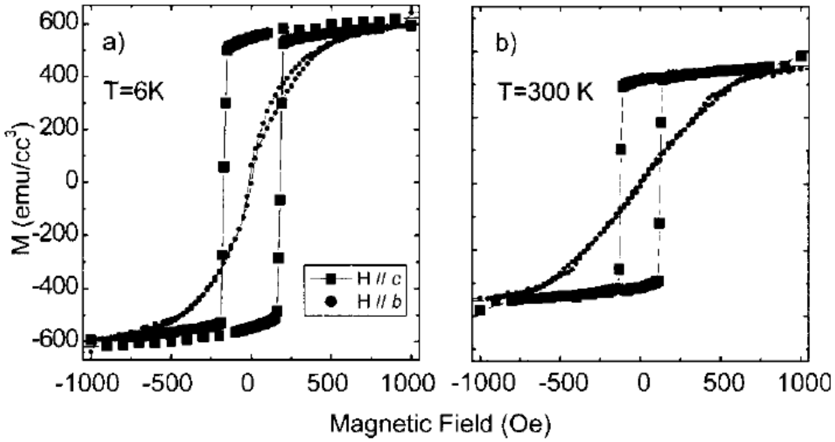


X. Li *et al.*, 1999.



Rutile structure

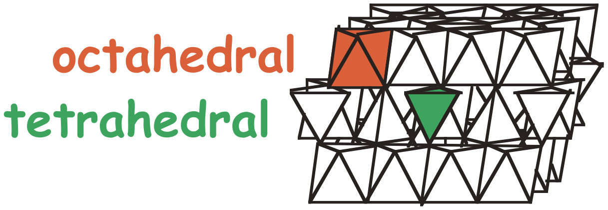
1375Å film

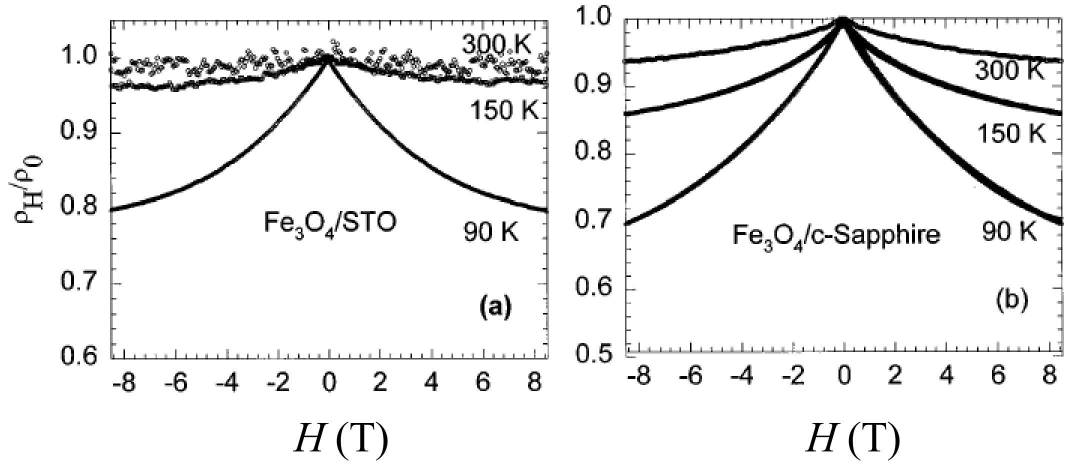


A. Anguelouch *et al.*, PRB**64**, 180408 (2001)

Fe_3O_4

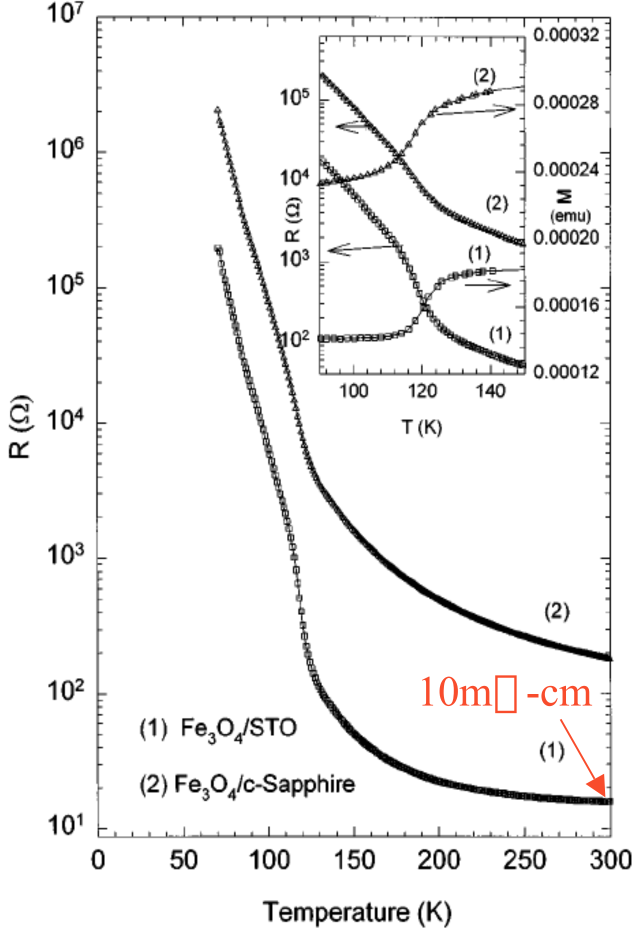
- Half-metallic
- High resistivity
- Verwey transition





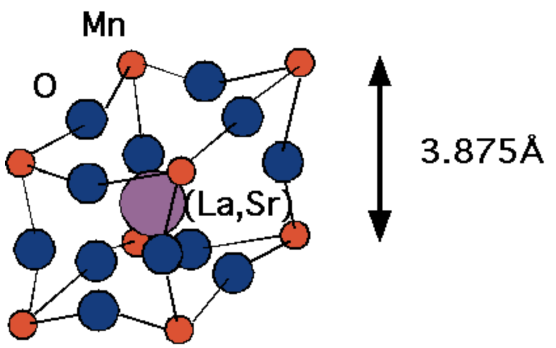
Ogale *et al.*, PRB **57** 7823 (1998)

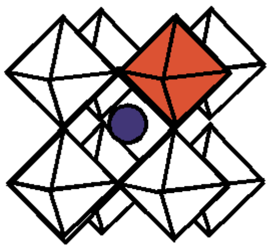
Verwey (CO) transition at 120K



$La_{0.7}Sr_{0.3}MnO_3$

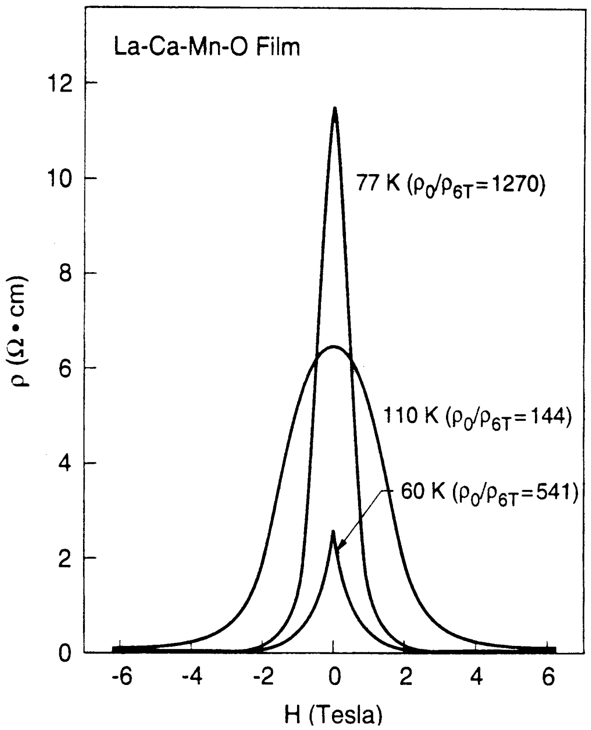
- Half metallic
- Colossal magnetoresistance



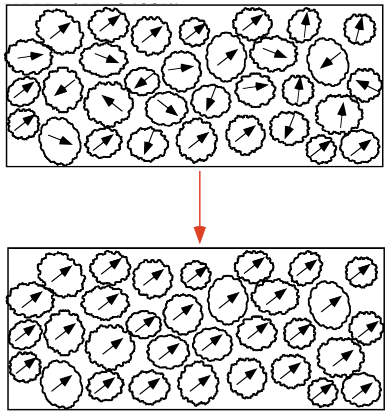


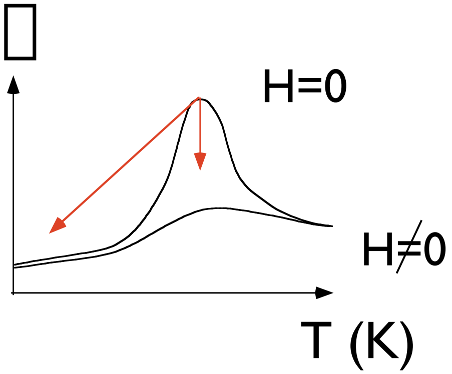
octahedral

rare earth doped alkaline earth



S. Jin et al., Science 264, 413 (1994)

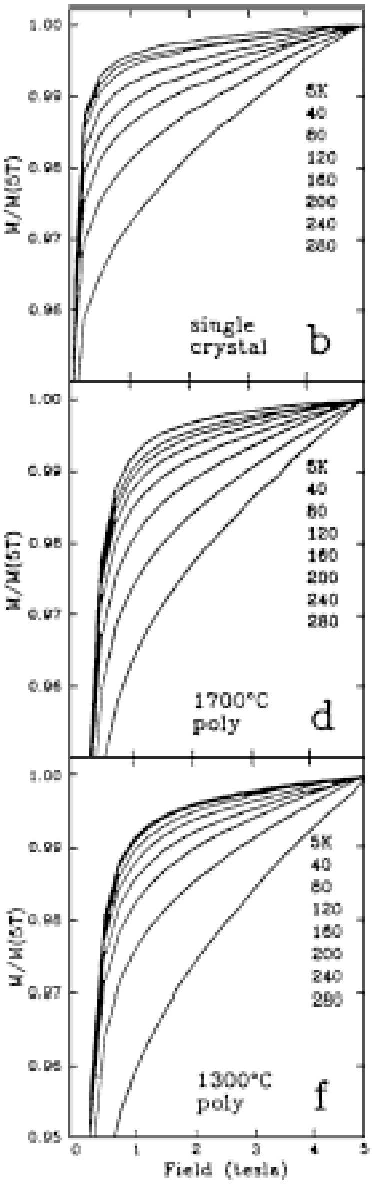




Polycrystalline vs. single crystal

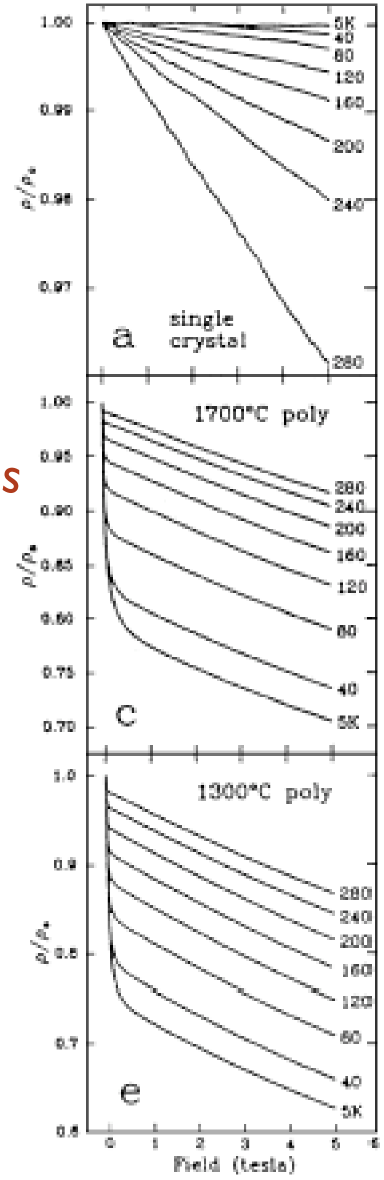
SINGLE CRYSTAL

POLYCRYSTAL



The role of the grain boundaries in

- Transport
    - *Increased scattering due to introduction of grain boundaries*
    - *Negative linear MR due to Suppression of magnetic fluctuations*
    - *Low field MR in poly due to intergrain effects*
- Magnetism
    - *similar field dependence of magnetization in single crystal and poly*



SINGLE CRYSTAL

POLYCRYSTAL

Fabricated Magnetic Structures

- Thin Film Synthesis plus Lithography
  - 1D or 2D structures
  - Feature sizes down to 10nm
- Self assembly
  - Spherical, cylindrical, lamellae structures
  - Features sizes below 10nm
  - Packing structure

Thin Film Synthesis

NON-EQUILIBRIUM PROCESSES

- Chemical Vapor Deposition

  MOCVD, OMVPE
- Physical Vapor Deposition

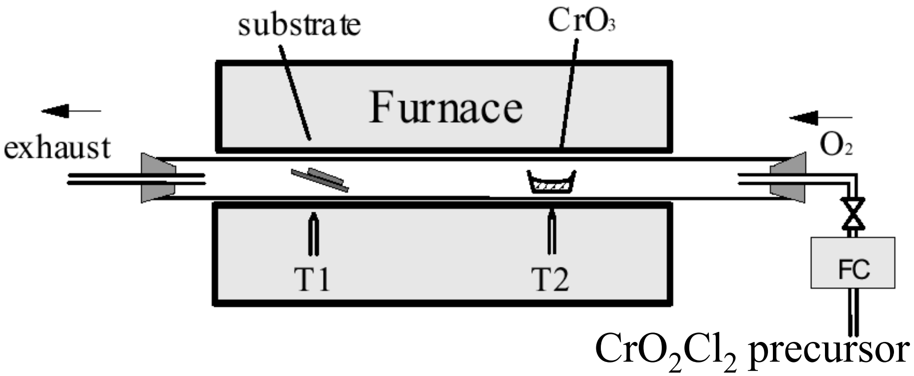
  Sputtering

  Molecular Beam Epitaxy

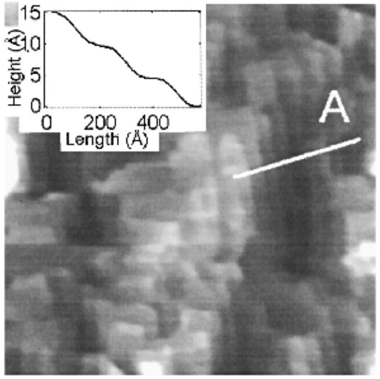
  Pulsed Laser Deposition

Chemical Vapor Deposition

400C Quartz tube, onto $TiO_2(100)$



$$CrO_3 \xrightarrow{O_2} CrO_2 + \frac{1}{2} O_2$$



X. Li *et al.*, 1999

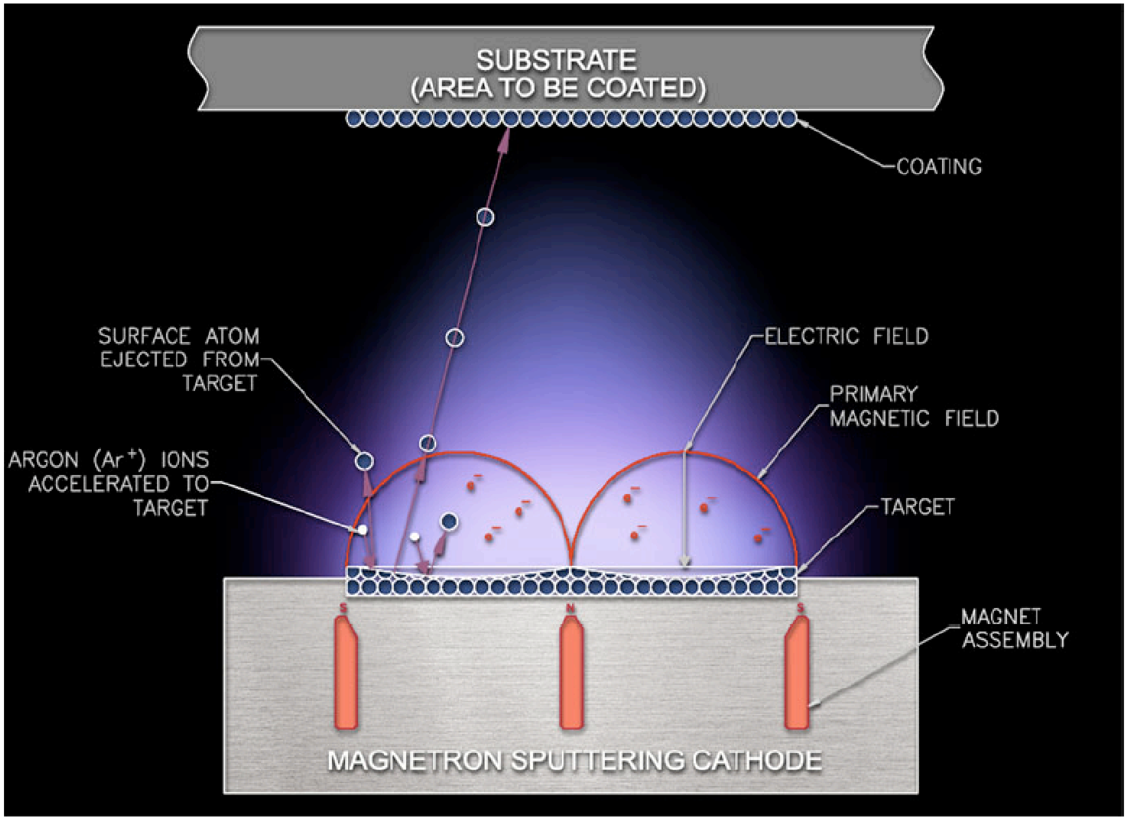
- Precursors to react with carrier gas at one temperature
- Condense the product onto substrate at lower temperature
- Diffusion dominated

Magnetron Sputtering

- Plasma of ions generated by high voltage across low pressure gas
- Ions strike target and eject atomic species (tenths of eV)
- Atomic species travel to substrate and are bonded

Metals, ceramics…….

Magnets confine glow discharge plasma and increase deposition rates

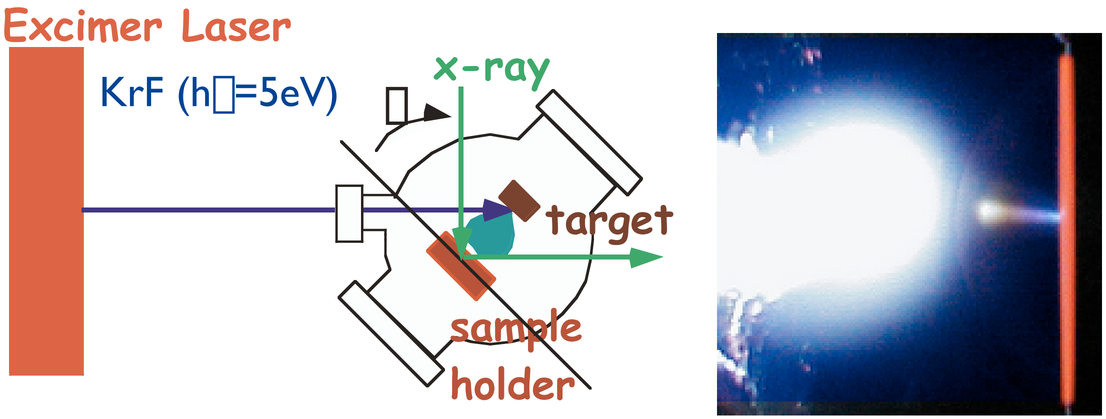


Magnetron Sputtering

- Co-sputtering versus single target sputtering of materials
- Sputtering of magnetic materials- *stronger magnetron field*
- Process is easily scaled up in dimension
- Ease of making multilayers
- Sputtering of atomic species makes stoichiometric control of material challenging- *complex stoichiometries difficult*
- Negative ion bombardment of substrate- *off-axis configuration necessary*

Pulsed Laser Deposition

- Efficient ablation of materials with significant UV absorption
- Complex laser-solid interaction results in a wide variety of plume constituents that then deposit on the substrate.
  - *Vaporization of target material*
  - *Transport of the vapor plume*
  - *Film growth on substrate*

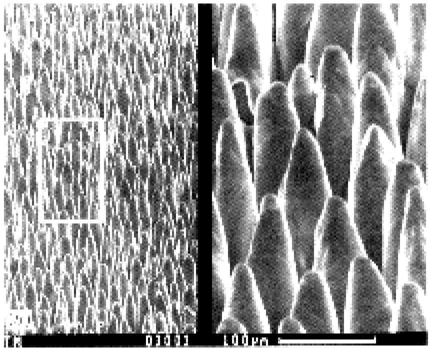


pulsed laser deposition

Pulsed Laser Deposition

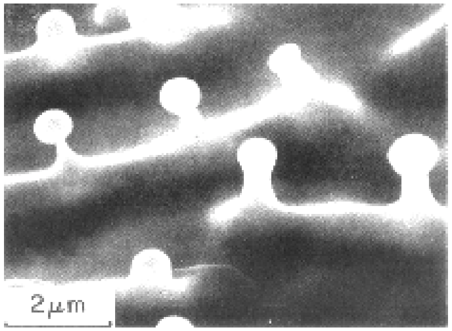
- Thermal sputtering
- Electronic sputtering
- Exfoliational sputtering
- Hydrodynamic sputtering

……..of ions, neutrals and molecular species at few eVs

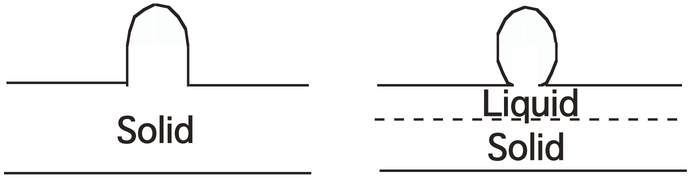


Foltyn (1994)

Cone formation due to shielding by impurities and redeposited ablation debris



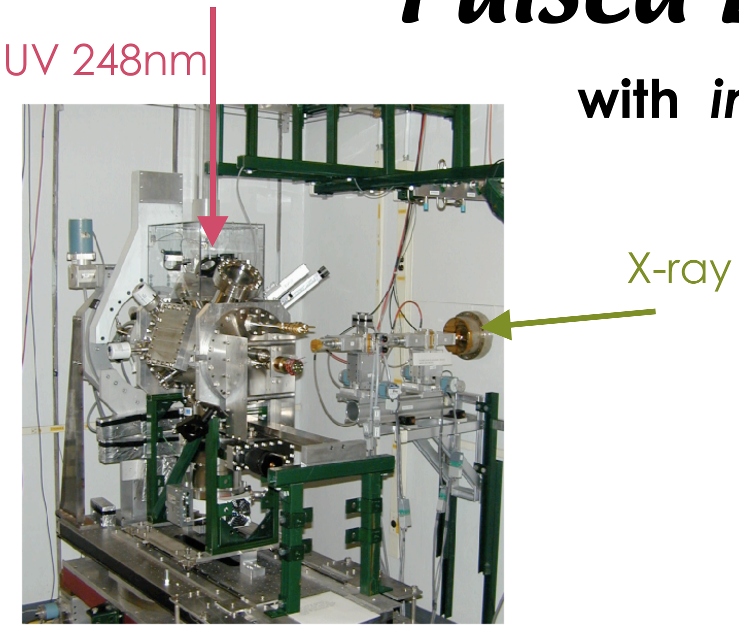
Kelly et al., Nucl. Instrum. Meth. (1995)



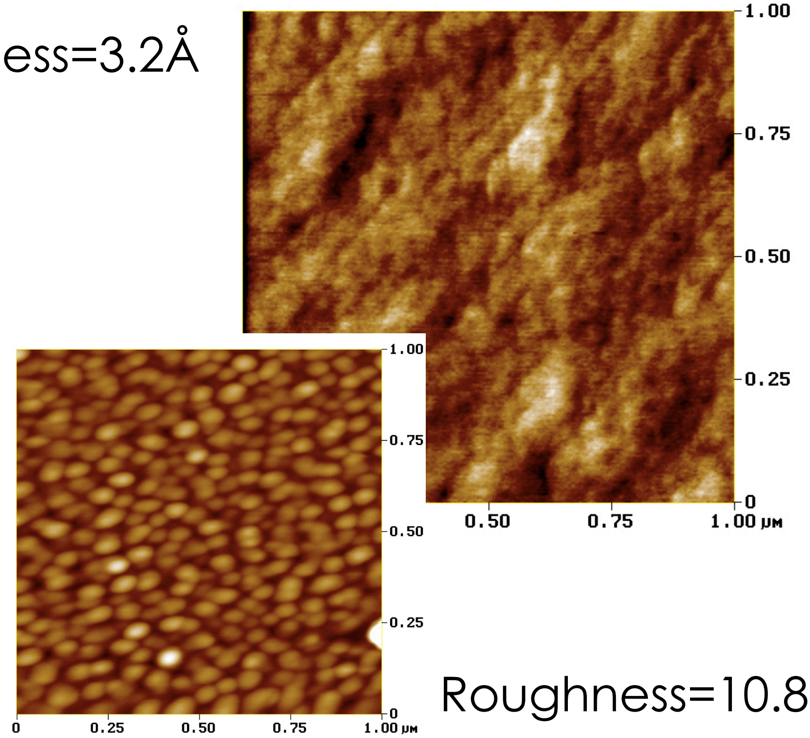
Droplets due to hydrodynamic sputtering

Pulsed Laser Deposition

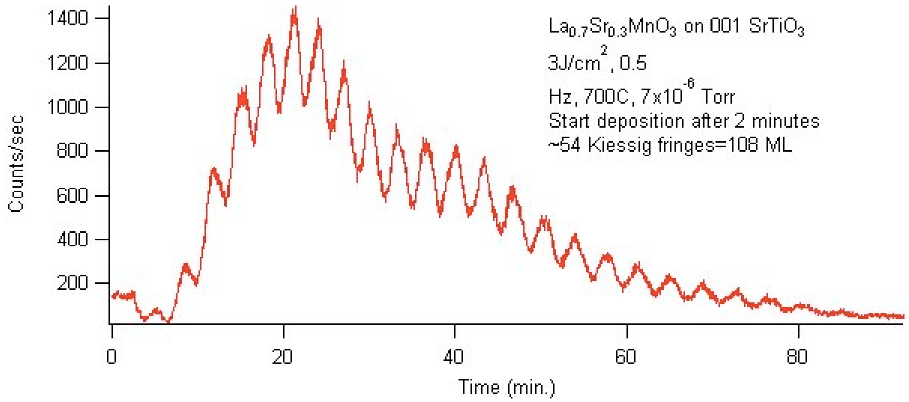
with *in-situ* X-ray scattering



Roughness=3.2Å



Roughness=10.8Å



Layer-by-layer growth control is crucial to the design of functional oxide thin films

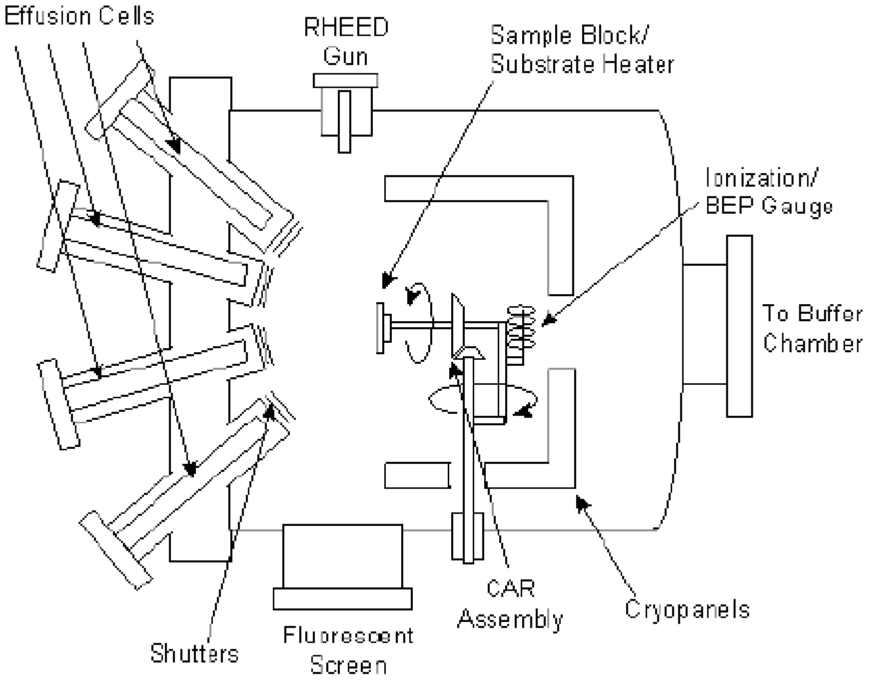
At G-line of the Cornell High Energy Synchrotron Source (CHESS), in collaboration with Aaron Fleet and Joel Brock (Applied Physics, Cornell).

Pulsed Laser Deposition

- Stoichiometric control of the target material onto the substrate
- Layer-by-layer growth possible
- Ease of making multilayers
- Small area deposition due to focused laser spot
- Not an ideal process for metals due to UV processing

Molecular Beam Epitaxy

- Thermally generated molecular or atomic beams are crystallized on the substrate surface
- Atomic species arrive at substrate with long mean free path- limited diffusion
- High oxygen fluxes necessary for oxide growth- ozone or atomic oxygen sources

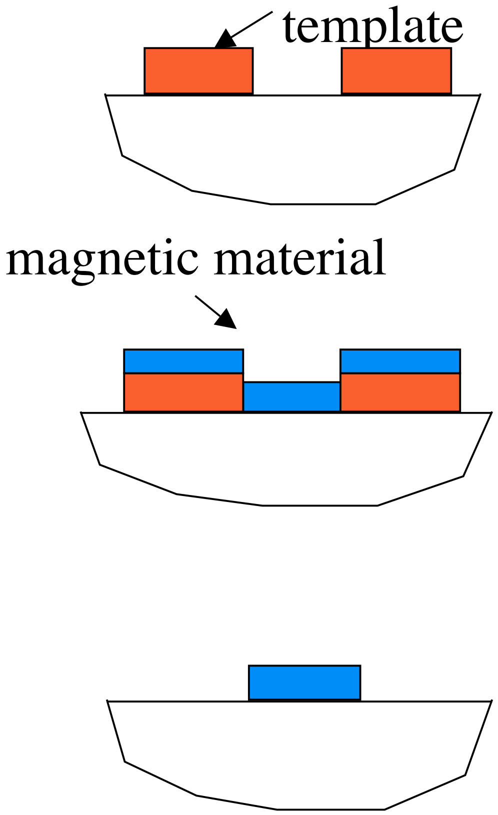


Molecular Beam Epitaxy

- Developing a layer-by-layer process
- Careful monitoring of deposition rates
- Role of defects in the properties of thin film materials
  - high Tc's
  - manganites

Lithography

- Additive patterning *does not require removal of magnetic material*

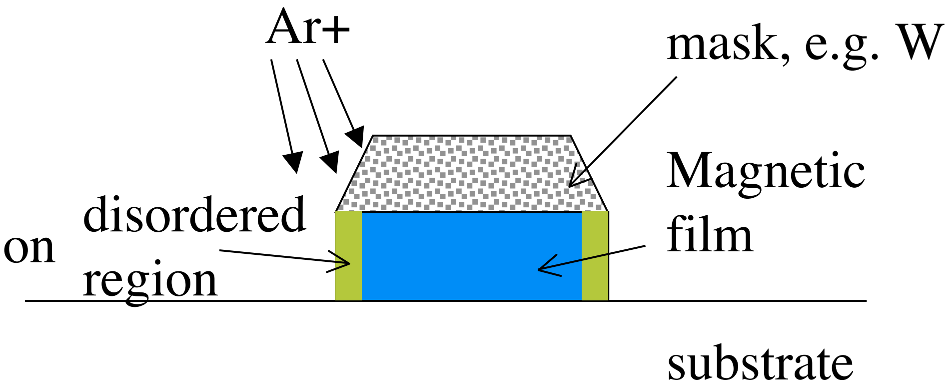


Deposit template

Deposit material on top of template

Remove template "lift-off"

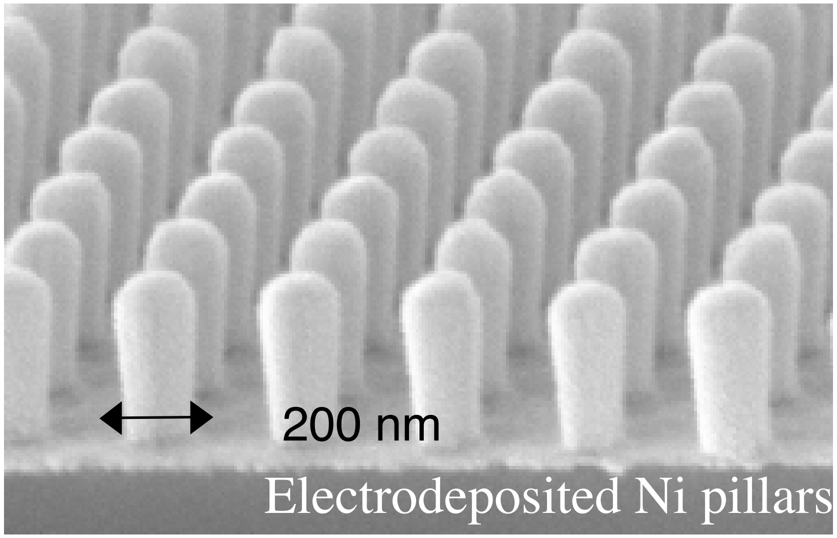
- Subtractive patterning *requires removal of magnetic material*



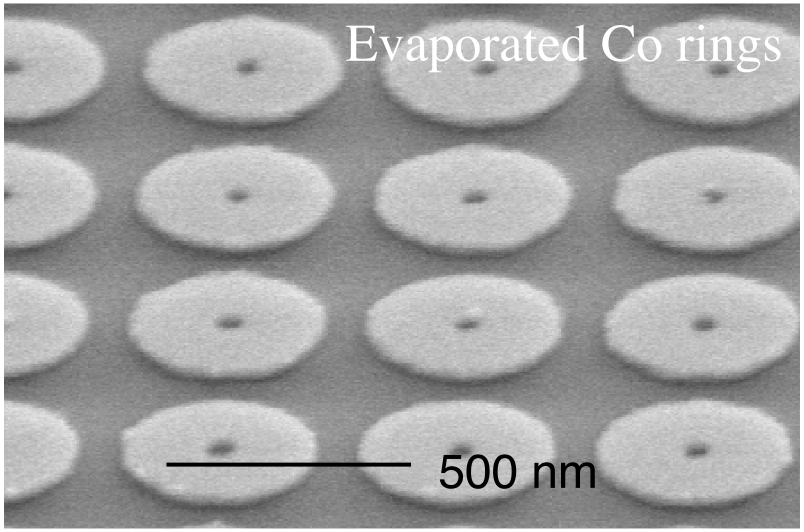
Caroline Ross (MIT)

Additive Patterning

- No removal of material
- Limited to deposition processes with bad step coverage
  - *Evaporation*
  - *Electrodeposition*
  - *Low pressure ion beam sputtering*
- Shadow masking for coarse features (~100μm)



Electrodeposited Ni pillars



Evaporated Co rings

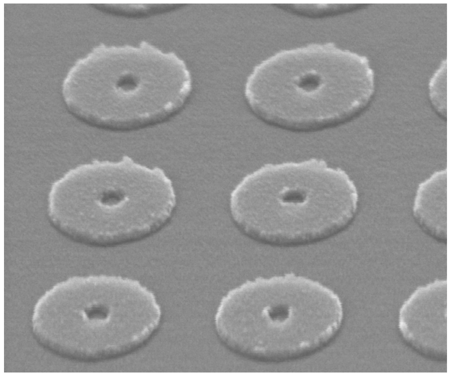
Caroline Ross (MIT)

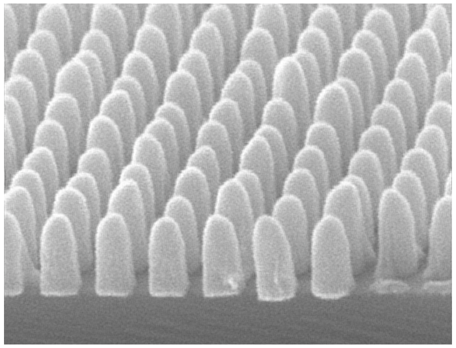
Subtractive Patterning

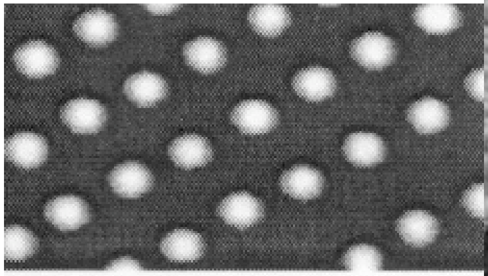
- Pattern magnetic material by a resist mask
- Flexibility in types of films to etch
- Etching of magnetic materials challenging
  - Chemical etching (*isotropic and thus not suitable for small structures*)
  - Reactive ion etching (*most magnetic materials resistant*)
  - Ion milling (*physical removal of material by ion bombardment causes damage*)

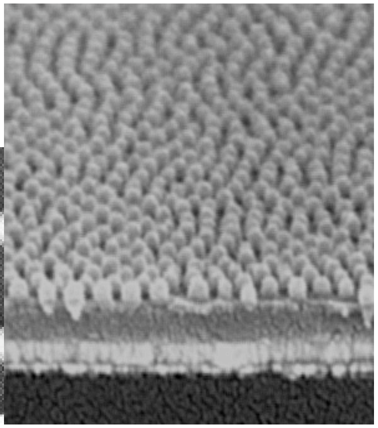
Lithography

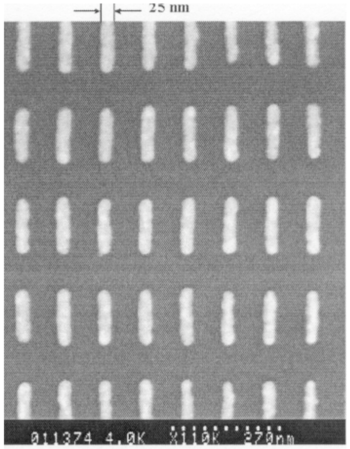
- Optical lithography
- Electron beam lithography
- Focused ion beam
- Interference lithography
- X-ray lithography

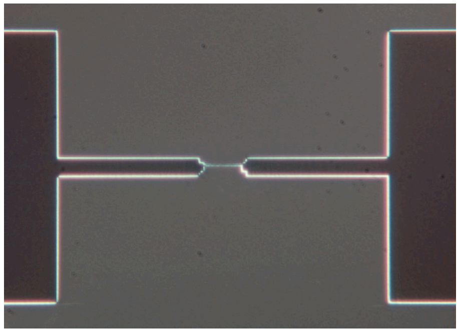








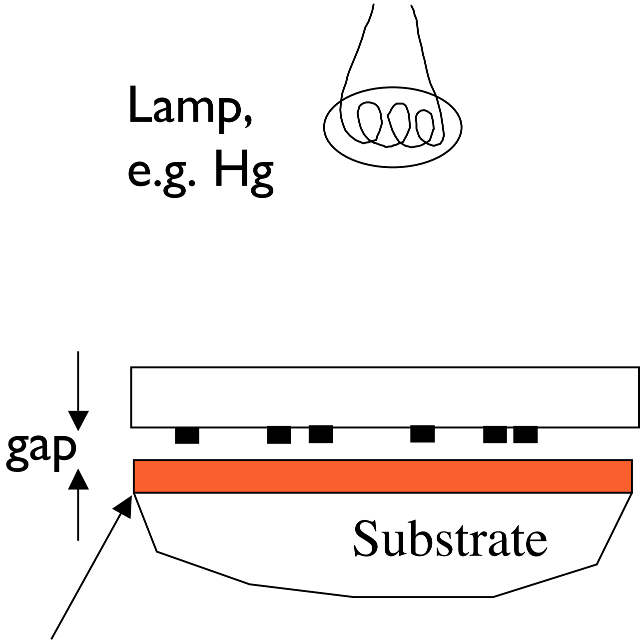




Optical Lithography

Contact printing

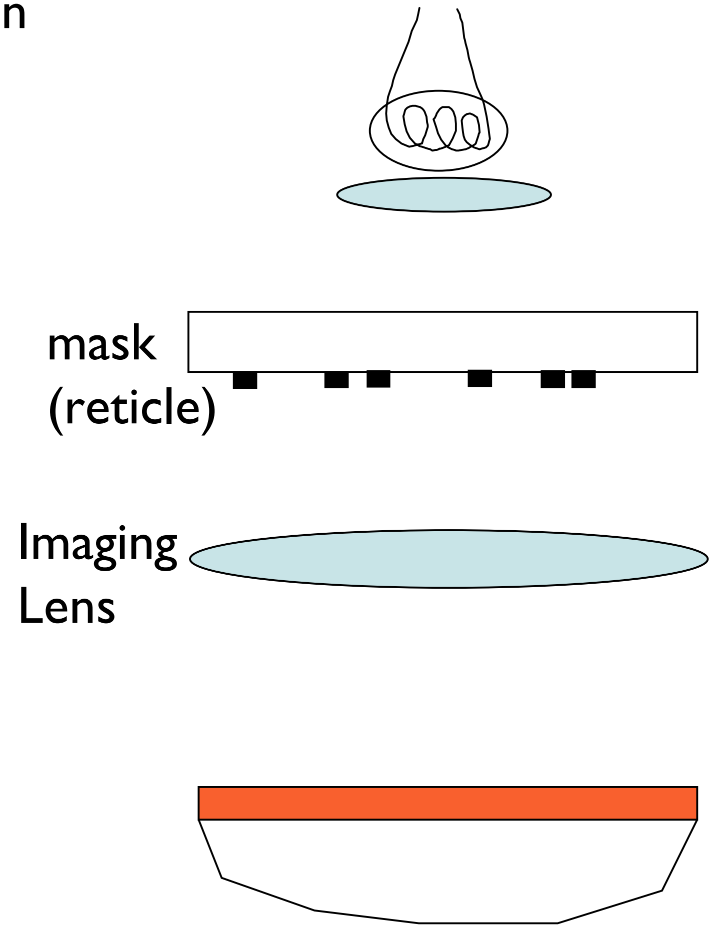
Pattern is same size as mask.
Mask-substrate gap determines resolution



mask: Glass with Cr or photographic pattern, or a laser-printed transparency

Reduction lithography

Mask features are reduced by e.g. 10x.



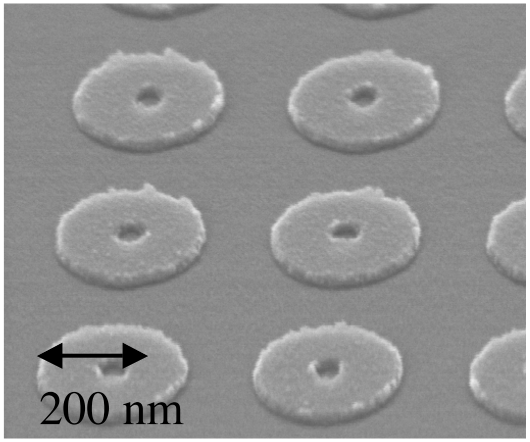
Caroline Ross (MIT)

Optical Lithography

- Feature sizes down to 0.5μm
- Reflective substrates can give rise to poorly defined resist edges
- Adhesion of resist to material is often poor
- Multi-level resists for a good undercut for improved lift-off

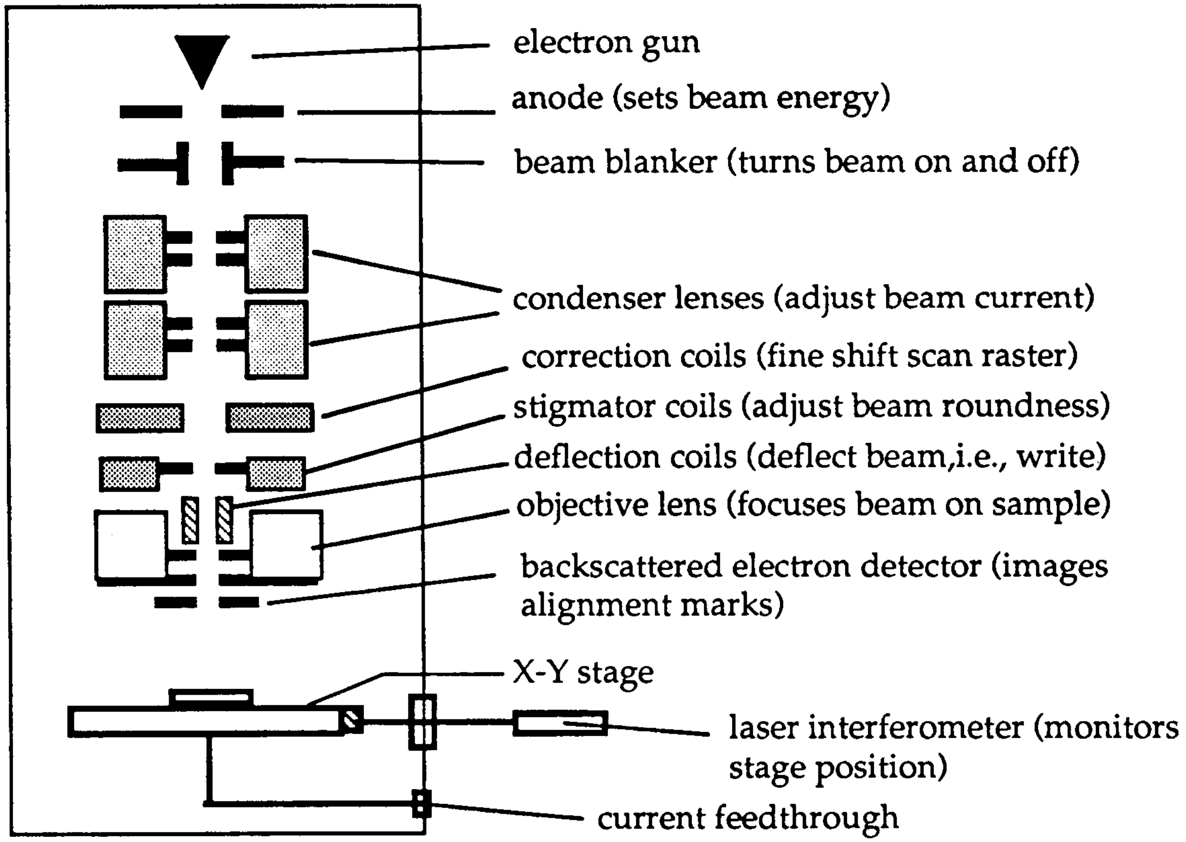
Electron Beam Lithography

- serial direct writing process
- feature sizes as small as 50nm



F.J. Castaño

SEBL system



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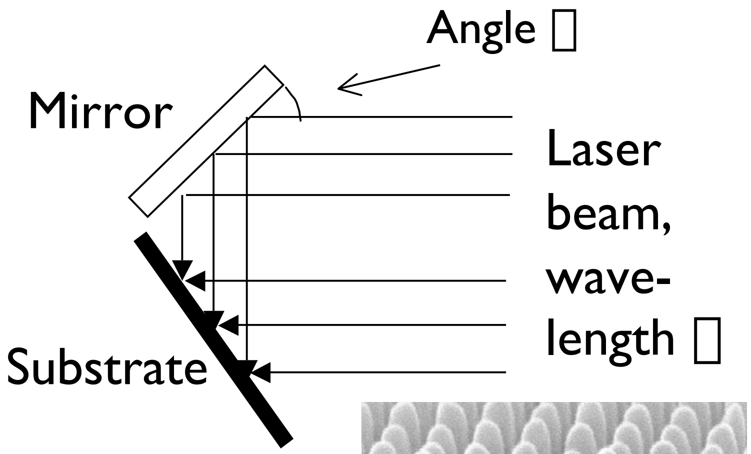
Electron Beam Lithography

- Serial writing process
- Features as small as 10nm with 5nm FWHM Gaussian beam spot size (Leica VB-6)
- Choose tone of resist to
  - Minimize writing area: positive (PMMA, KRS), negative (HSQ, NEB31)
  - Obtain requisite resolution: HSQ and PMMA for high resolution
  - Obtain requisite contrast: HSQ poor, PMMA excellent
  - Obtain requisite etch/mill resistance: PMMA etches rapidly
- Stitching areas (655µm field with 2.5nm step)
- Removability of resist
- Smoothly curved features are difficult
- Writing large and small features
- Proximity effect (due to backscattered e-) change the required exposure for closely spaced features

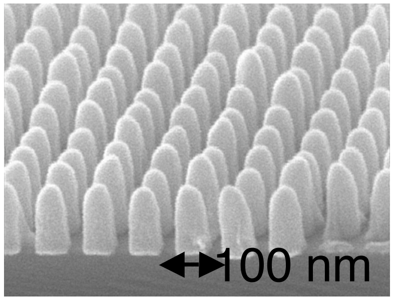
Other Lithographic Techniques

- ***Interference lithography***

Optical standing wave to create gratings with period □/2



Laser beam, wave-length □



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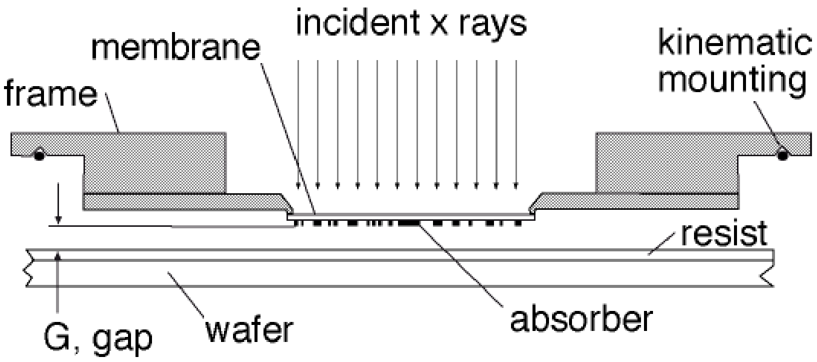
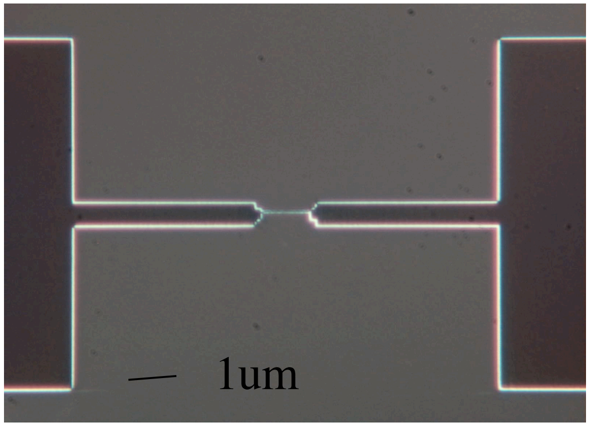
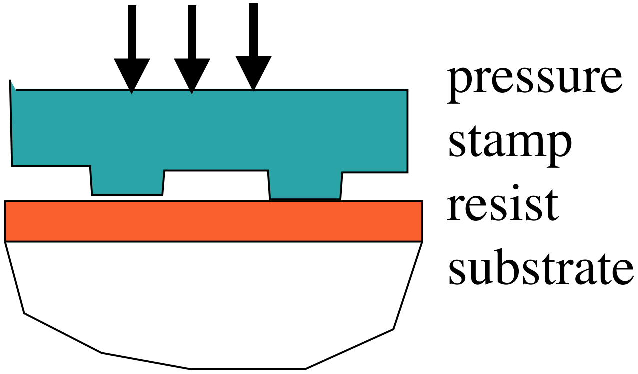
- ***X-ray lithography*** □=0.4-4.5nm

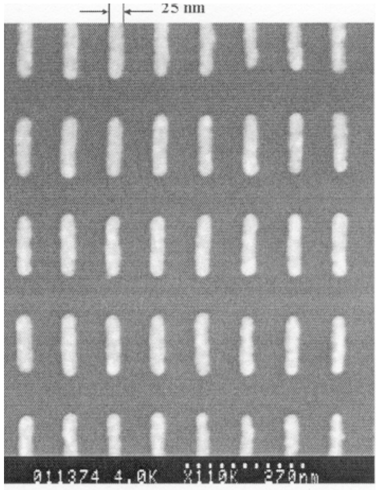




Other Lithographic Techniques

- ***Imprint lithography***

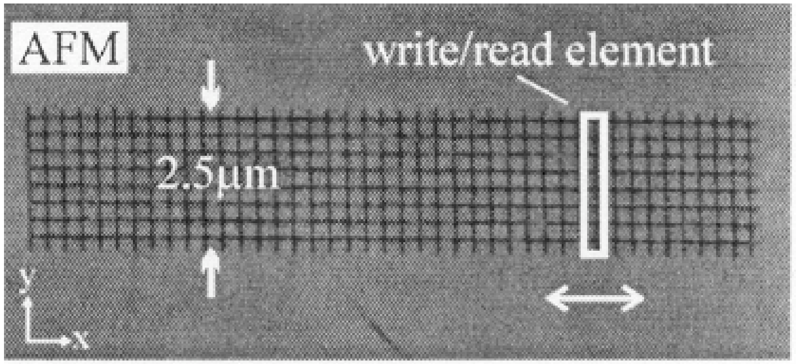




25 nm wide bars made by imprint lithography.
Wu et al, JVSTB 16 3825 (1998)

- ***Focused Ion Beam Lithography***

Serial direct writing process by ion milling with Ga^+ beam

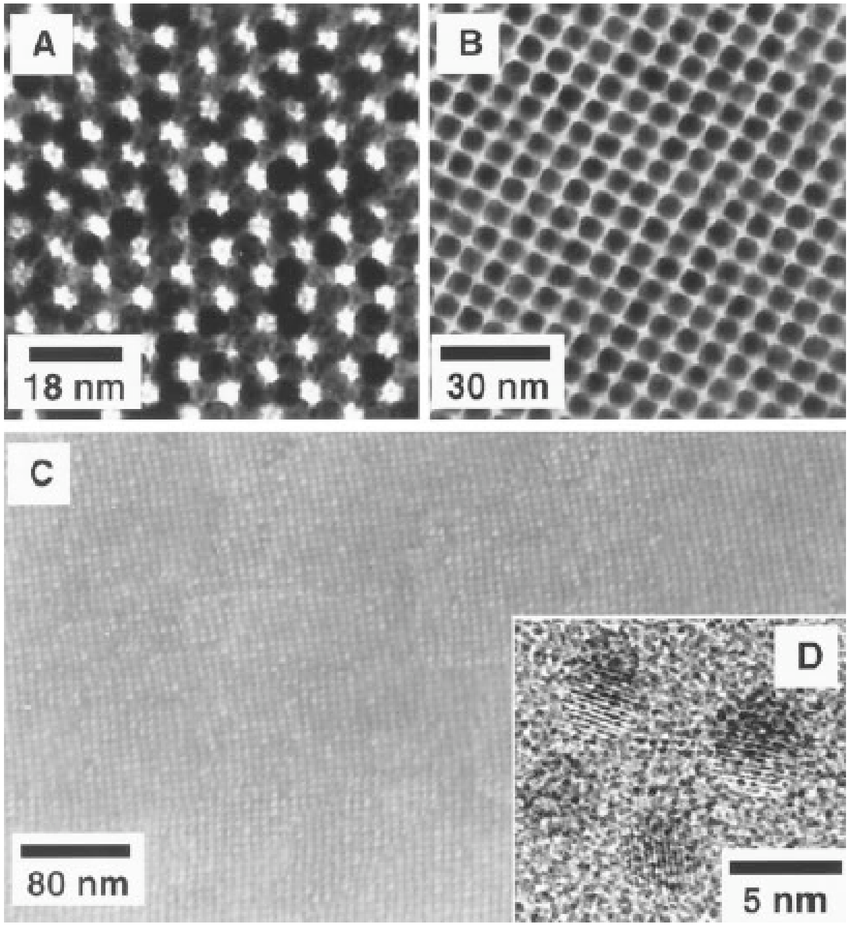


250 nm islands defined in a film by a FIB.
Lohau et al, Appl Phys Lett 78 990 (2001)

Self Assembly

- Diblock copolymers
- Colloidal suspensions
- Precipitation

Synthesis of Magnetic Particles

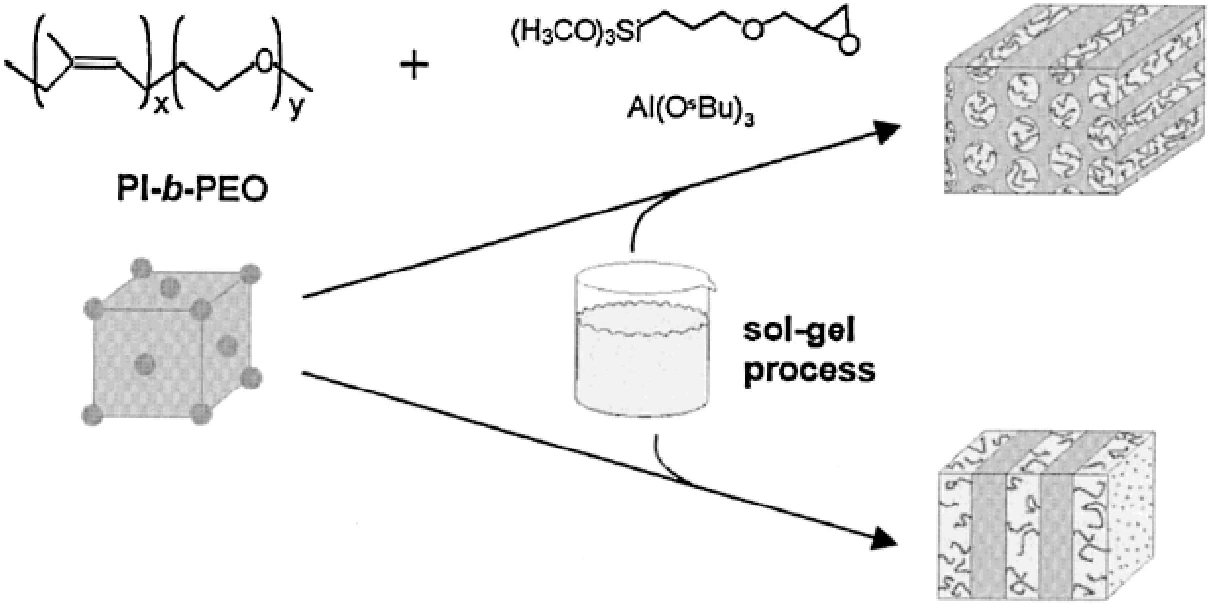


Monodispersed FePt colloids from “polyol” process

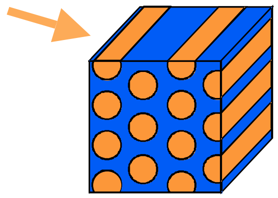
Sun et al. Science
287 1989 (2001)

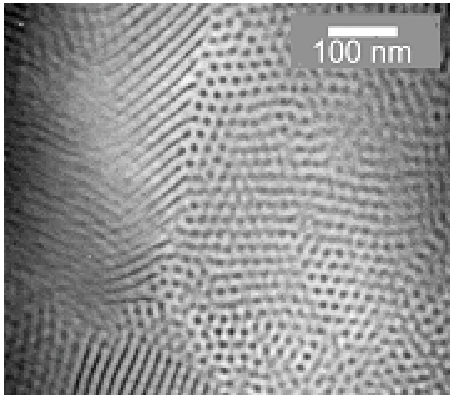
Synthesis of Magnetic Particles

Diblock Copolymers



Iron doped silica





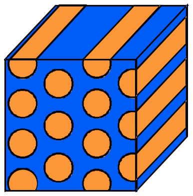
Magnetic cylinders
in an organic matrix
via self assembly

Simon et al., Chem. Mater. 13 3464 (2001)

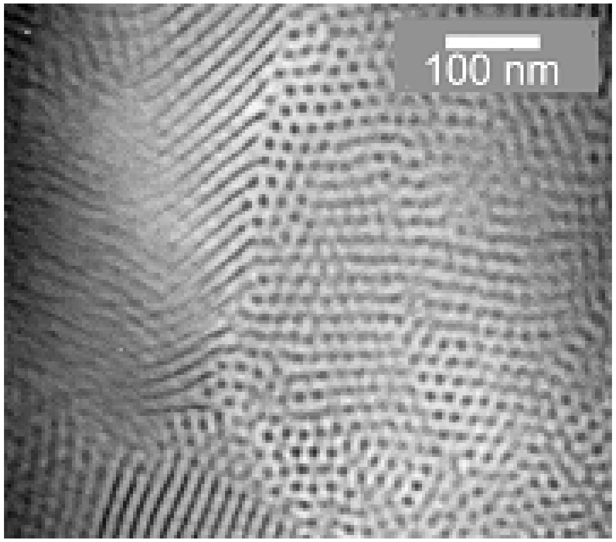
Synthesis of Magnetic Particles

Magnetic Nanocylinders

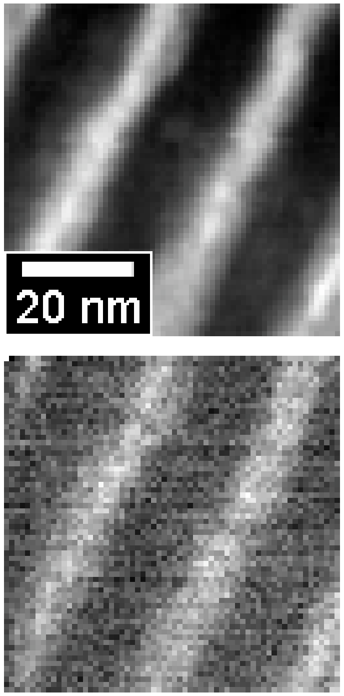
TEM



25 mol% Fe

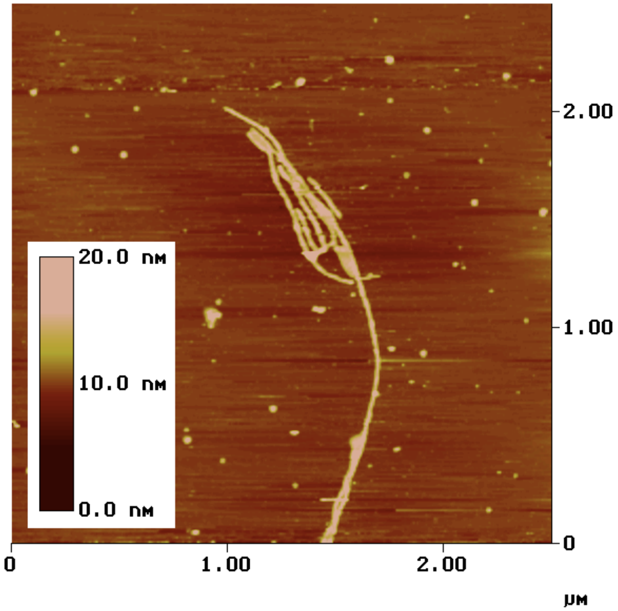


STEM



Energy Filtered for Iron (EELS)

AFM



Wiesner et al. (unpublished)

Lectures on Fabricated Magnetic Structures

- Synthesis and fabrication techniques for magnetic structures
- Magnetic behavior in small magnetic structures
  - Review of fundamentals: energies, interactions
  - Magnetization process
  - Examples from the literature
- Magnetic Junction Devices

References

- Robert C. O'Handley, "Modern Magnetic Materials: Principles and Applications," Wiley Interscience, New York, NY (2000).
- Soshin Chikazumi, "Physics of Ferromagnetism," Oxford University Press,Oxford, U.K. (1997).
- B.D. Cullity, "Introduction to Magnetic Materials," Addison-Wesley Publishing Co., Reading, MA (1972).
- Nicola Spaldin, "Magnetic Materials: Fundamentals and Device Applications," Cambridge University Press, Cambridge, U.K. (2003).