The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
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IAEA
International Atomic Energy Agency

1866-3

School on Pulsed Neutrons: Characterization of Materials

15 - 26 October 2007

Nanostructured Materials

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Nanostructured Materials

23. October 2007

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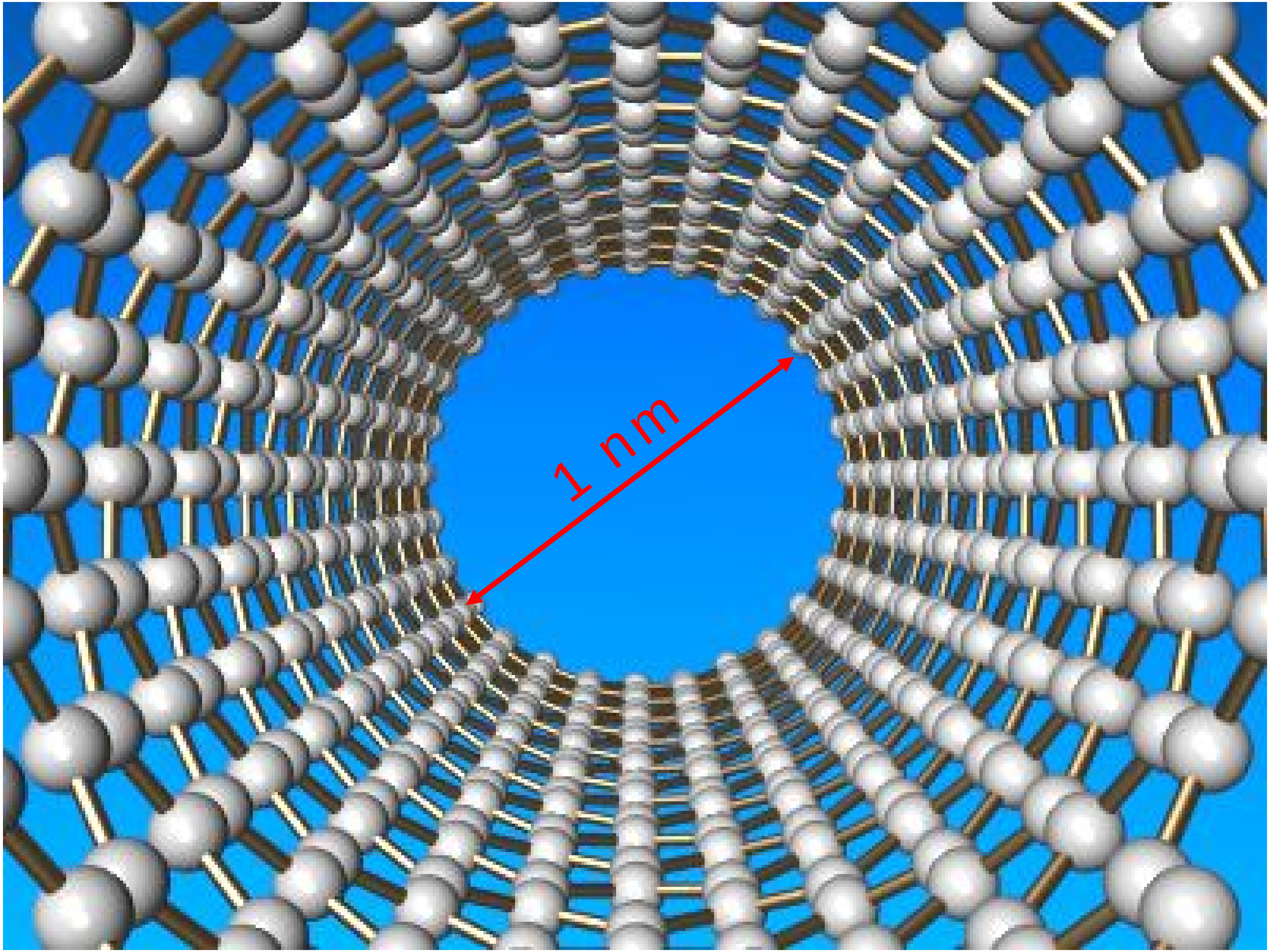
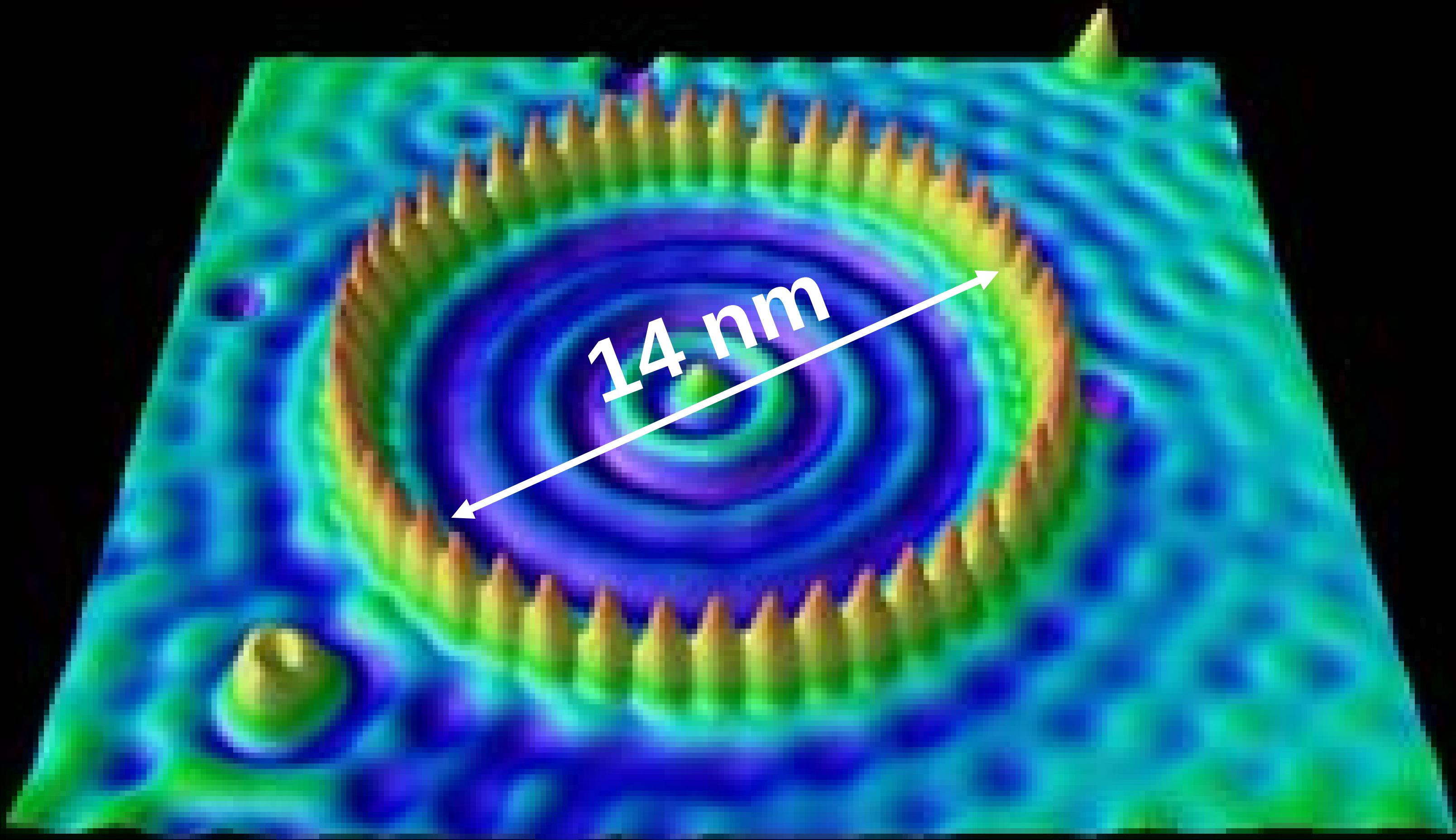
School on Pulsed Neutron Sources

Trieste - Italy, 15 - 26 October 2007


1 nm

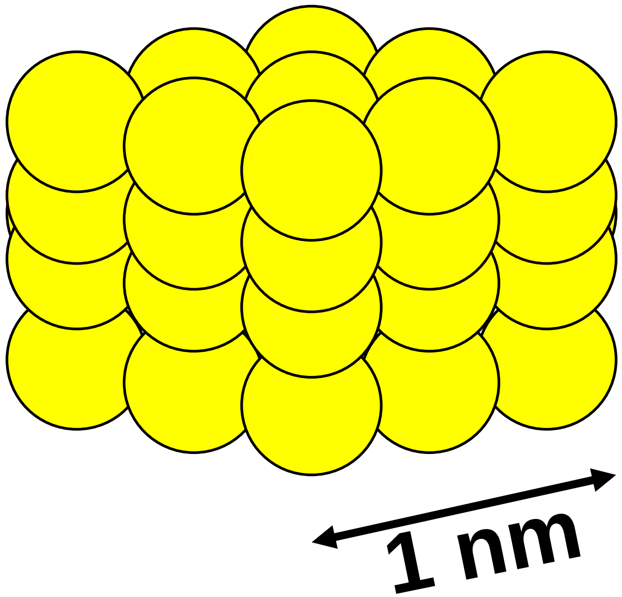
Fe - atom collar



D. Eigler. IBM, Almaden

Things are different at the nanoscale

Nano-Cube



50 – 100 atoms

Structure?

Metal?

Semiconductor?

Superconducto?

Magnetic?

Transparent?

When things get small....

http://ischuller.ucsd.edu/movies/

Nanostructures

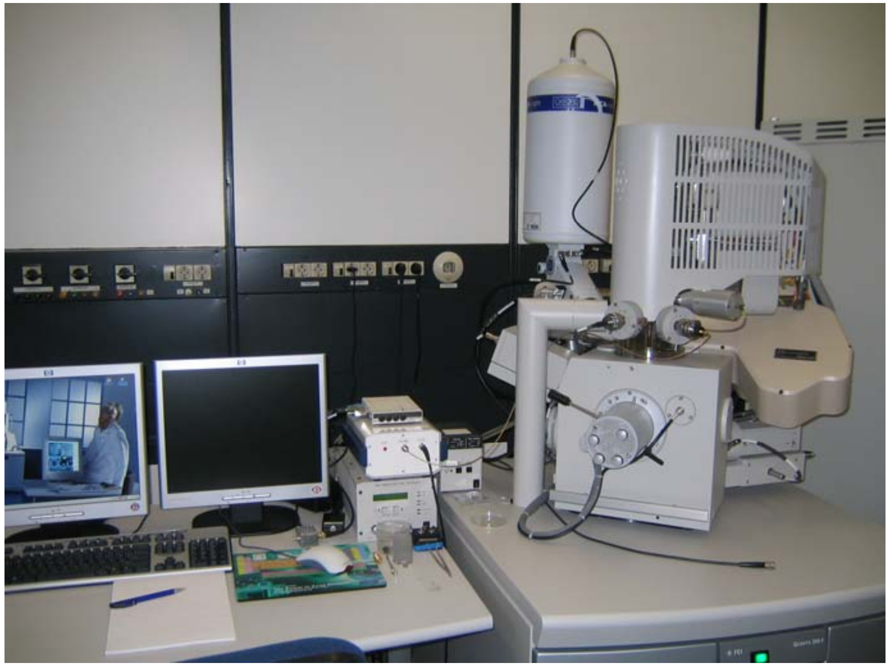
Top-down approaches (scanning control):

- lithography
- atomic force microscopy

Bottom-up approaches (self assembly):

- dendrimers
- molecular arrangements (e.g. micelles)
- approaches of molecular biology

Lithographic tools



Lithography:
Laser, e-beam, focused ion beam, x-ray, AFM cantilever

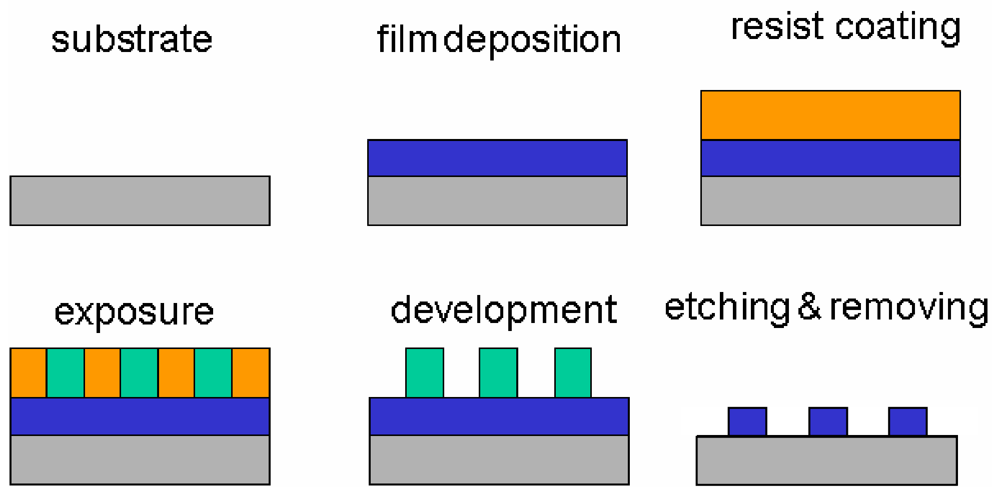
Etching:
Wet, dry, ion beam, plasma

Resin, spin coating, annealing, etc.

Lithographic sample preparation

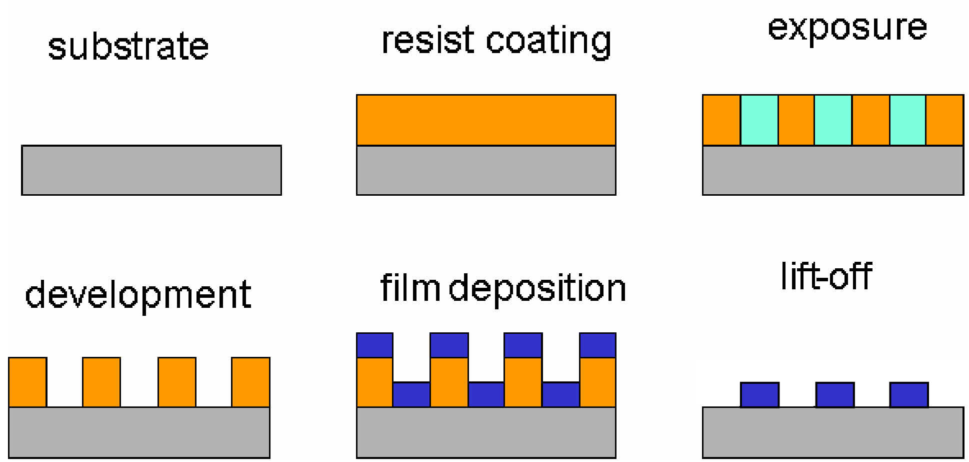
Negativ resist

“writing“



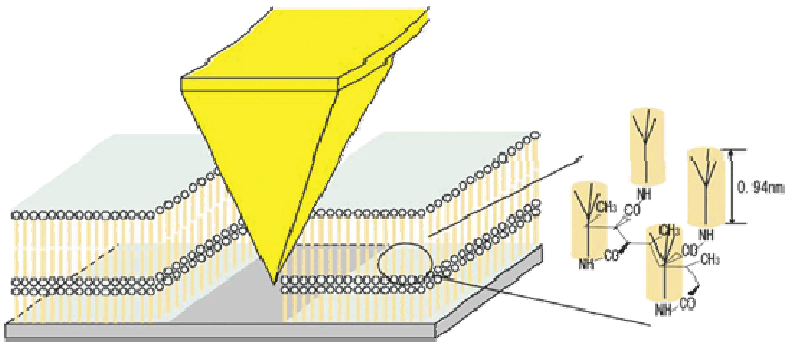
Positiv resist

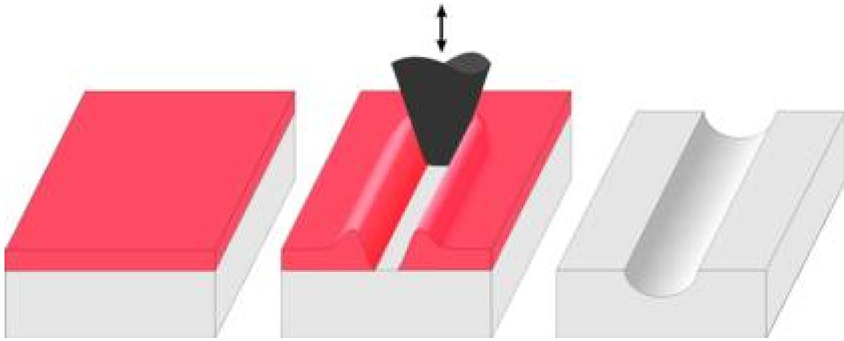
“engraving“



AFM lithography

Carving in the PMMA



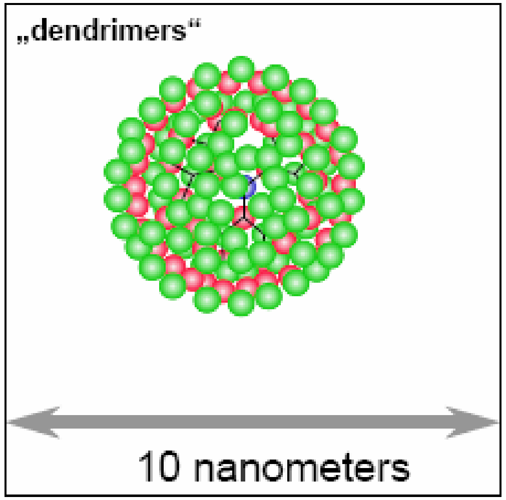


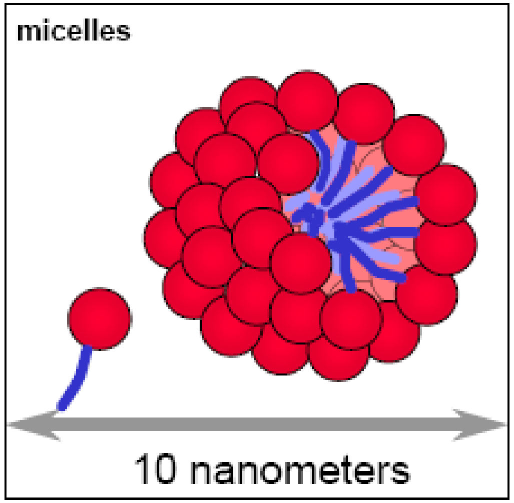
The AFM is operated in the tapping mode where the tip vibrates against the sample surface. Full penetration is obtained at an amplitude which is enhanced by a factor of typically 5-12 compared to imaging mode. Commercial Si tips with 5-10 nm radius of curvature can be used for lines up to 1 mm length.

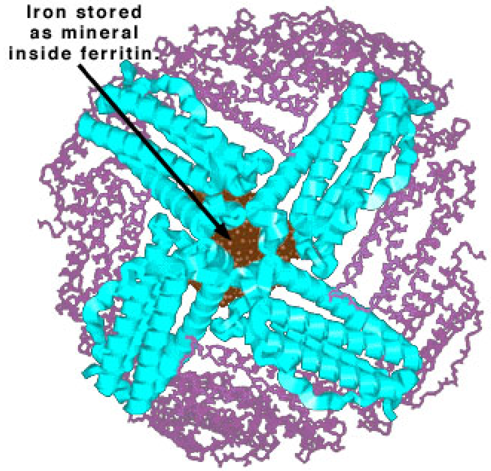
U. Kunze, Nanolab, RUB, Bochum

T. Mikayama, et al. *Polym. J.*, **37**, 854 (2005) .

Alternative techniques I: molecular self-assembly to defined structures







The advantages of molecular self-assembly:

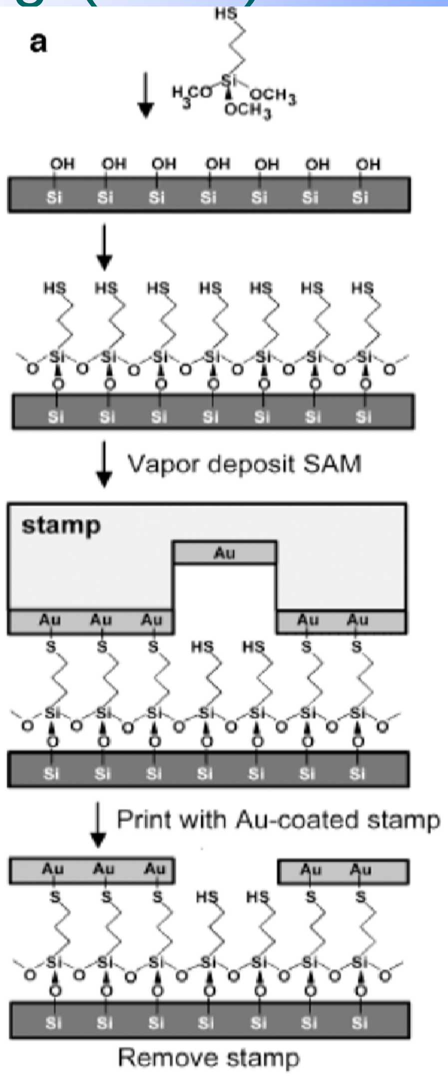
- directly nm-sized technique by assembly of molecules to defined structures
- potential for better versatility
- 3-dimensional structures possible
- imitation of structures of nature

Alternative techniques II:
Nanotransfer printing (nTP)

Schematic representation of the nanotransfer printing (nTP) procedure to create gold patterns on Si substrates.

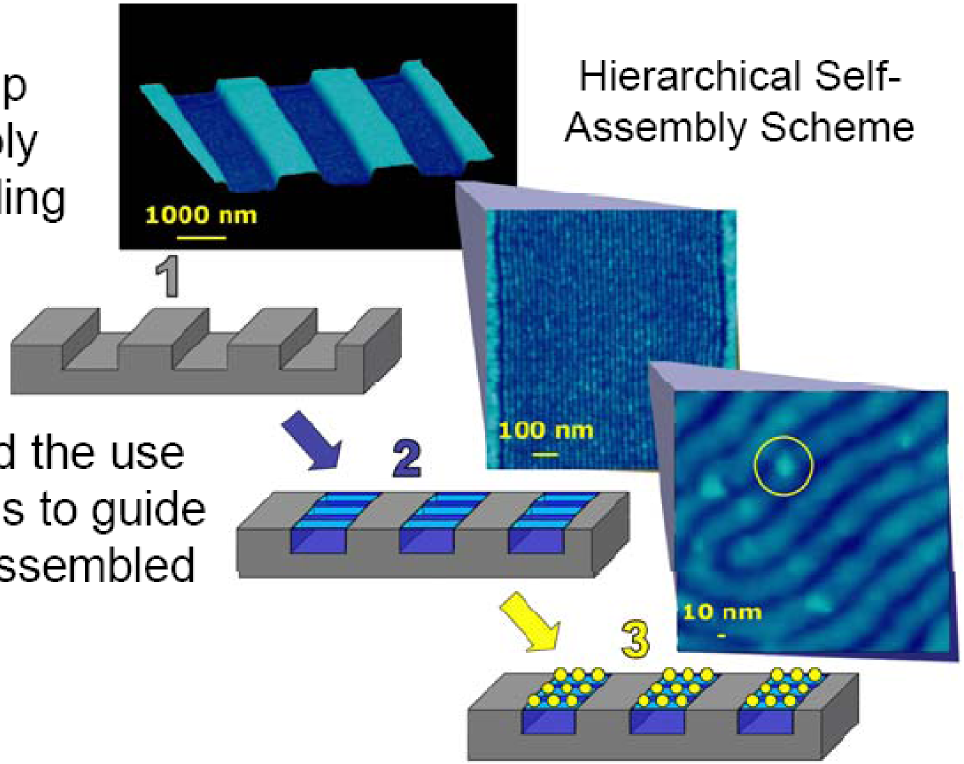
NOTE: stamp is fabricated by top-down lithography.

From H. Lipsanen



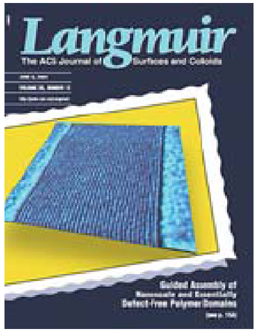
Alternative techniques III:
Polymeric Templating of Magnetic Nanostructures

- A combined top-down/bottom-up hierarchical approach is arguably the most powerful route to building nanostructures



Hierarchical Self-Assembly Scheme

- We have demonstrated the use of lithographic channels to guide the alignment of self-assembled polymer domains

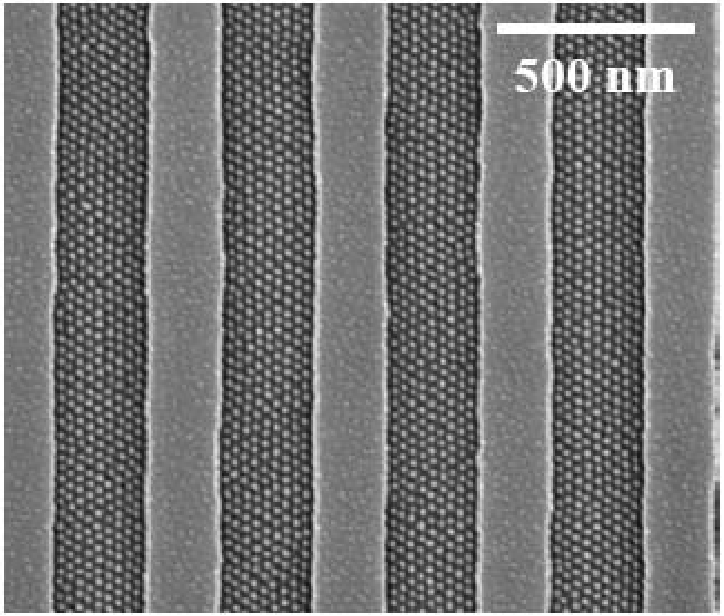


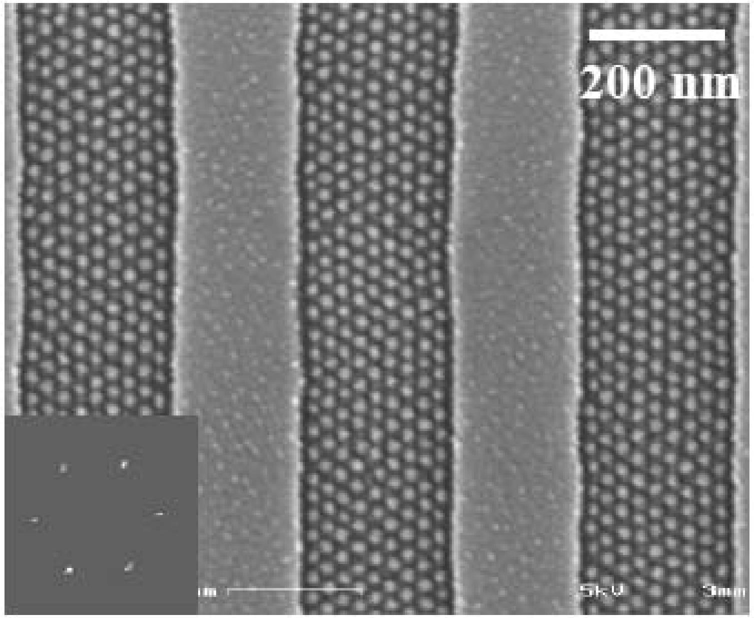
- Next, we aim to use these aligned scaffolds as templates for the organization of functional magnetic nanoparticles

http://www.msd.anl.gov/highlights/docs/darling_polymeric_hl.pdf

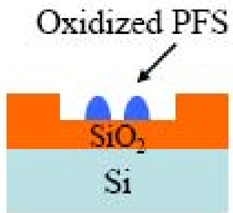
S.B. Darling, S.D. Bader, A. Samia, X.-M. Lin, J. Schlueter, ANL, USA

Templating with polymer stripes and grooves





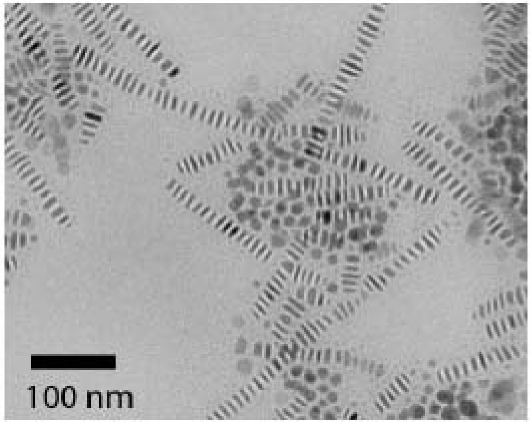
- Long-range ordered block copolymers inside the groove.
- No grain boundaries observed.
- Polymer domains align with the groove edge.
- 9 rows of polymer domains in a 230 nm wide groove.



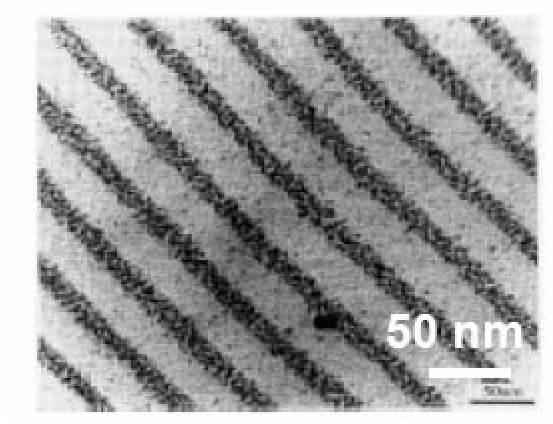
From E.L.Thomas, C.A. Ross, MIT

Assemblies of magnetic nanoparticles

8 nm Co nanoparticles in cylindrical Al_2O_3 pores



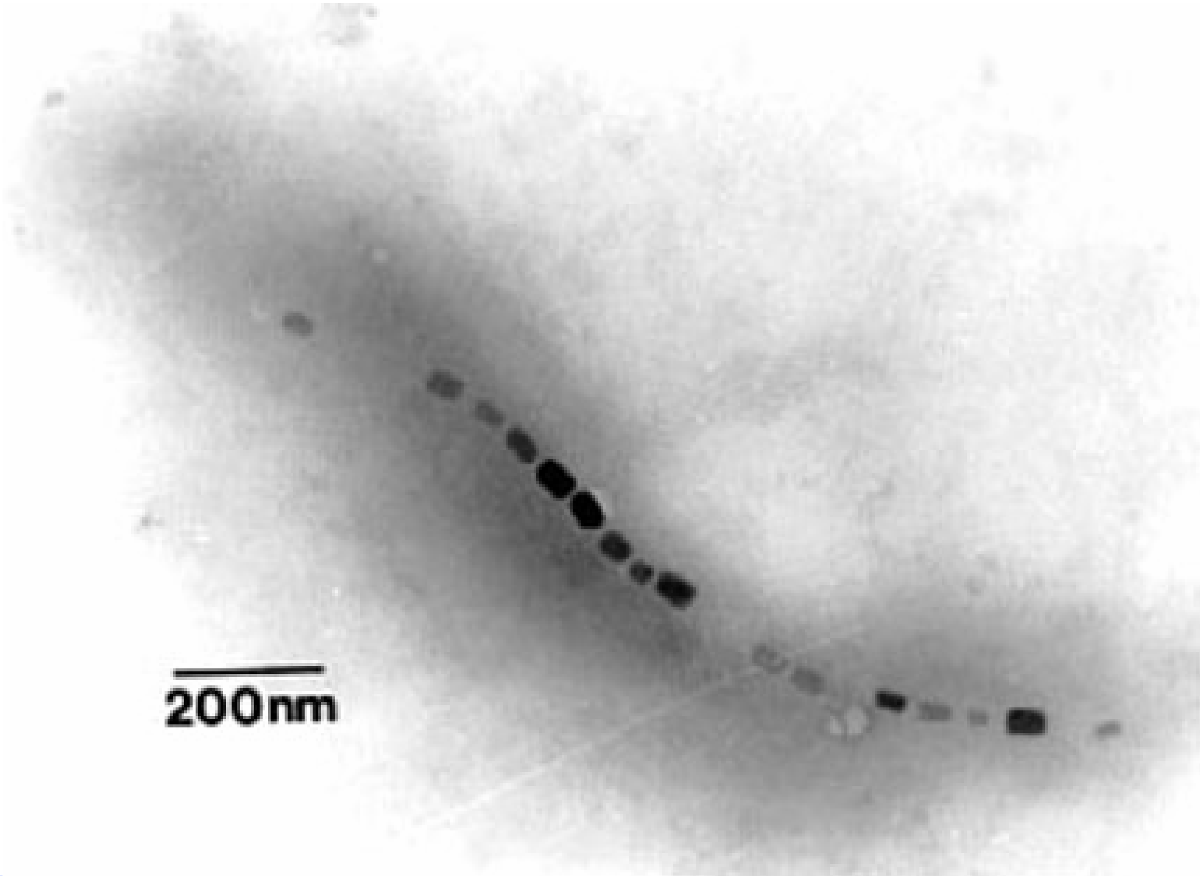
Self-assembly of Co nanodiscs

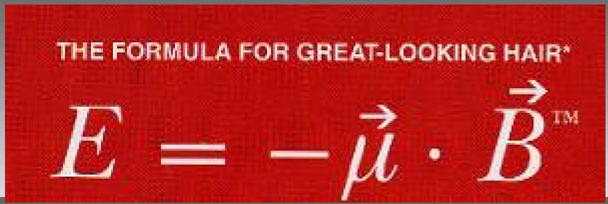


Polymer-templated assembly of 5 nm Co nanospheres

Meigan Aronson, Sue Inderhees, Omar Yaghi, Jinsang Kim, Nick Kotov, and Glenn Strycker, University of Michigan, Ann Arbor

Magnetosome bacteria



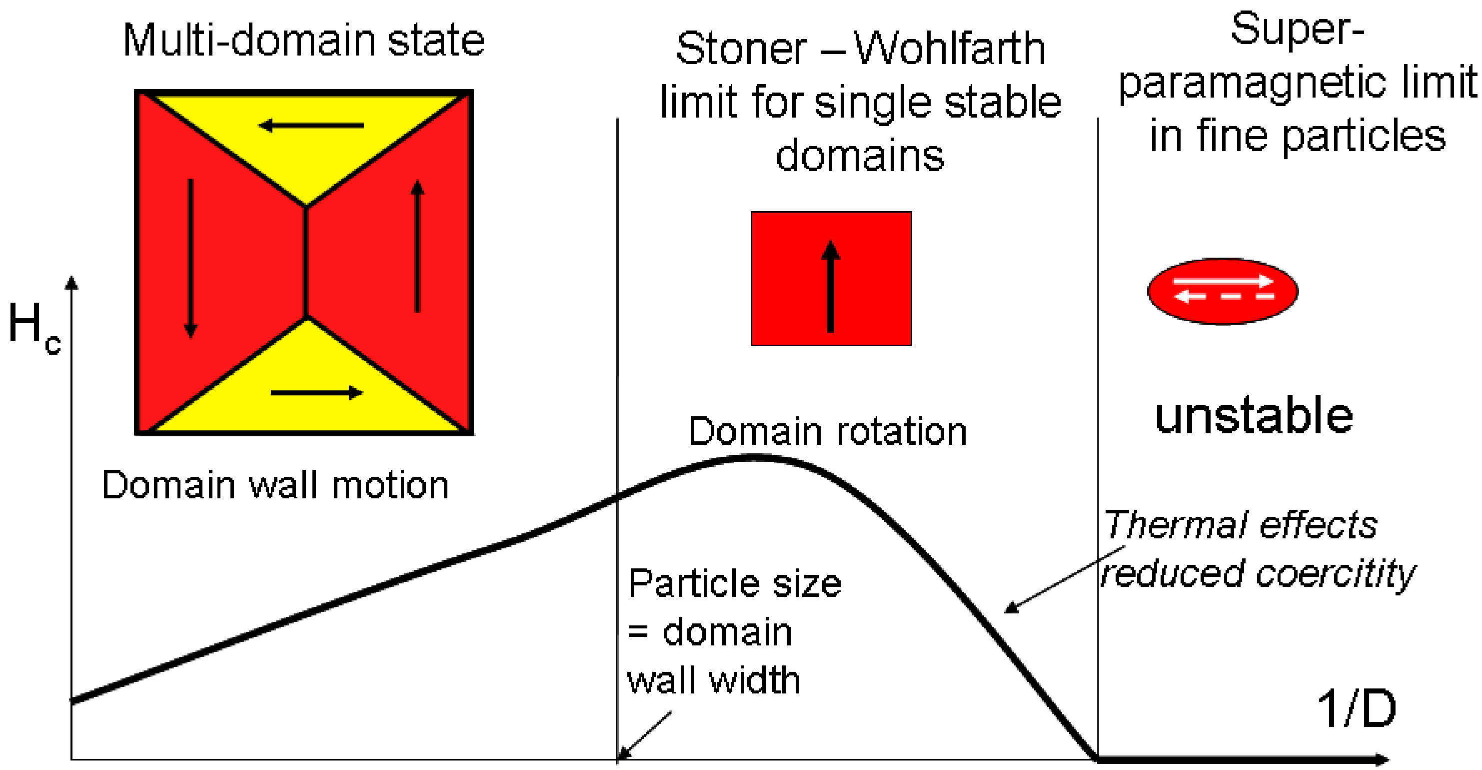


Warning: $E = -\vec{\mu} \cdot \vec{B}$ is trademarked.

Magnetic domains

Brown's Fundamental Theorem:

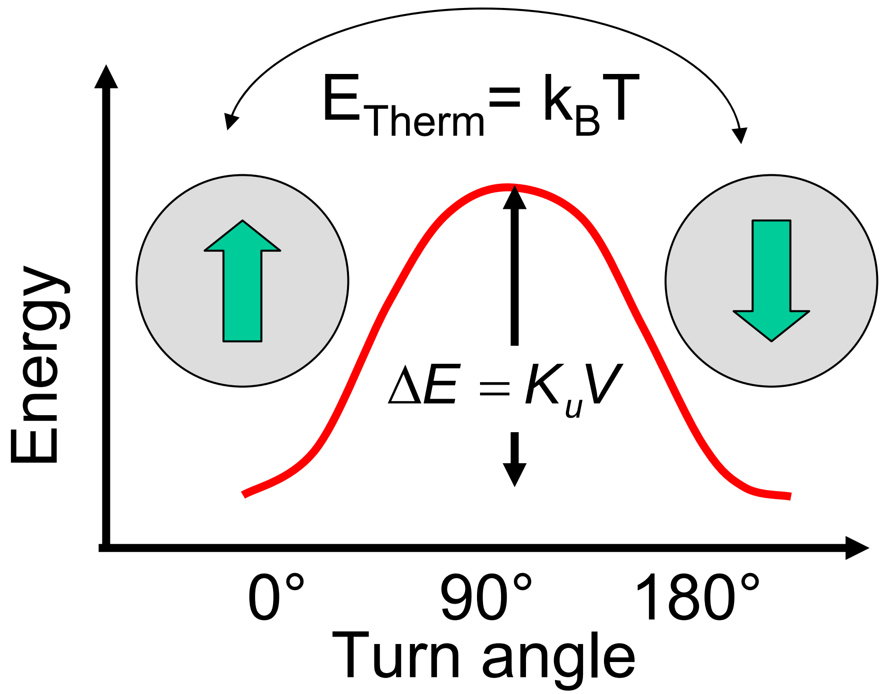
'As a magnet is reduced in size, there should be a point where exchange dominates over demagnetisation and where the magnet must, hence, adopt the single-domain state.'
(W.F. Brown, JAP 39, 993 (1968)



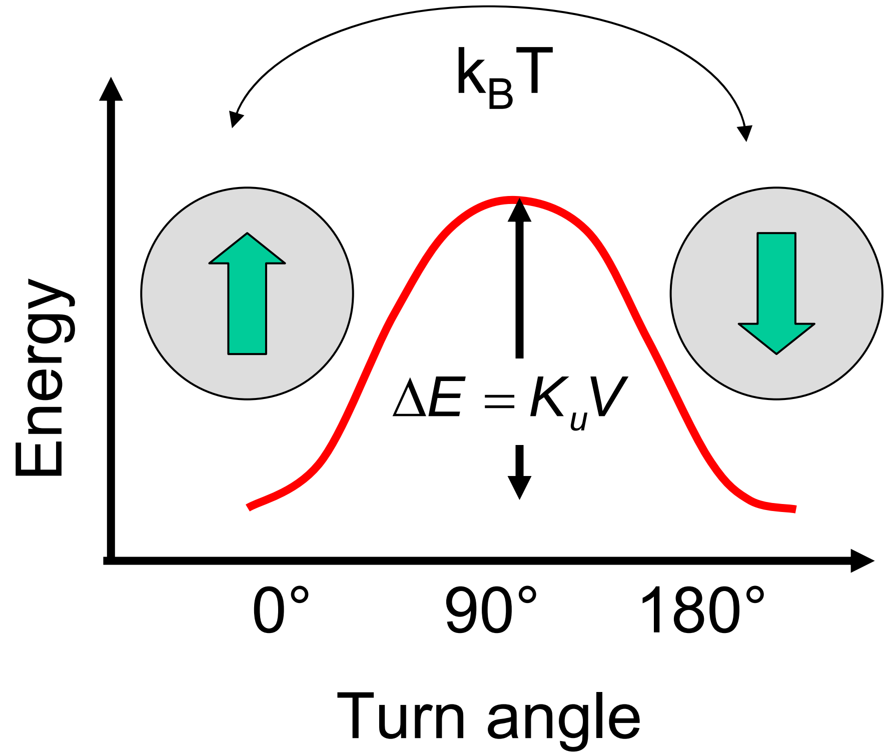
Two stable degenerate states

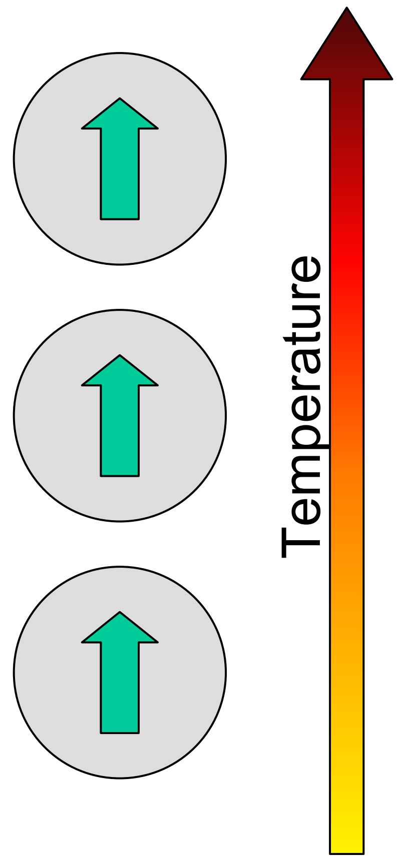
Anisotropy keeps magnetization aligned in one or the other direction.

Switching costs energy



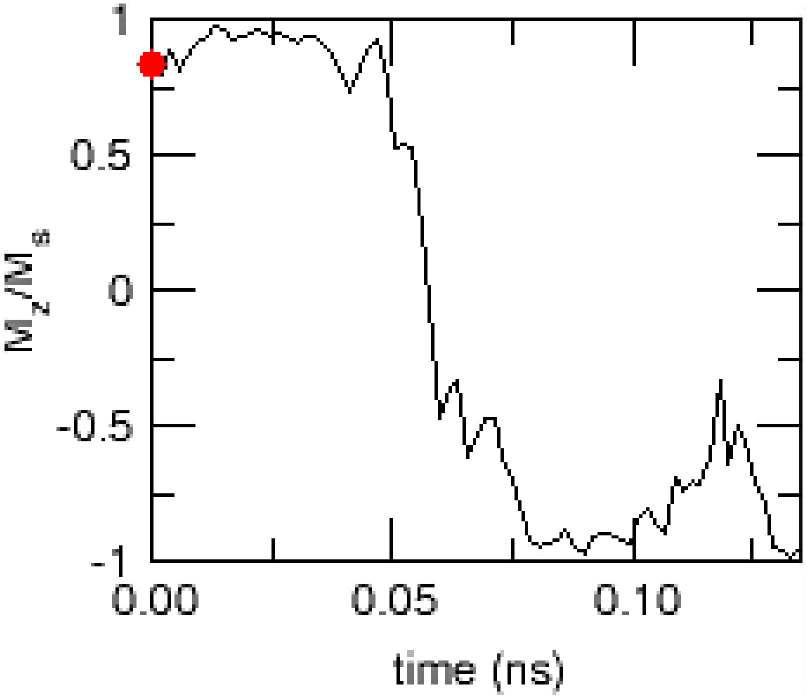
Superparamagnetism

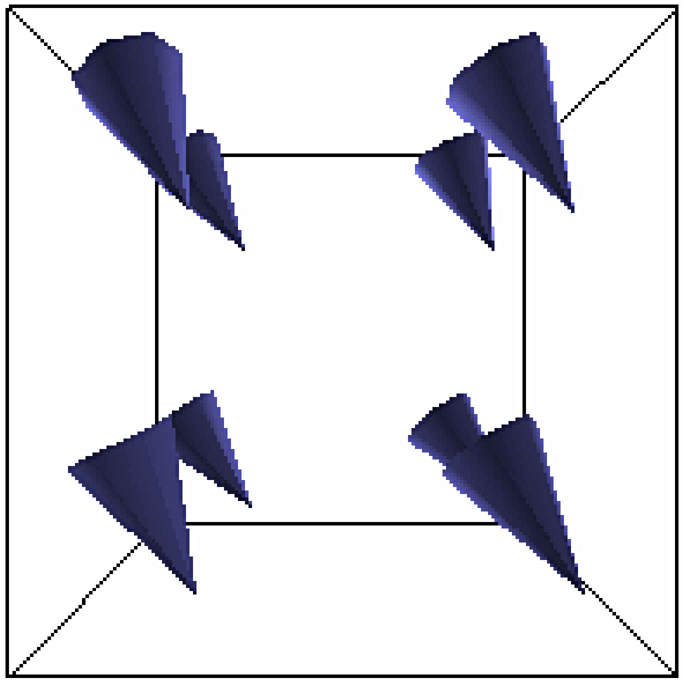




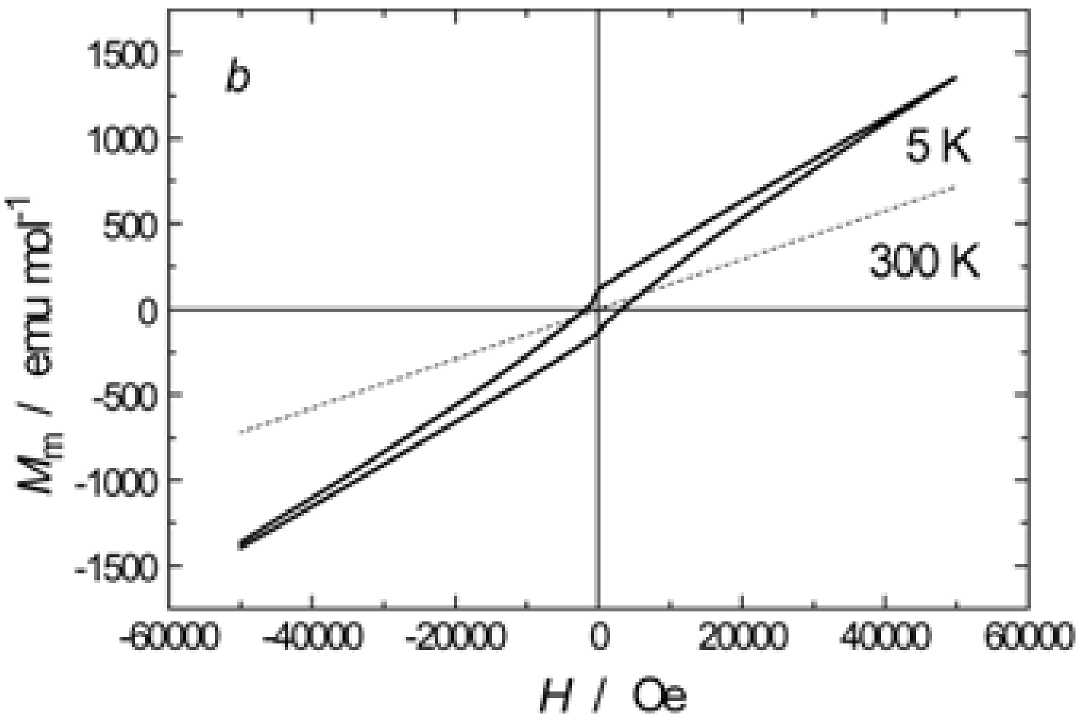
Life time: $\tau = \tau_0 \, exp\left(\frac{K_u V}{k_B T}\right)$

Thermal switching





Ferromagnetism versus Superparamagnetism

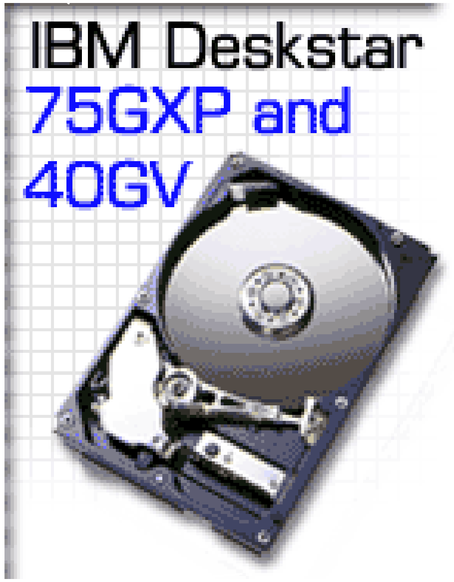


Scaling

5 Mbyte

70 kbits/s
2 kbits/in^2
50x 24 in dia disks
$10,000/Mbyte
1973

40 Gbyte
75 Gbyte

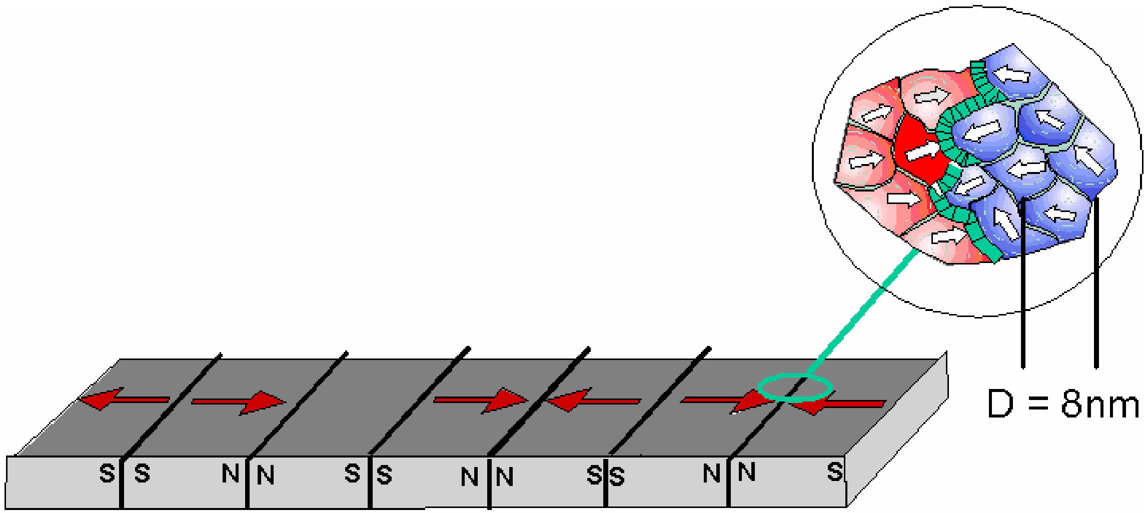


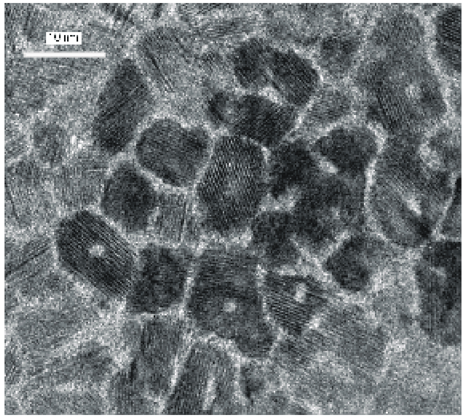
372 Mb/s
14.3 Gbits/in^2
2 x 3.5"glass disks
$0.01/Mbyte
2000

1 Gbyte

Microdrive
1999
15.2 Gbits/in^2
1 x 1" dia disk

Writing track





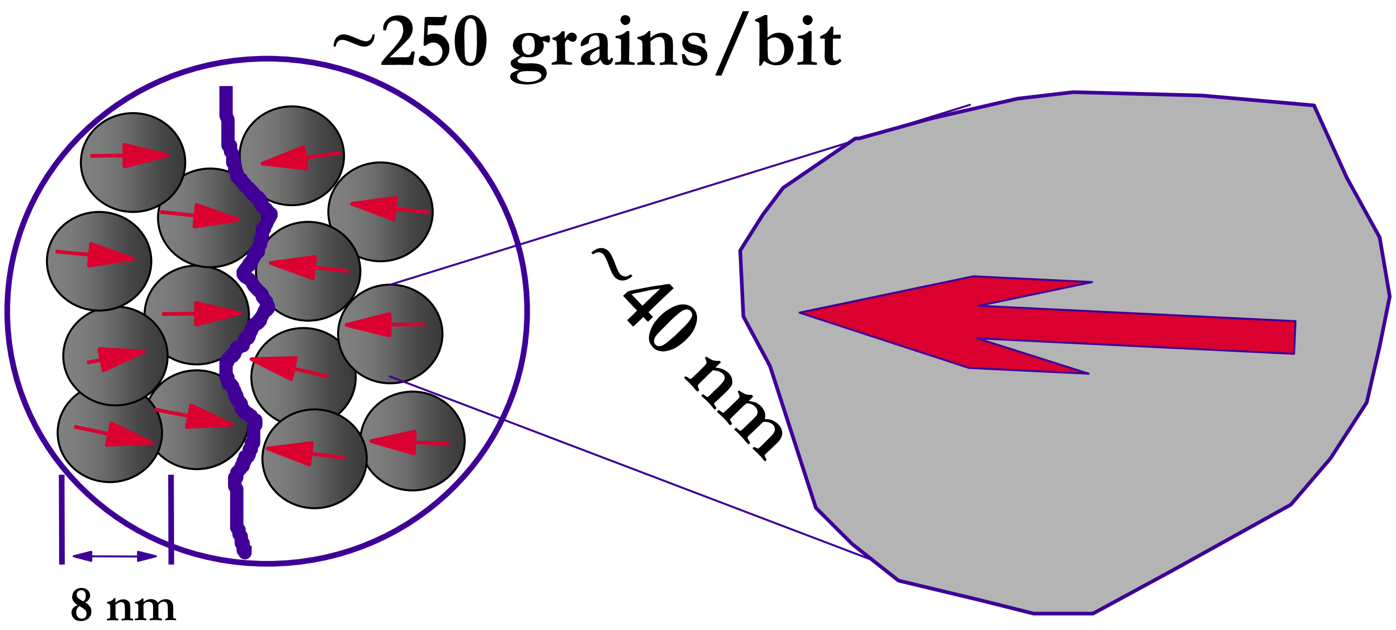
TEM picture of grains in a disk

Crucial parameter for the bit size and bit separation is the grain size D and the coercive field H_c.

With grain size of 8 nm and bit size of 40 nm = 250 grains/bit), storage density of 25 Gbite/in^2 can be reached.

Number of grains must stay constant to keep signal – noise ratio.

Superparamagnetic effect



Anisotropy energy per grain (for 10 year stability):

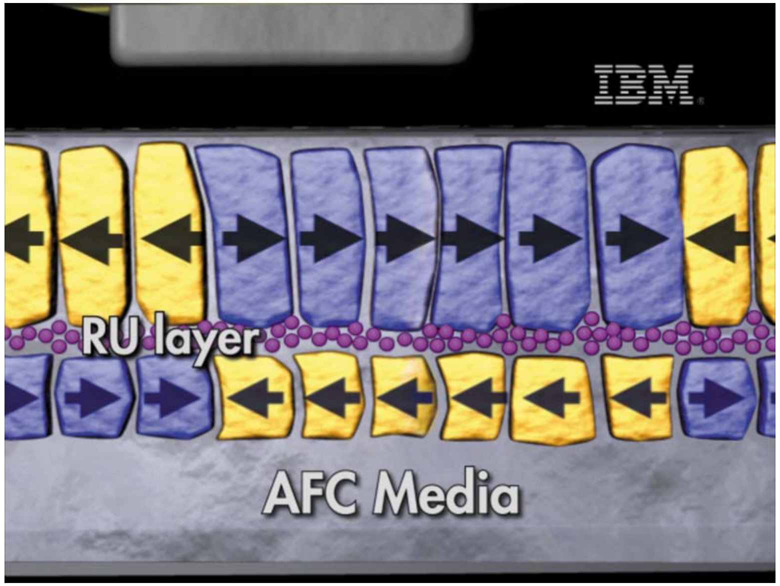
$E = K_U V > 55\ k_B T$, coercivity $H_c = K_U/M < H_{head}$

The product $K_U V$ must stay constant. If V is reduced for higher density, K_U must be increased.

Disk development at IBM

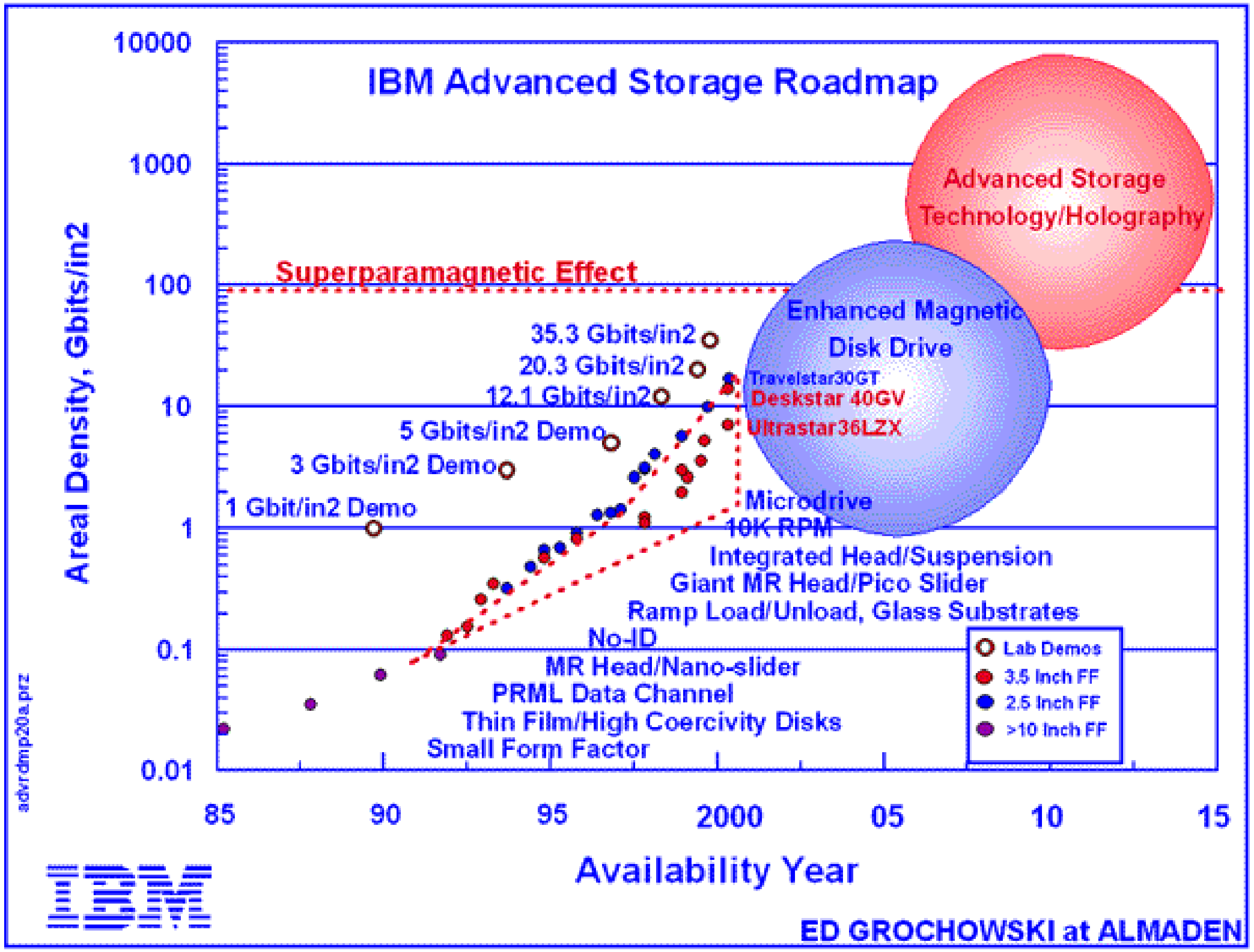
present: 35 Gb/in^2

future: more than 100 Gb/in^2

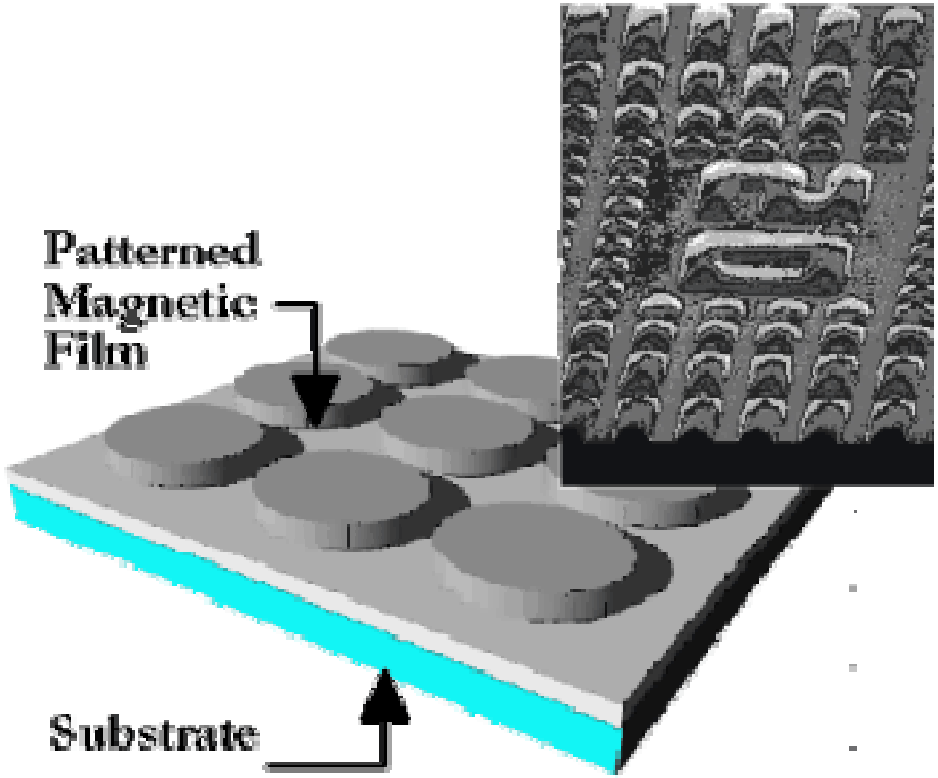


Antiferromagnetic coupled bits
to enhance the coercivity

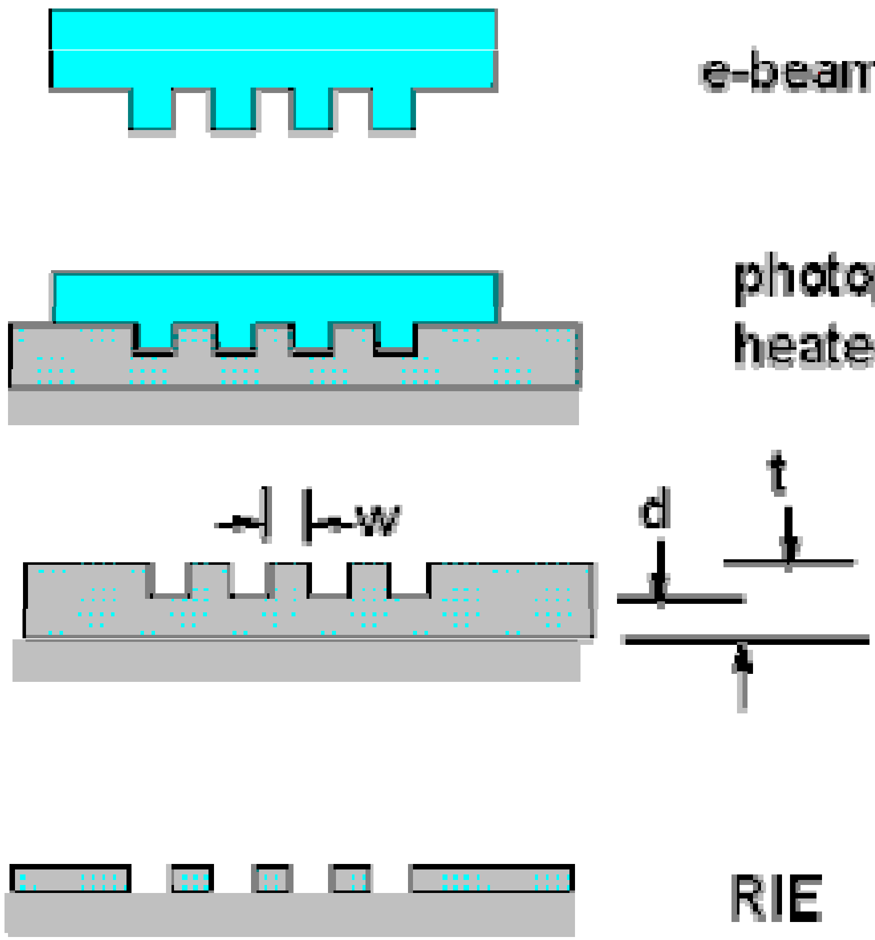
New approaches for increasing storage density



Patterned magnetic films, Hitachi

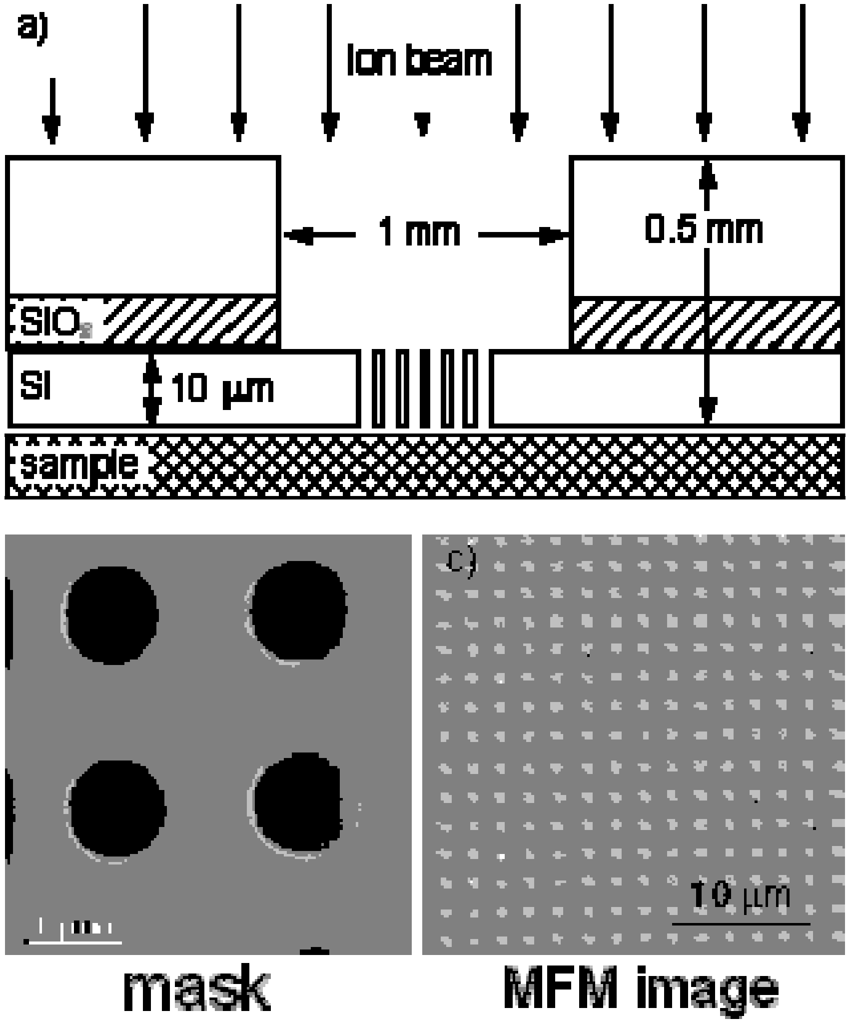


Stamping technique, Hitachi



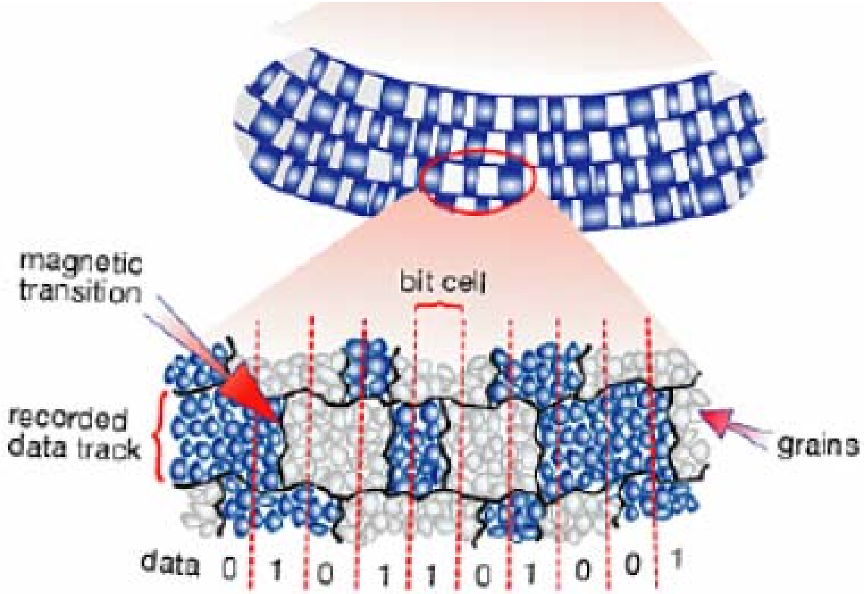
- electron beam written masters
- thin polymer films can be stamped with 50 nm or smaller features.
- The stamped polymer film serves as etch mask

Ion beam patterning, Hitachi

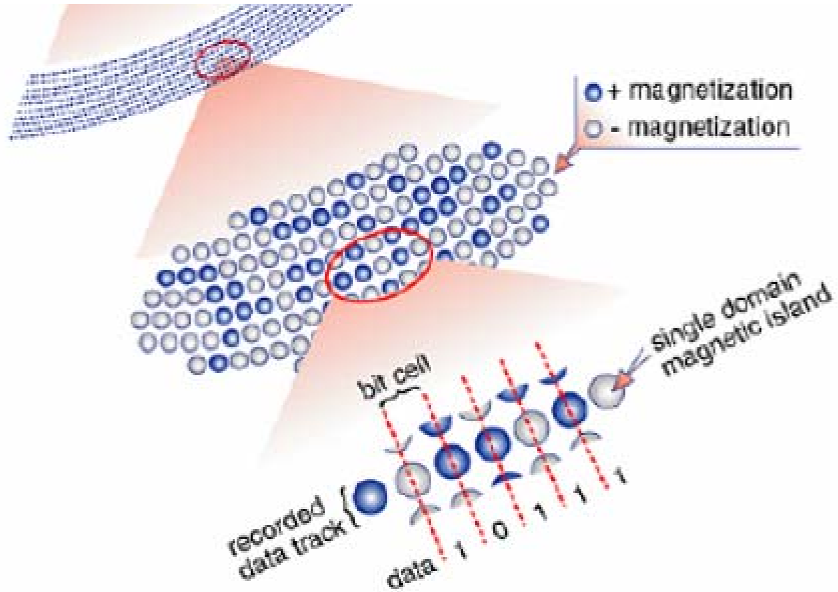


Patterned Media, Seagate

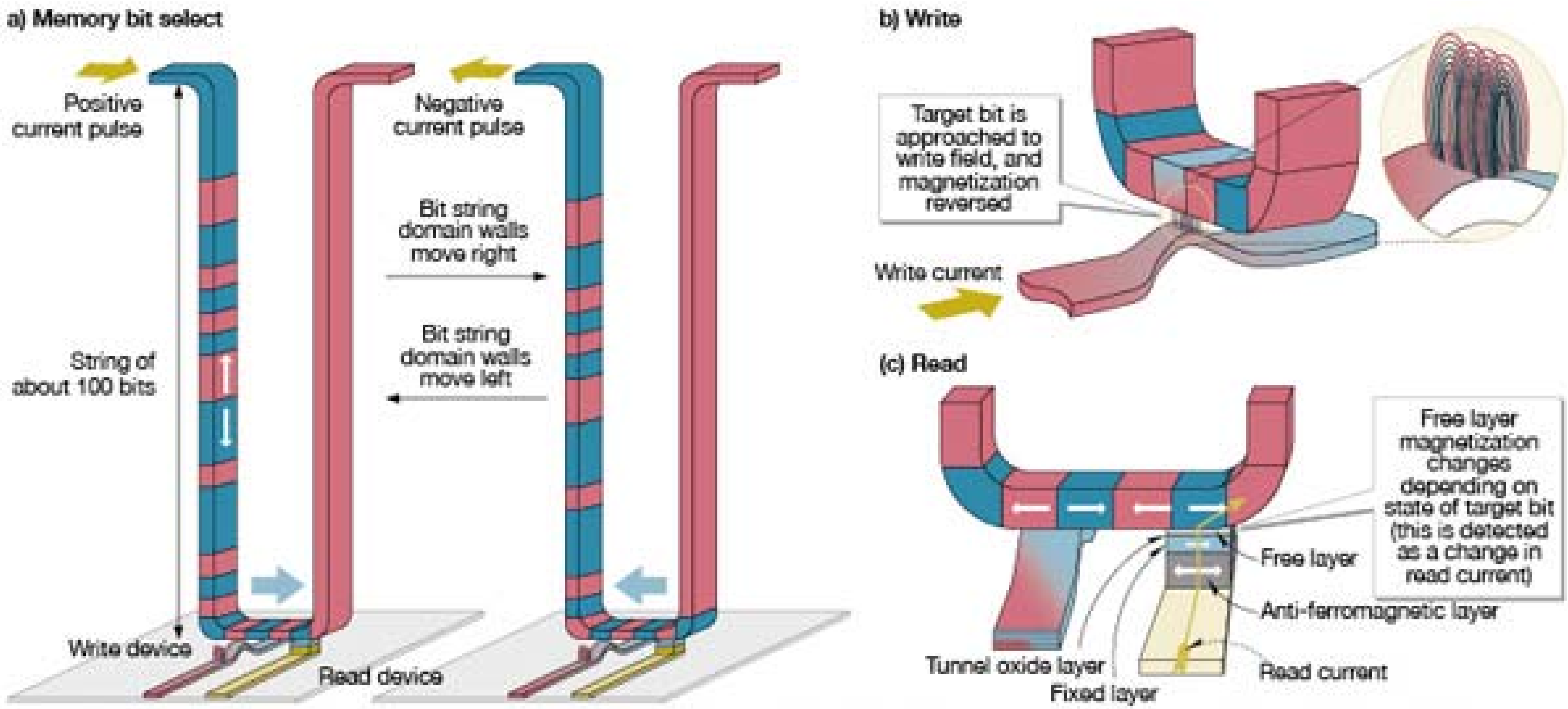
Present hard disk media:
many small random grains make one bit (10 Gbit/in^2)



The 9 Tbit/in^2 future:
single pre-patterned magnetic clusters individually addressable

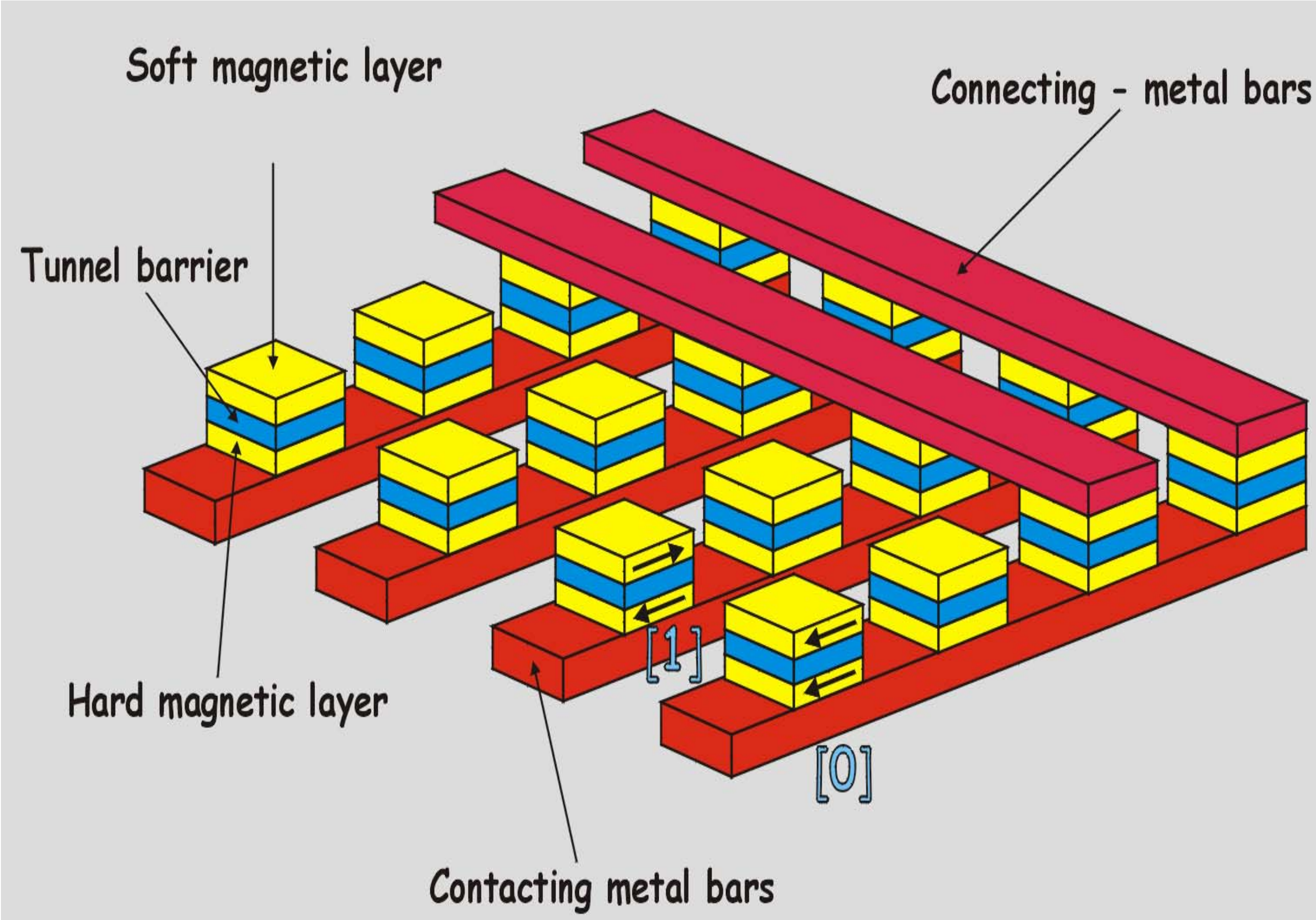


Race track Memory, IBM

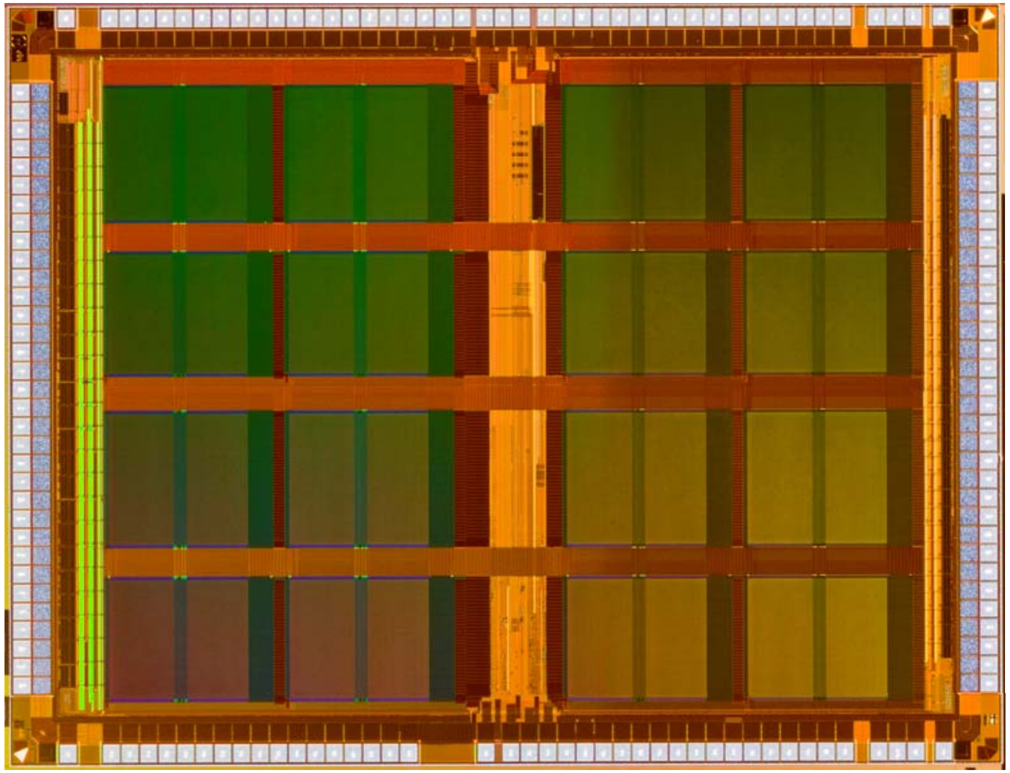


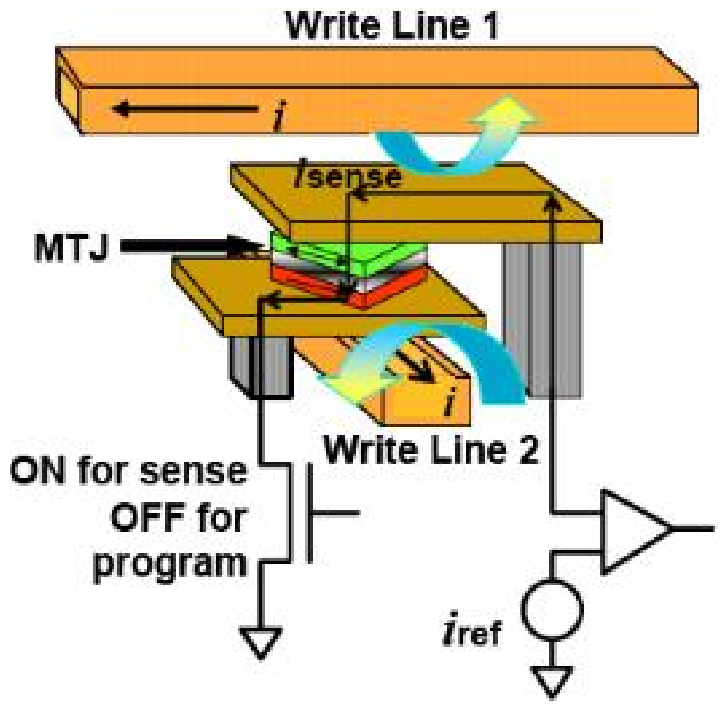
Stuart S.A. Parkin, IBM

MRAM, non-volatile data storage media



MRAM, Freescale

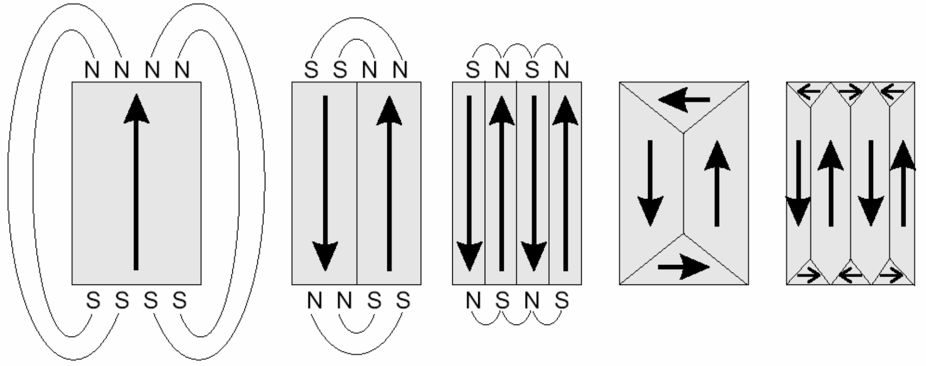




Energy terms

- Exchange energy
- Magneto-crystalline anisotropy
- Shape anisotropy
- Zeeman energy
- Surface anisotropy

$$F = \left(f_{Zeeman} + f_{crystal} + f_{shape} + f_{exchange}\right)V + f_{surf}A$$



(a) (b) (c) (d) (e)

Ground state and magnetization reversal

Ground states:

- dipolar
- vortex
- domain state…

Magnetization reversal:

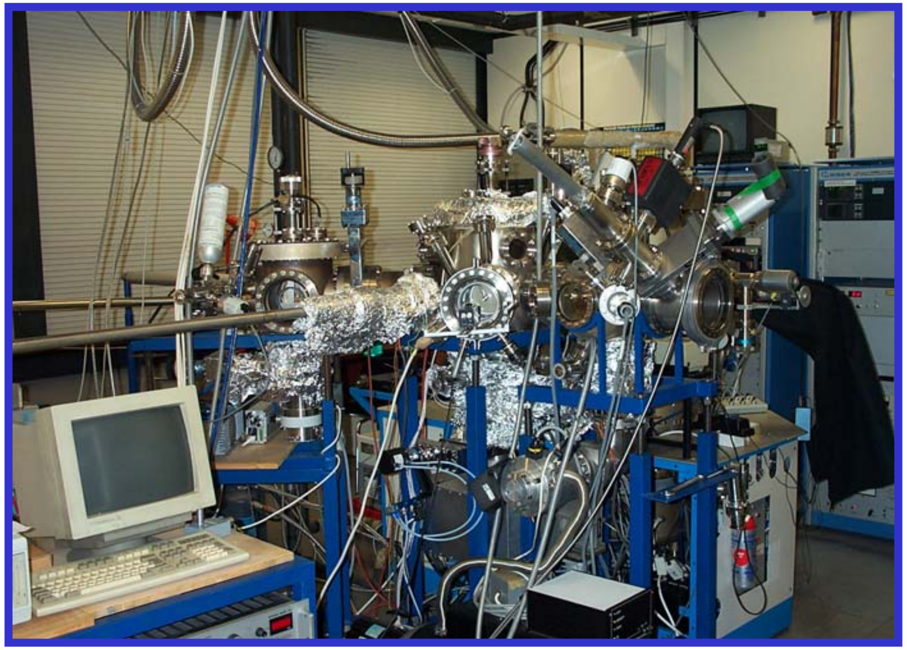
- coherent rotation
- nucleation and growth
- domain wall motion

Controlling factors:

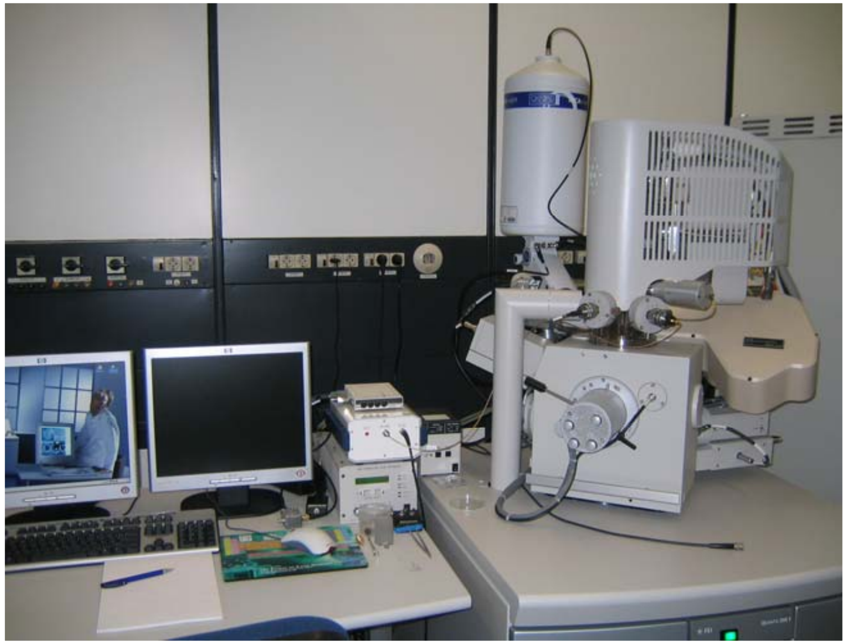
- Shape and aspect ratio
- Material and magneto-crystalline anisotropy
- Interactions for single elements and arrays

Control over material and shape

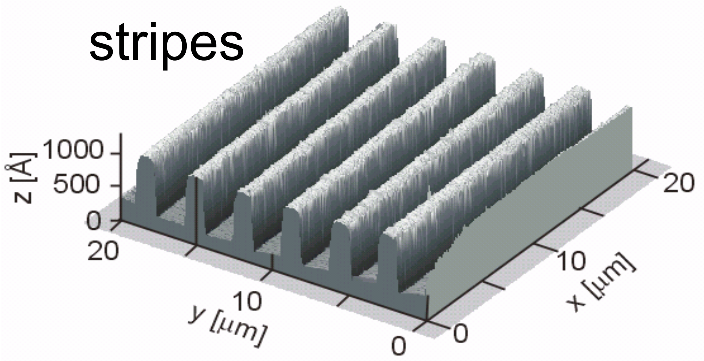
Choice of Materials:
Metal MBE



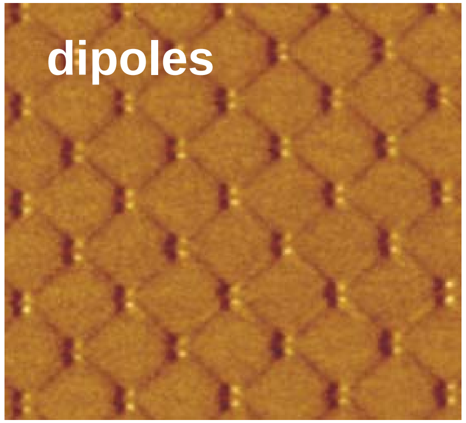
Choice of shapes:
e-beam lithography



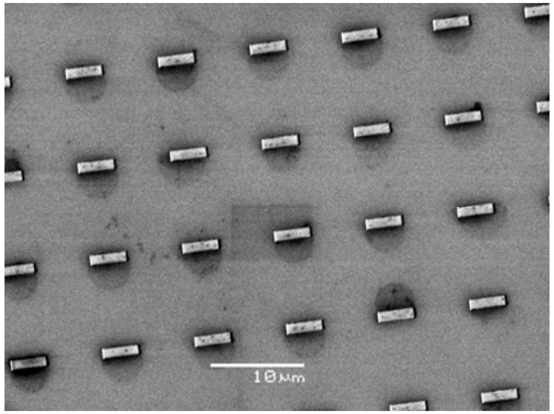
Lateral magnetic structures



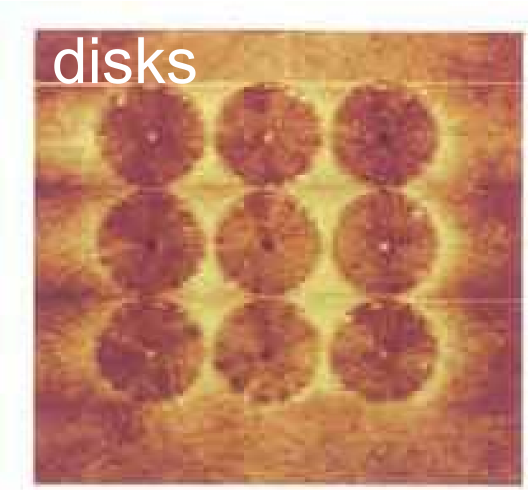
H. Brückl, Bielefeld



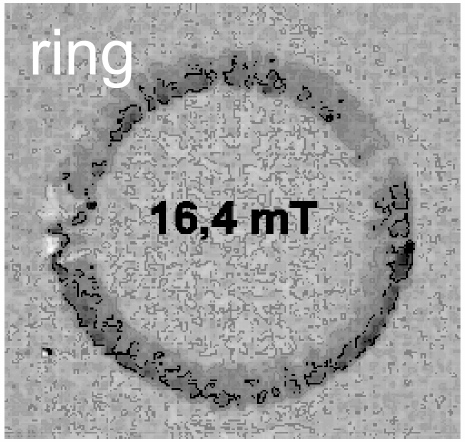
A. Remhof, Bochum



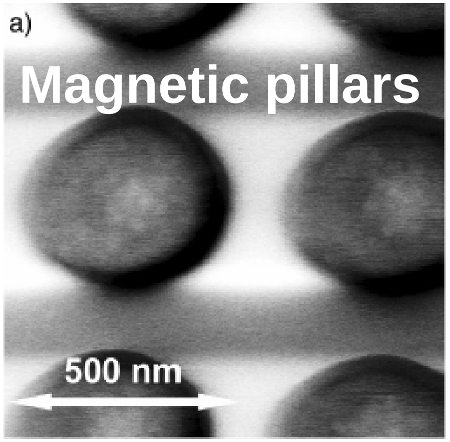
K. Temst, Leuven



Shinjo et al. Kyoto

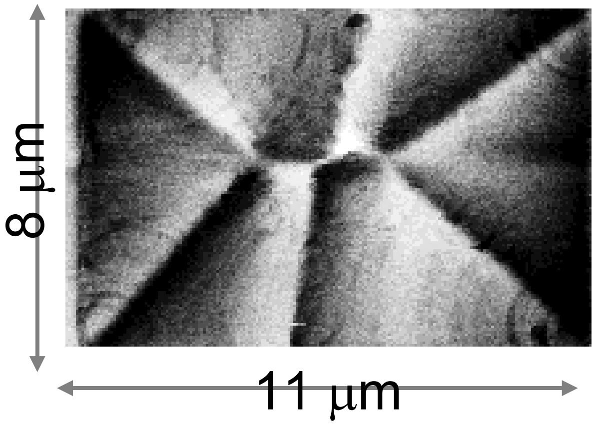


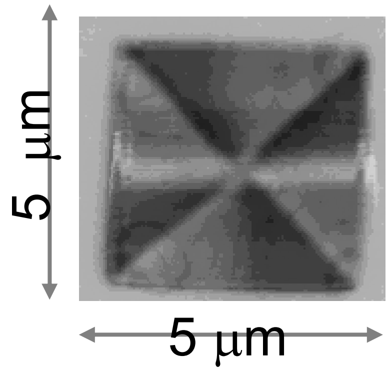
D. Buntix, Leuven

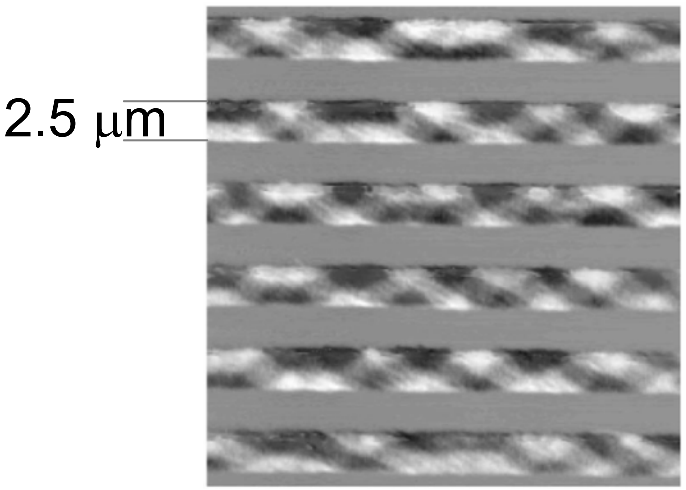


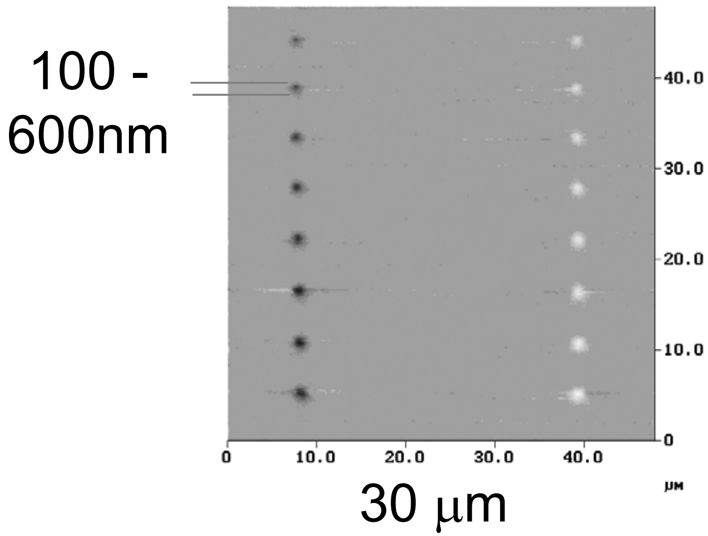
R. Brucas, Uppsala

Control of magnetic domain state





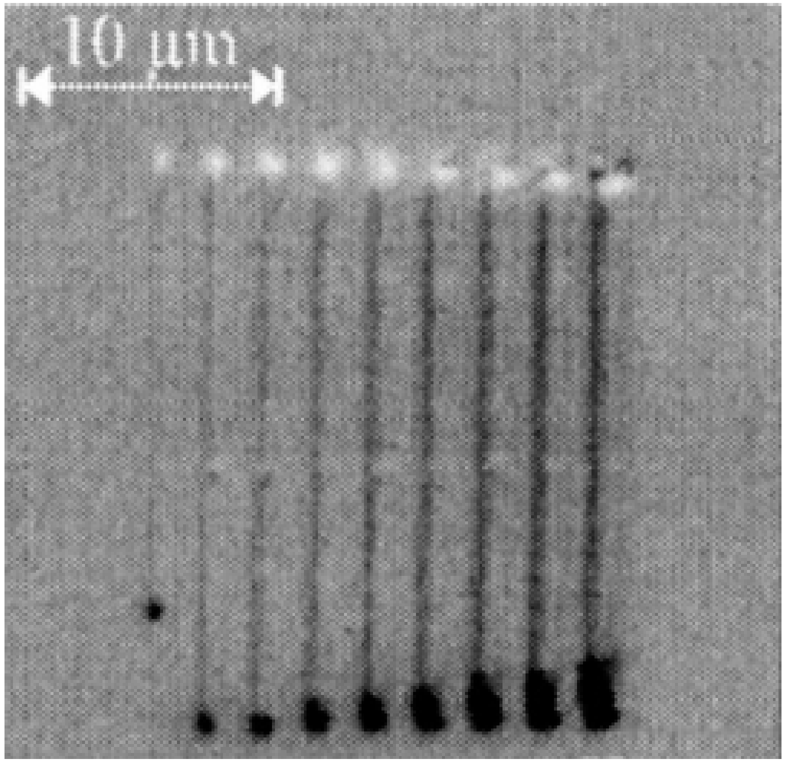




Th. Last, T. Schmitte (Bochum), J. McCord (Dresden)

Why Permalloy?

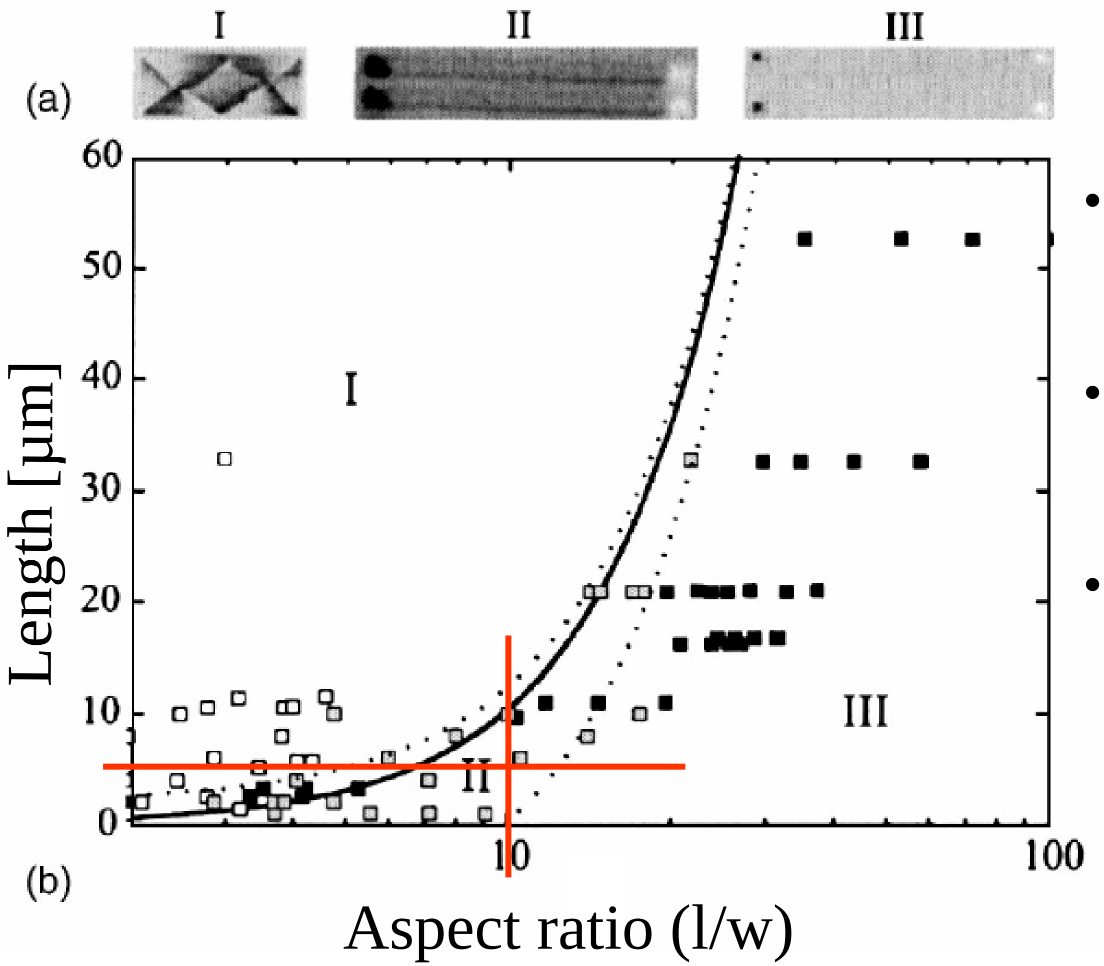
- No crystal anisotropy
- Shape anisotropy dominates
- Well known properties



T. Last et al., J. Appl. Phys. 96, (2004) 6706

Permalloy Stripes

Aspect ratio governes the remanent state

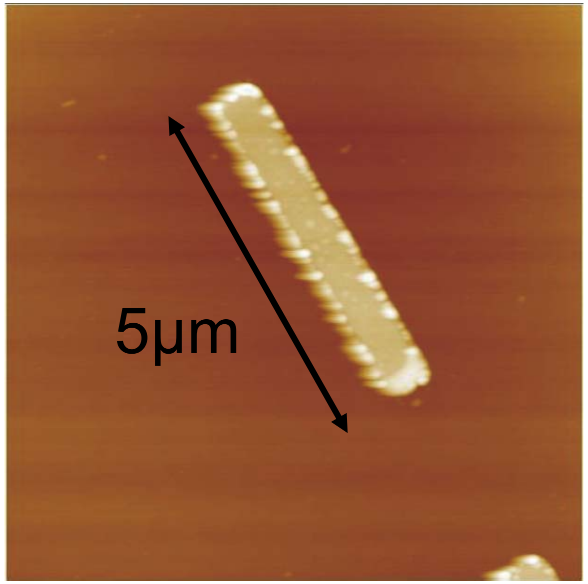


- Low aspect ratios (I)
  multidomain state
- intermediate (II)
  high remanent state
- High aspect ratios (III)
  single domain state

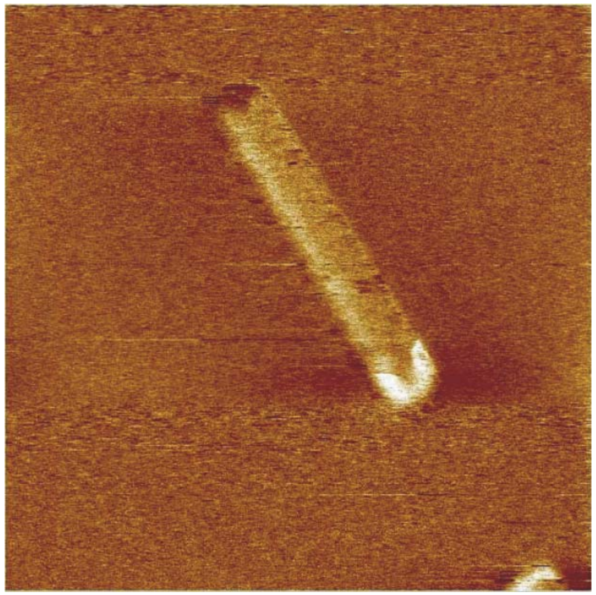
T. Last et al., J. Appl. Phys. 96, (2004) 6706

Building blocks

High remanent single domain Py bars
Aspect ration: 10 (compromise between dipole character and appreciable stray fields for MFM)

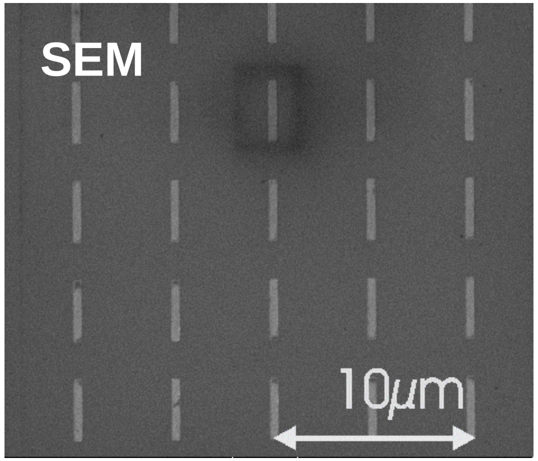


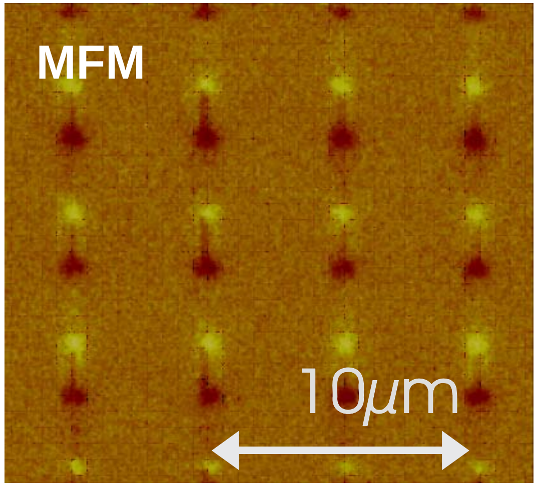
AFM

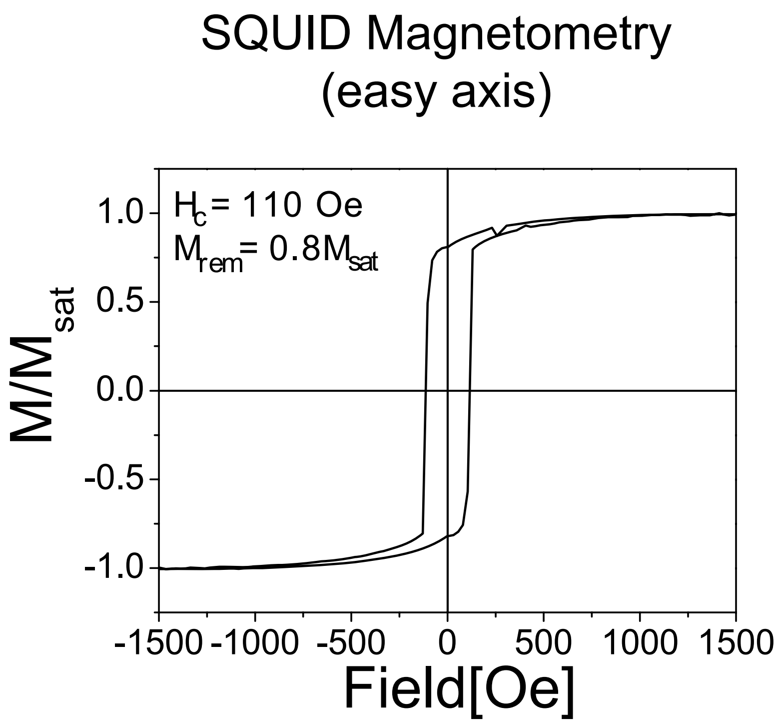


MFM

Stripe arrays

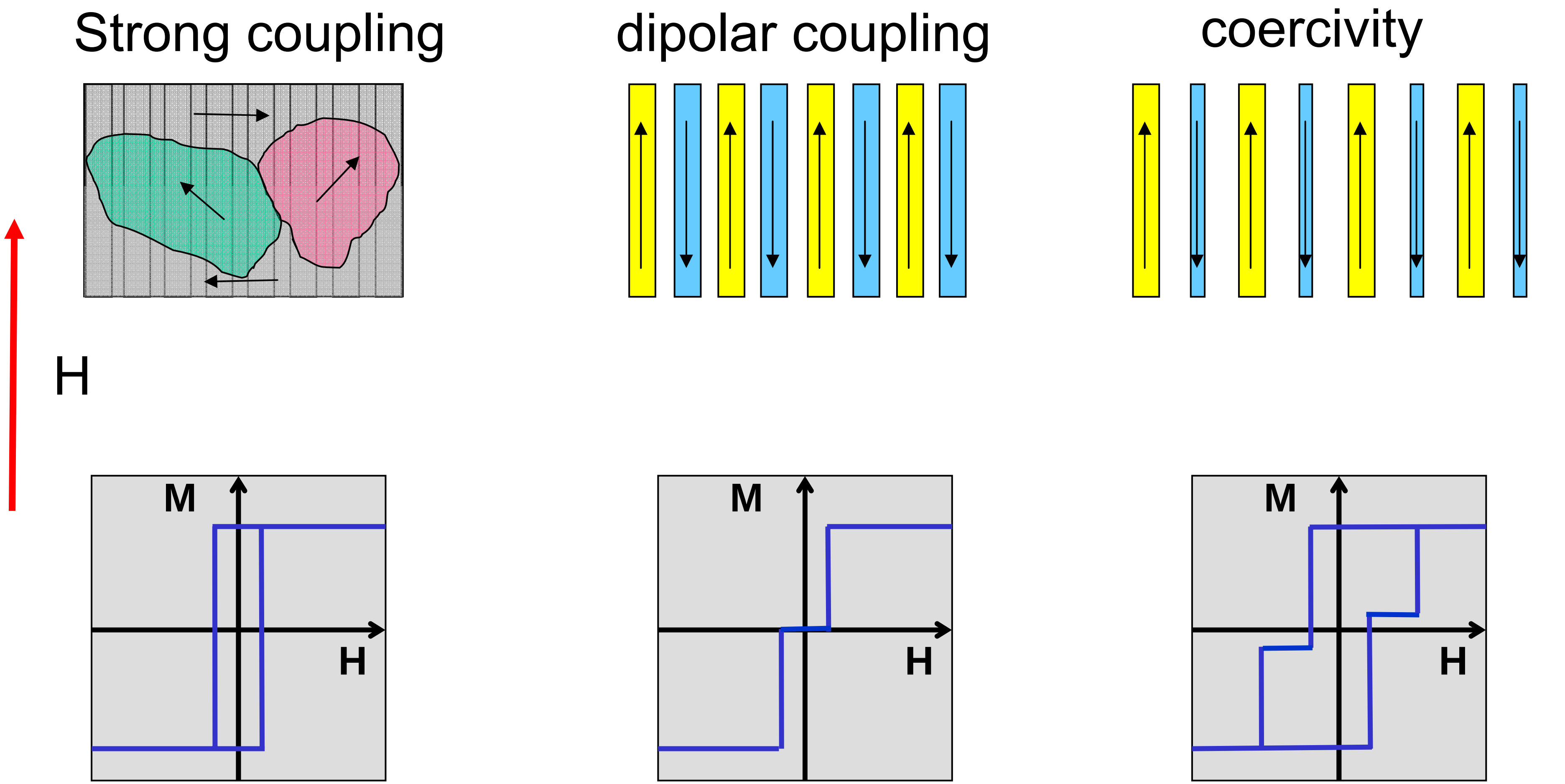




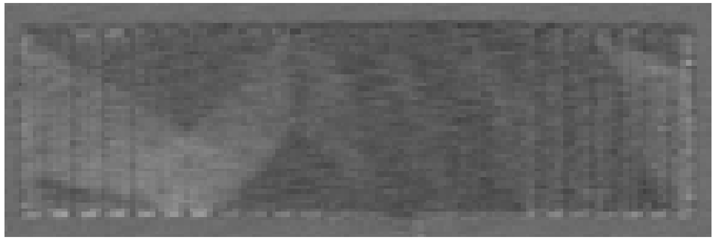


- Each stripe acts as a magnetic dipole
- No MOKE effect because of missing spin-orbit coupling

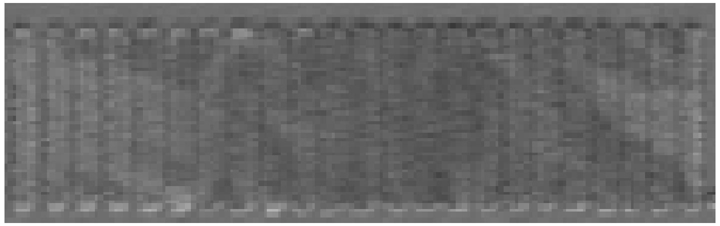
Coercivity versus interaction of magnetic dipoles (easy axis reversal)



Stripe arrays with strong dipolar coupling



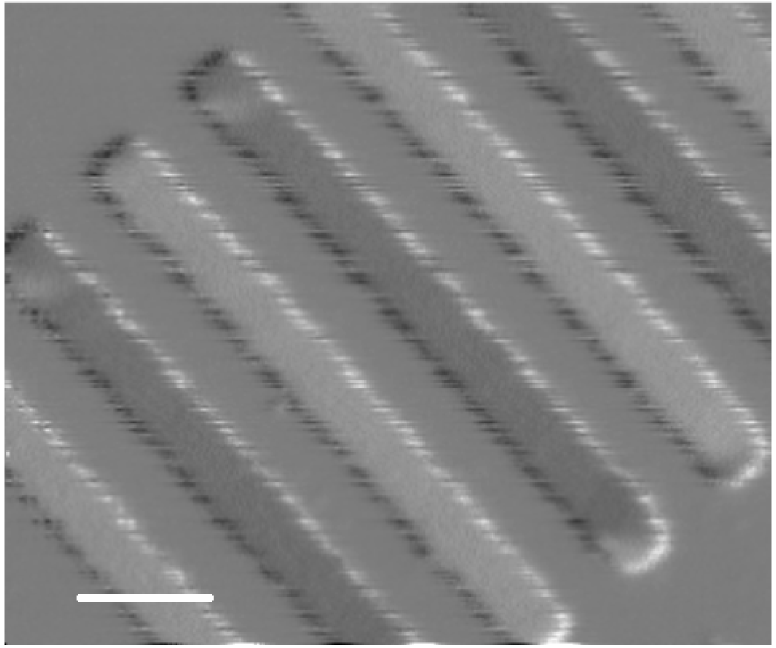
Separation: 0.5 μm
Strong interaction, domain formation across dipoles



Separation: 0.8 μm
Weaker interaction, still domain formation

S-PEEM: Thomas Eimüller

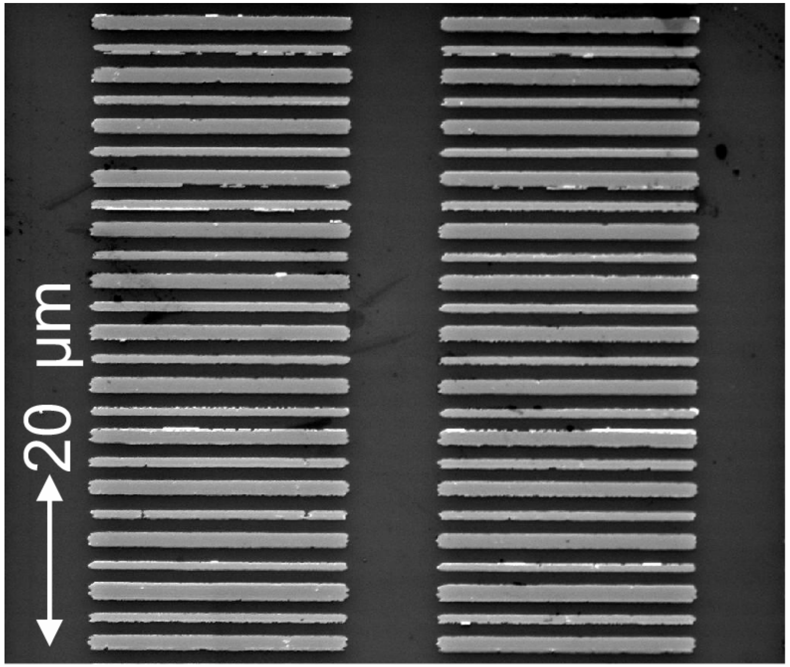
Stripe arrays with AF dipolar coupling

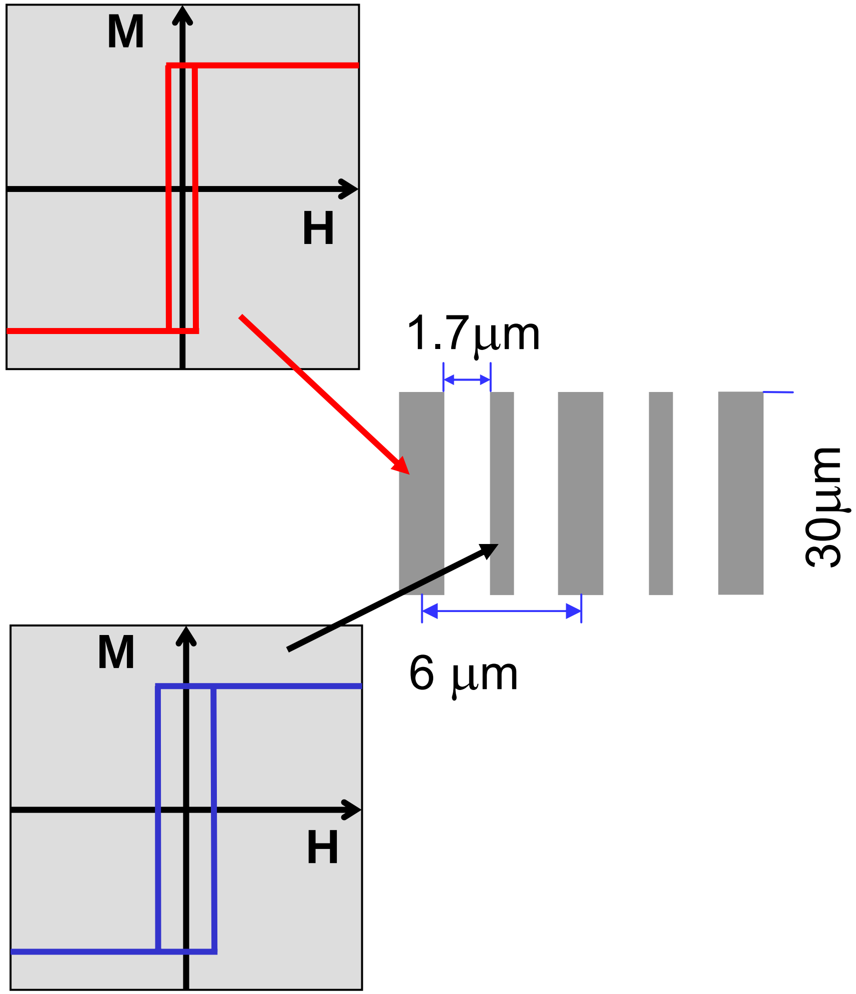


Separation: 1.0 μm
AF coupling of dipoles

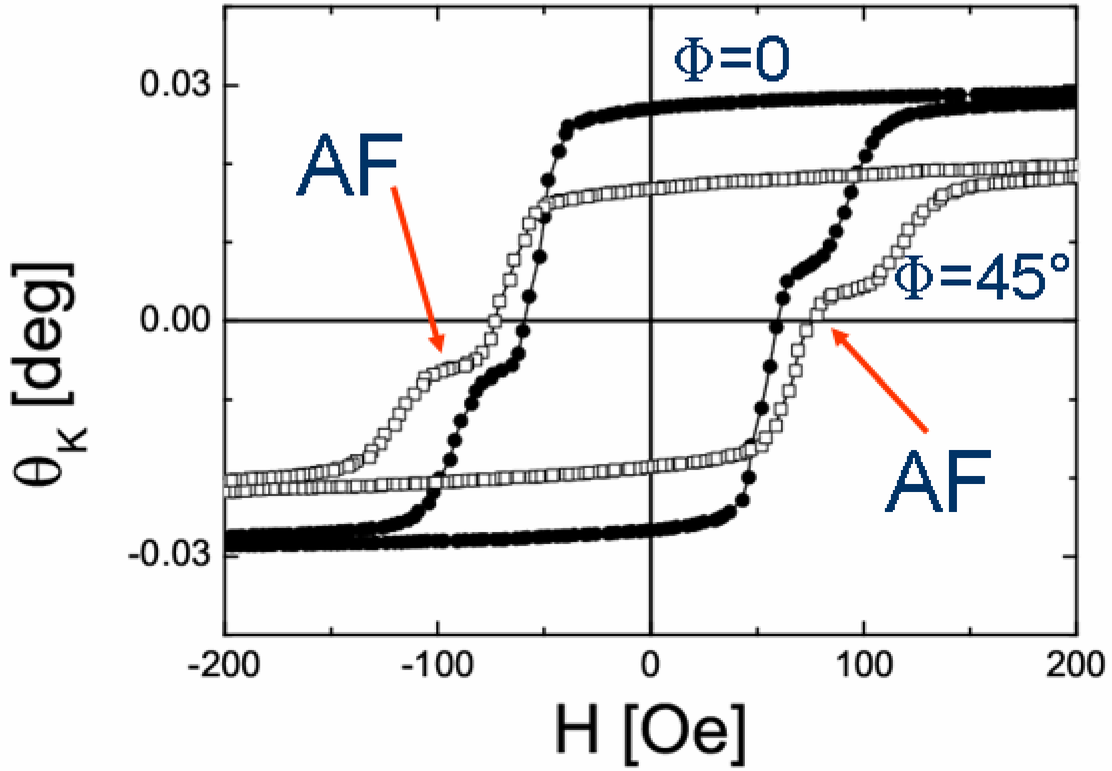
S-PEEM: Thomas Eimüller

Lateral Fe bar array with alternating widths





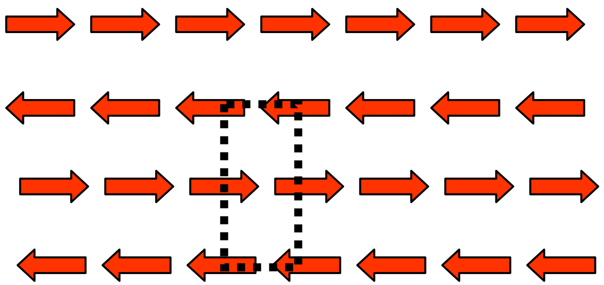
Two-step hysteresis



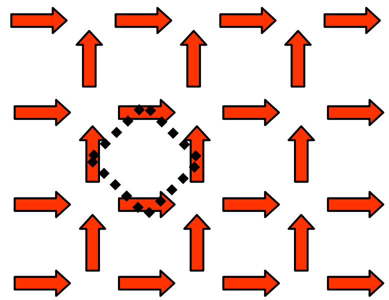
Two step hysteresis due to different coercive fields instead of dipolar coupling

Dipole patterns with different lattice symmetries

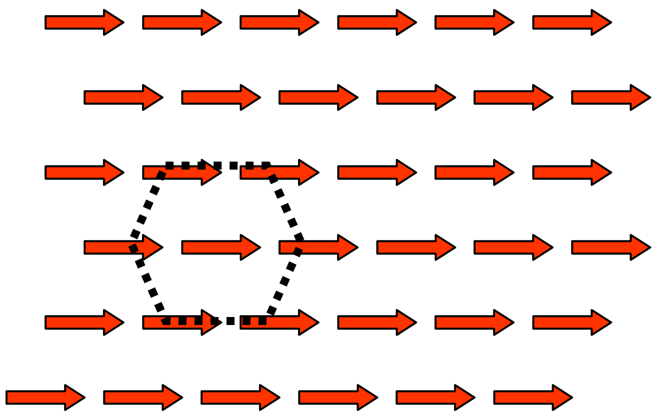
rectangular AF lattice

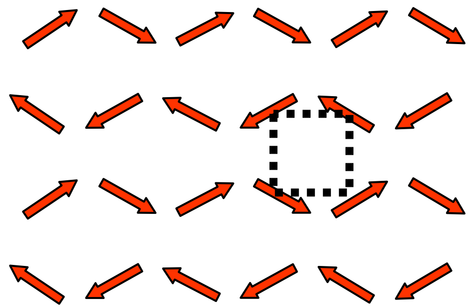


square lattices



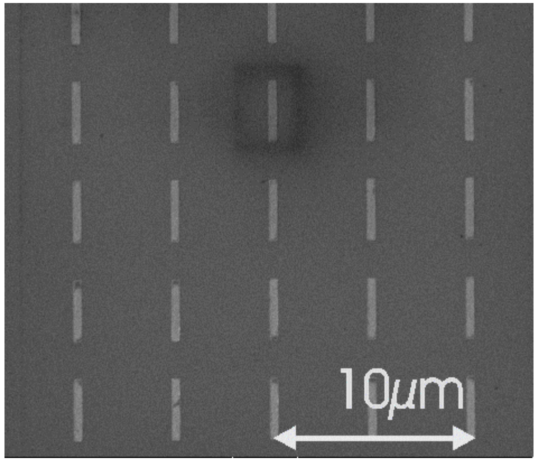
triangular lattice

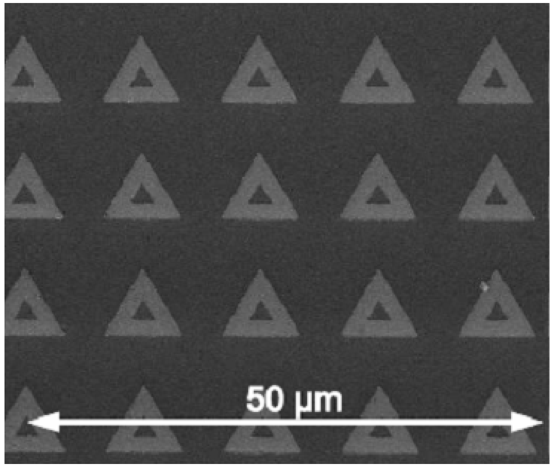


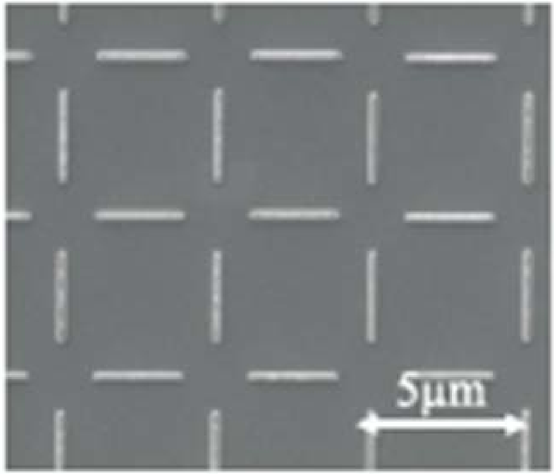


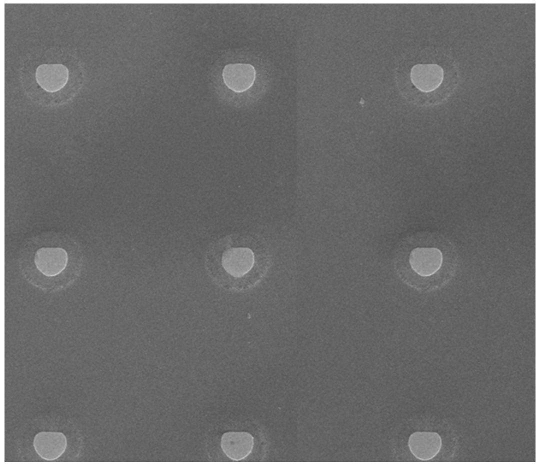
Interaction, correlation, frustration

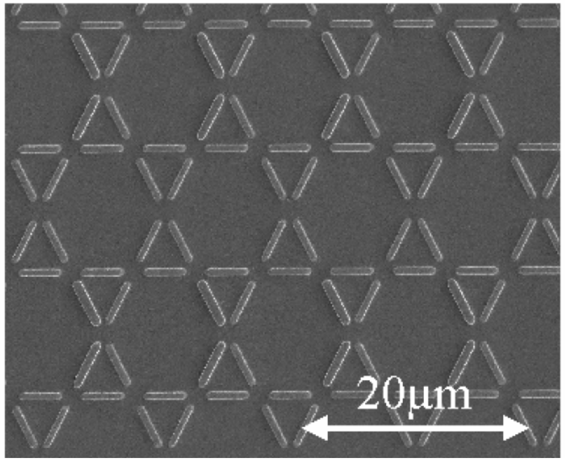
Lateral magnetic arrays

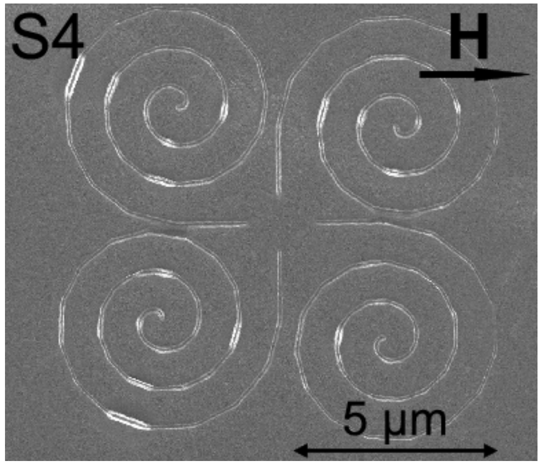




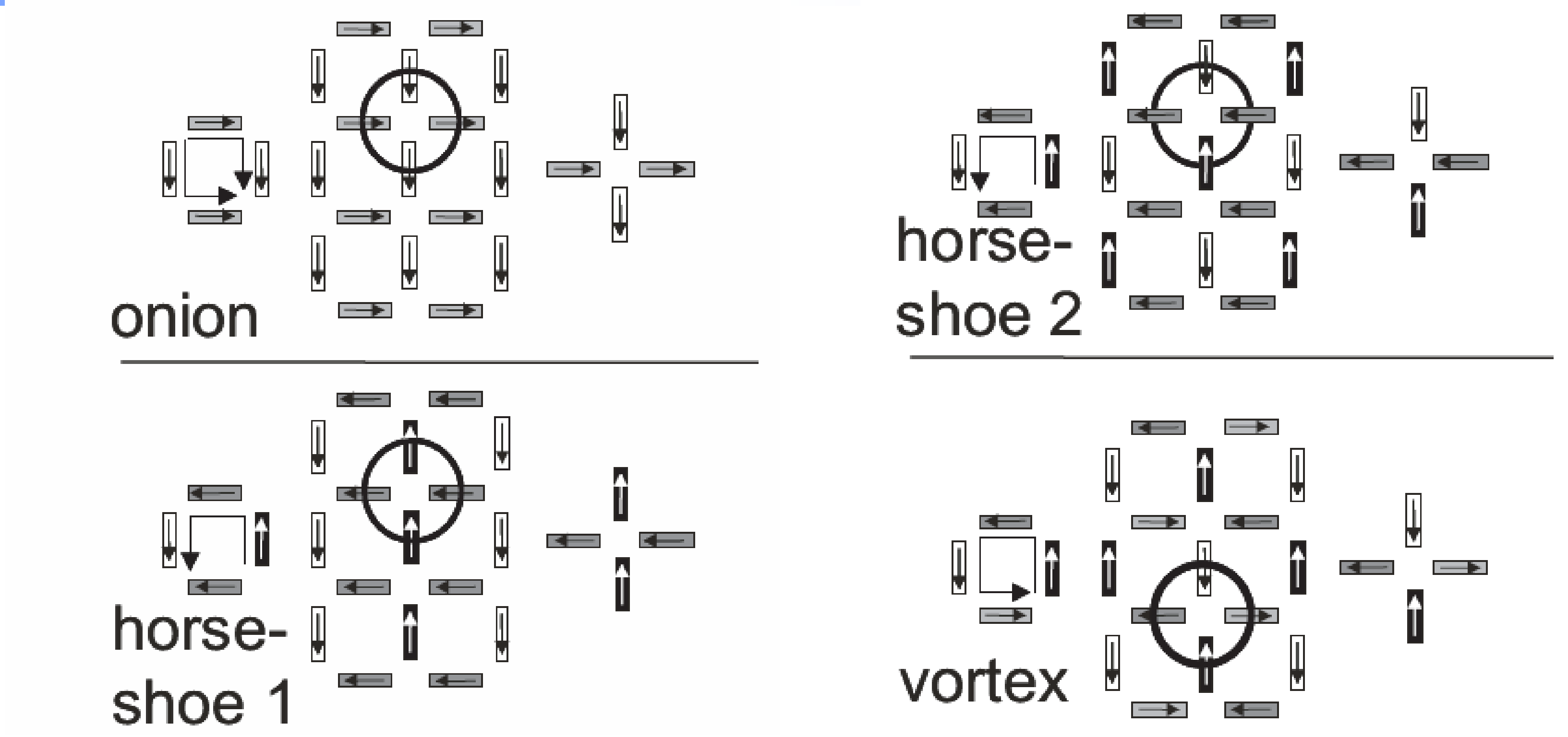








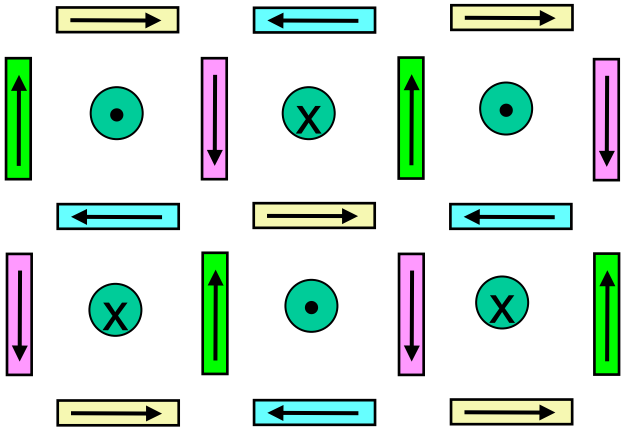
Remanent “frustrated” states



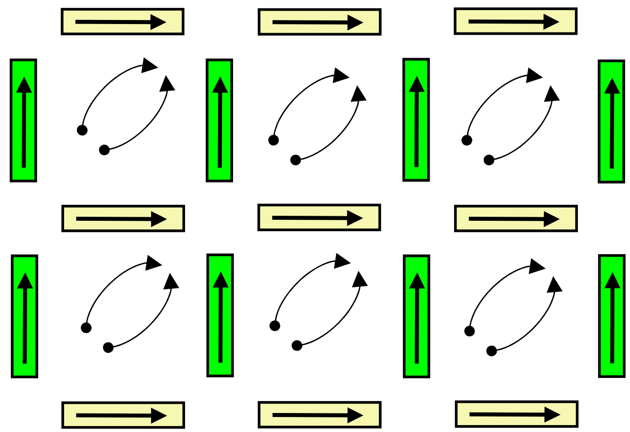
one in, three out = horse shoe 2
two in, two out (same side) = onion, horse shoe 1
two in, two out (opposite) = vortex, spin ice
three in, one out = horse shoe 2

Configurations

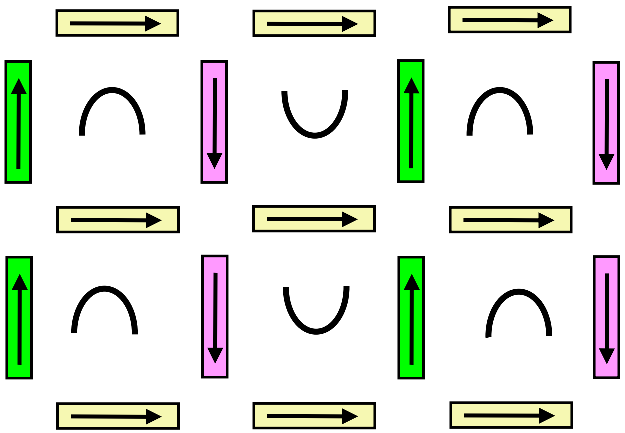
Vortex



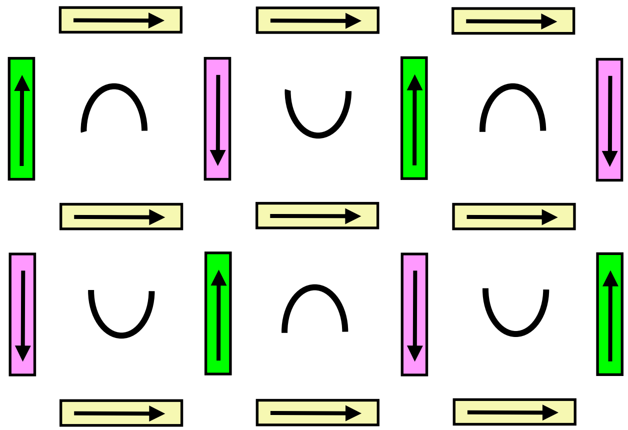
Onion



Horse shoe I

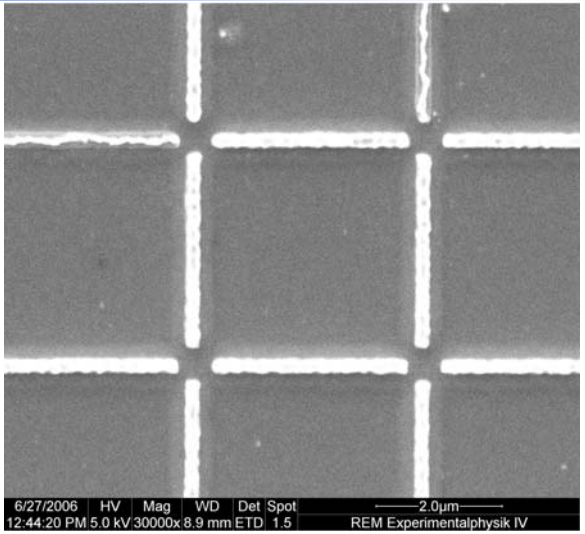


Horse shoe II

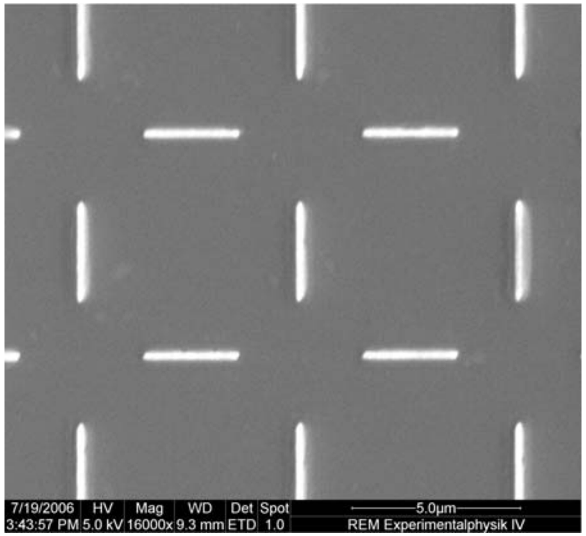


Magnetization in diagonal direction

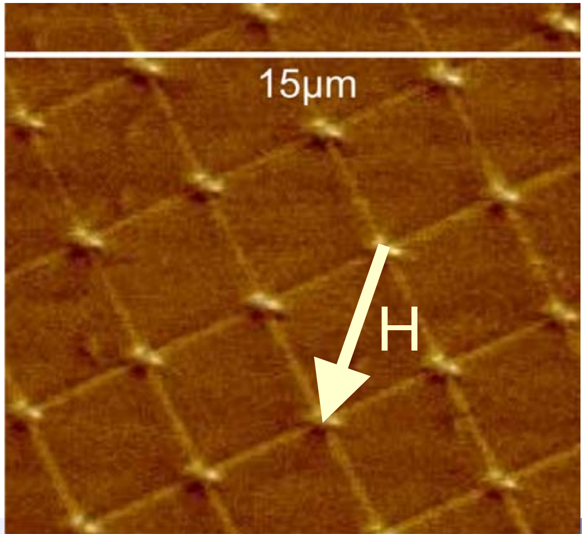
SEM
0.42 µm



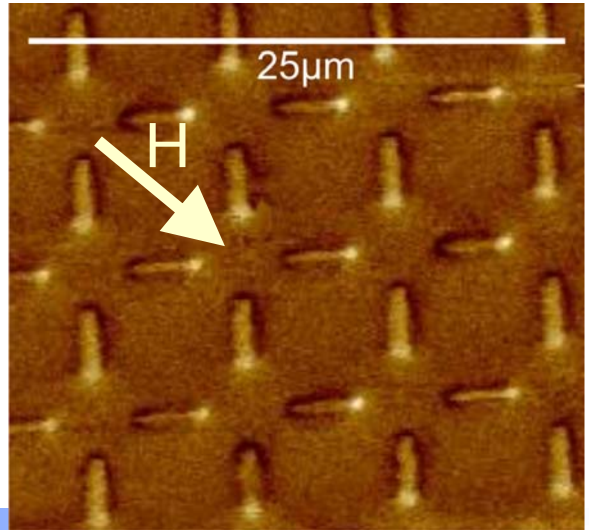
SEM
3.36 µm



MFM



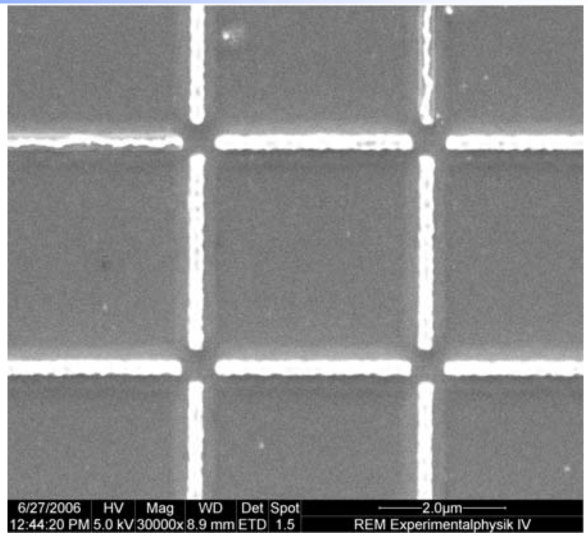
onion-state



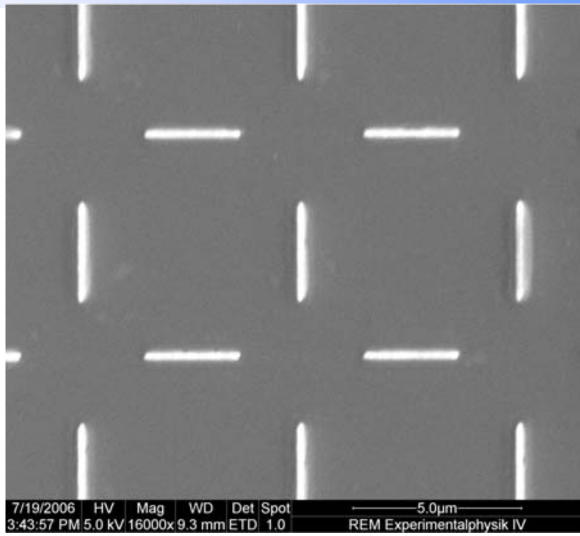
A. Schumann, Diploma Thesis, RUB 2006

Magnetization in parallel direction

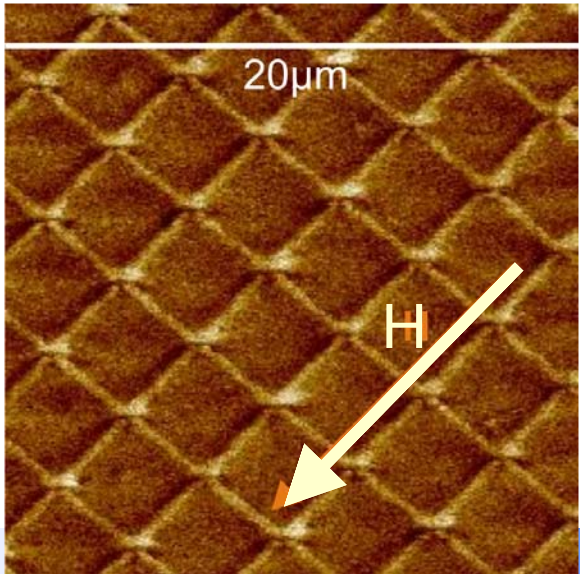
SEM
0.42 µm

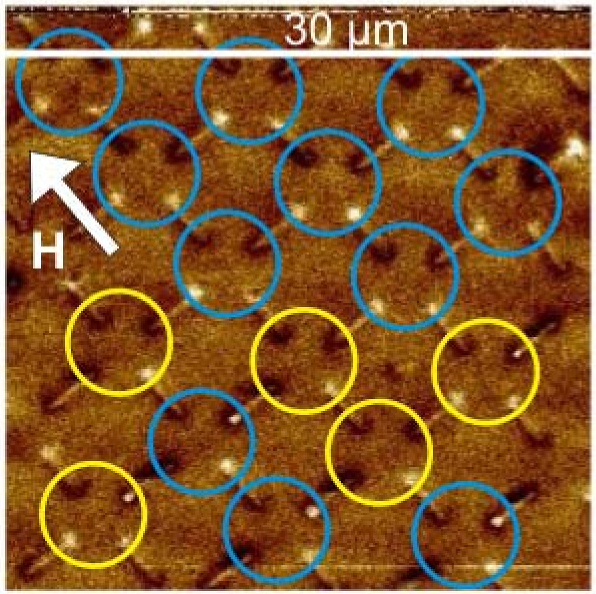


SEM
3.36 µm



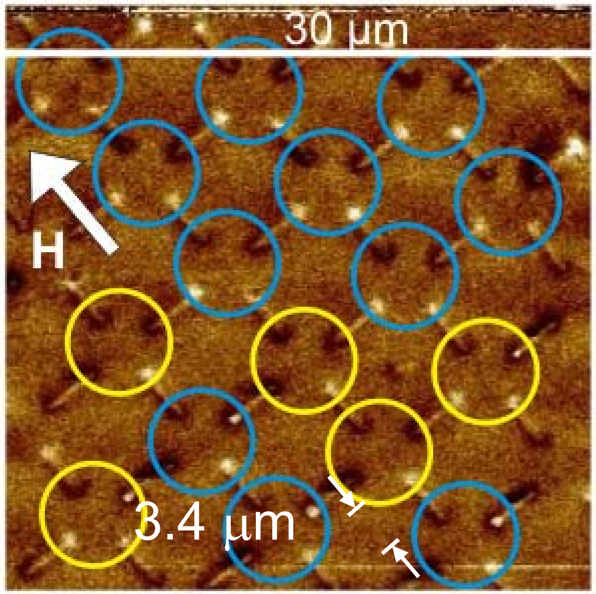
MFM

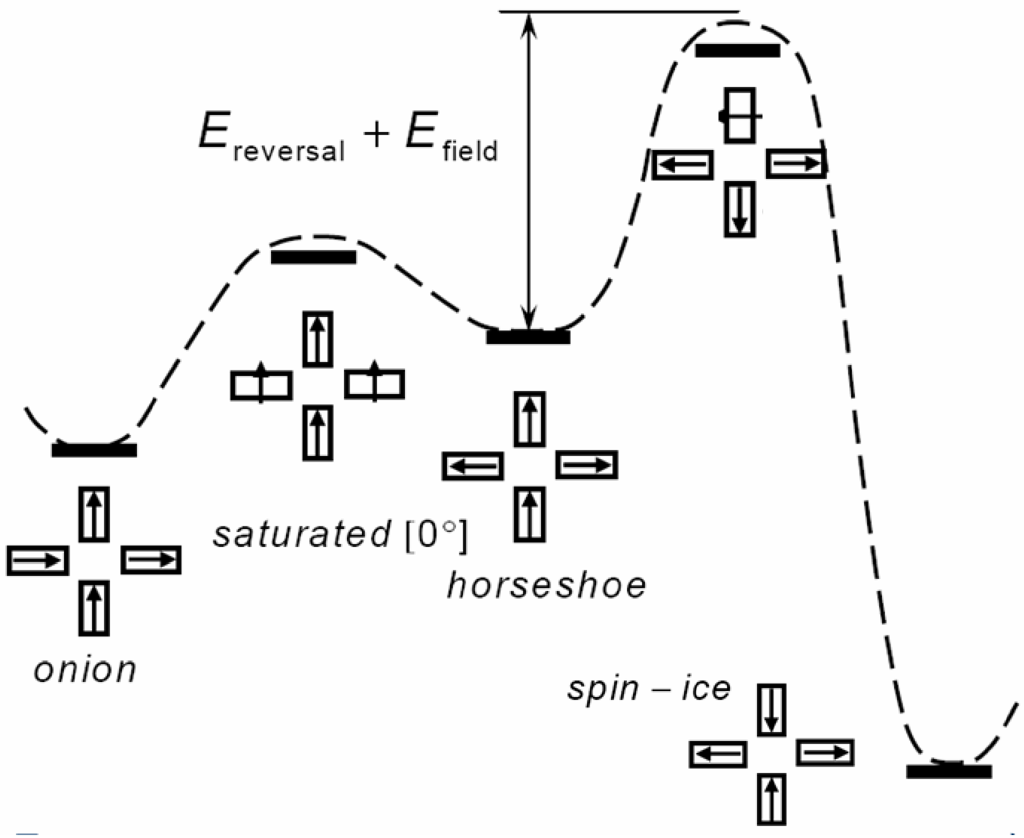




A. Schumann, Diploma Thesis, RUB 2006

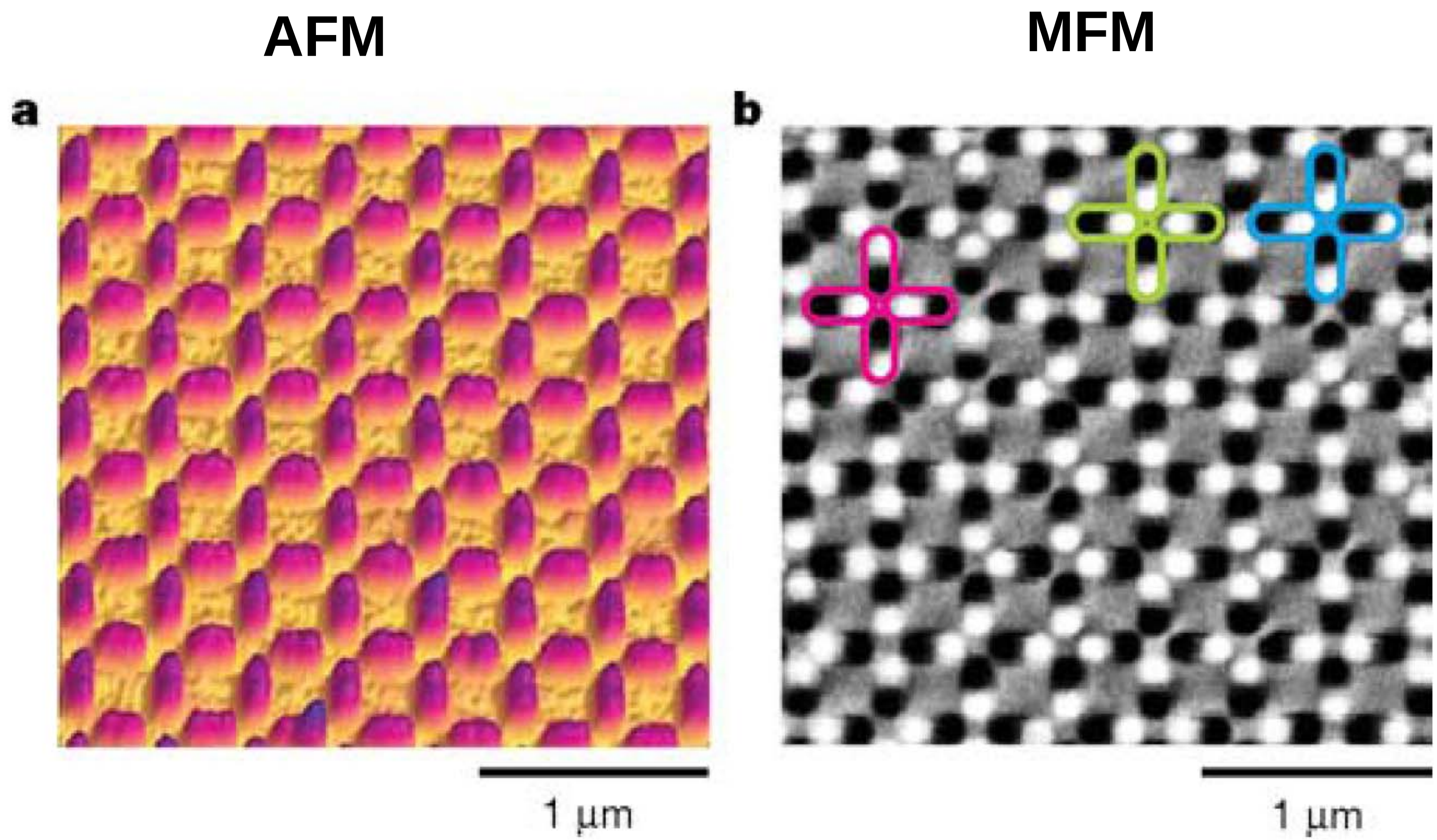
Energy landscape for H || stripes





2:1 ratio predicted and observed

Artificial spin-ice

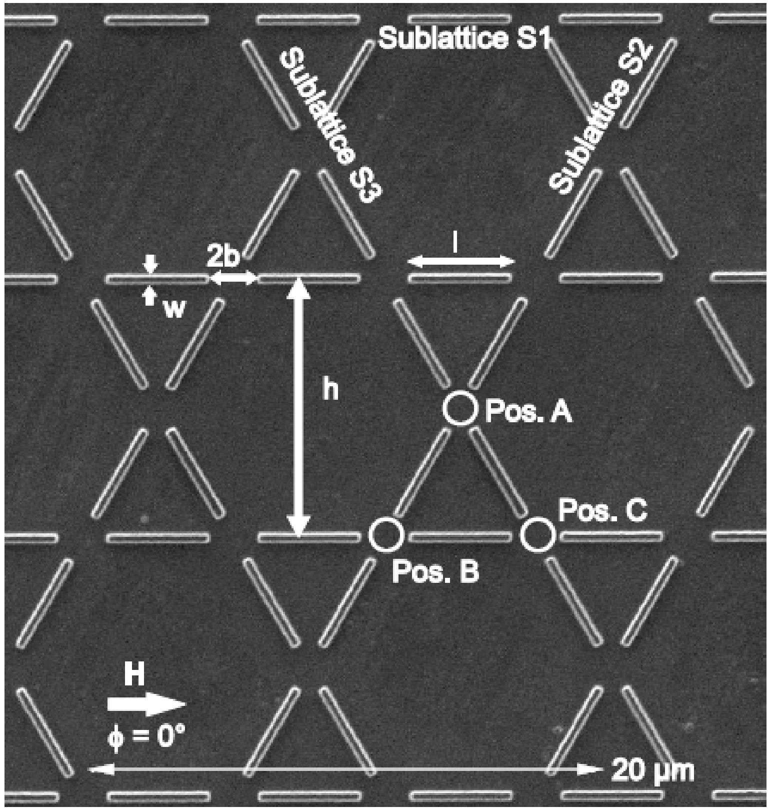


Demagnetized state

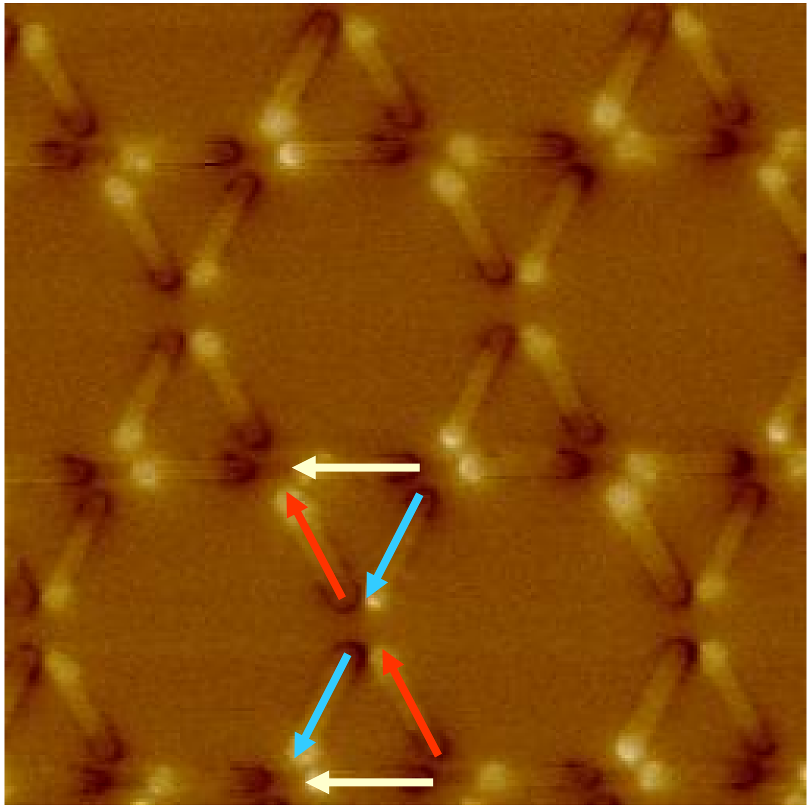
R.F. Wang et al. Nature **439**, 303 (2006)

Kagomé – lattice of magnetic dipoles

SEM



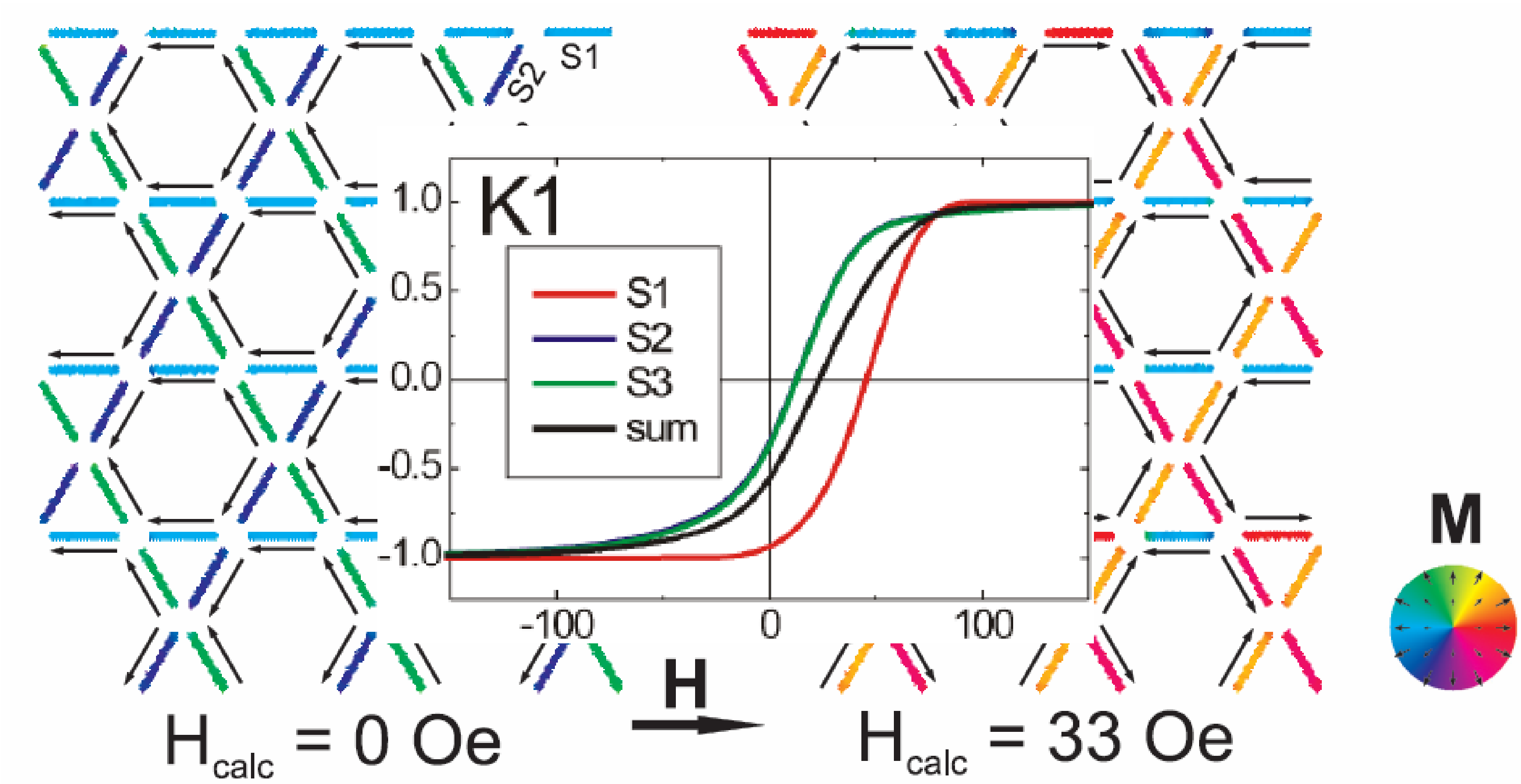
MFM



Three sublattices: S1, S2, S3

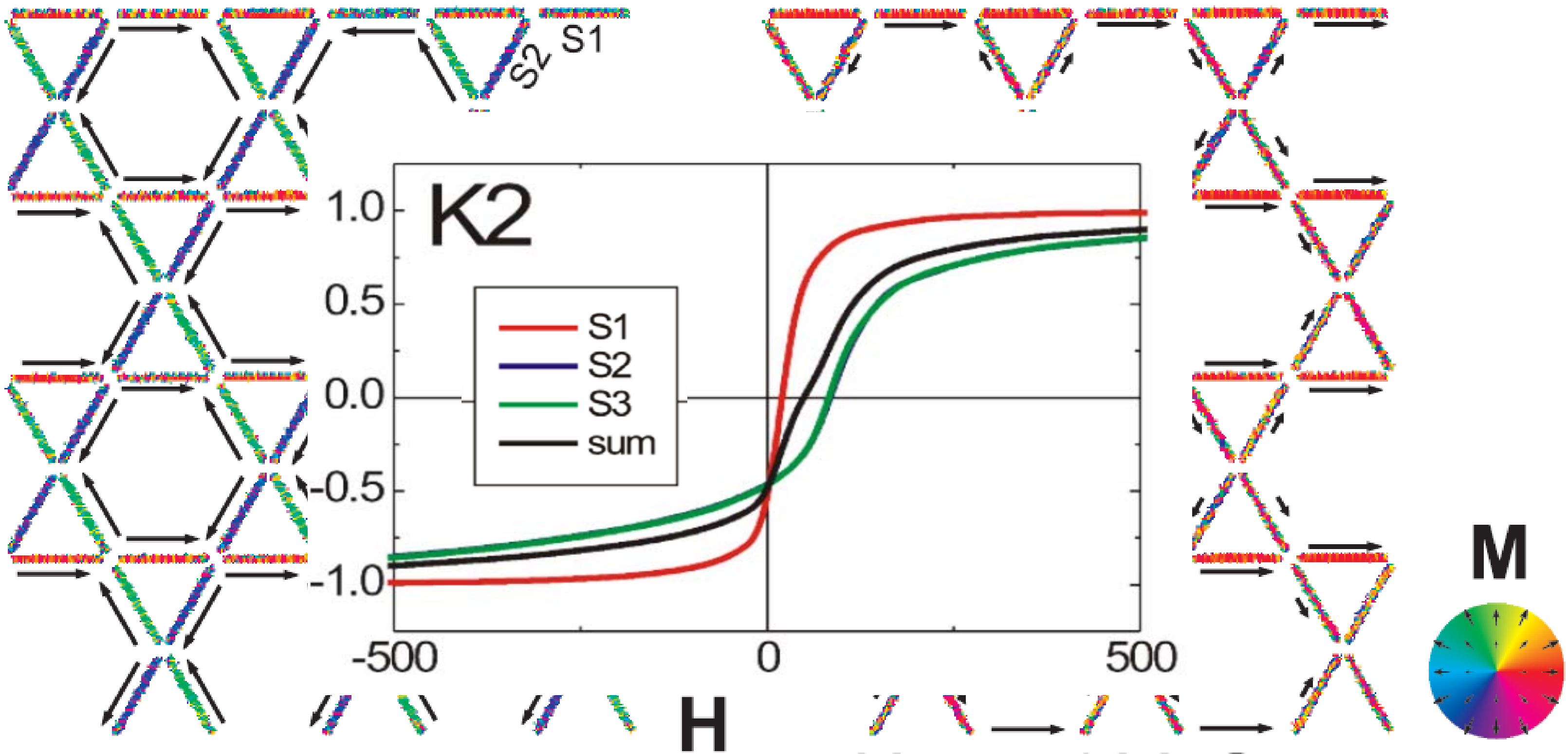
Two main field orientations: 0° (e.a.) & 30° (h.a.)

Reversal of K1 (2b/l=1)



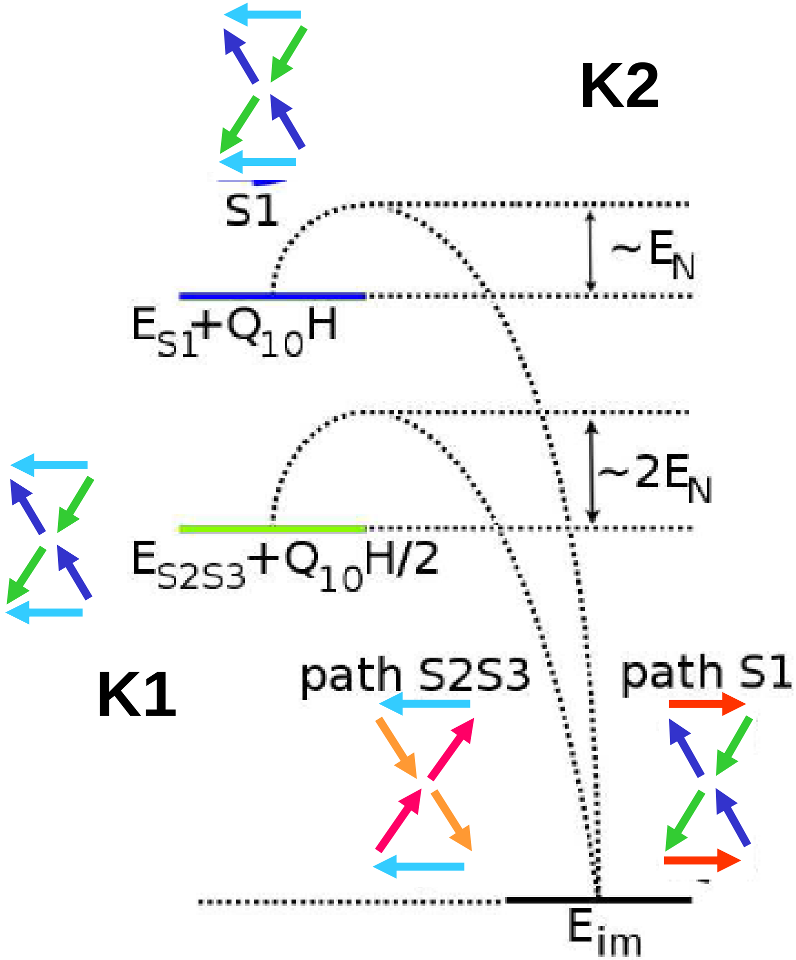
$H_c(S1) > H_c(S2) = H_c(S3)$

Reversal of K2 (2b/l=0.43)



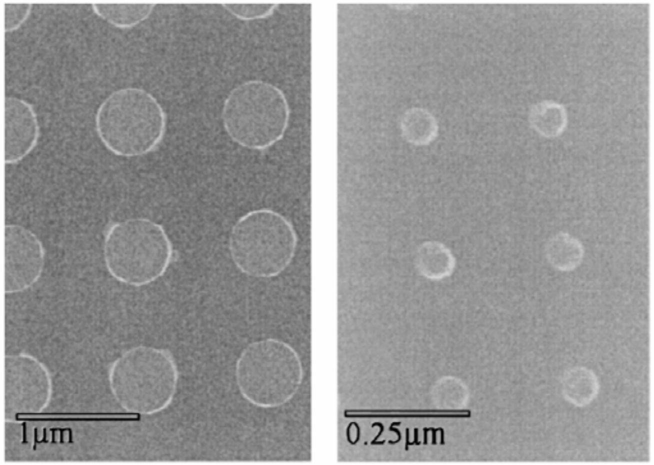
H_{calc} = 33 Oe → H_{calc} = 100 Oe

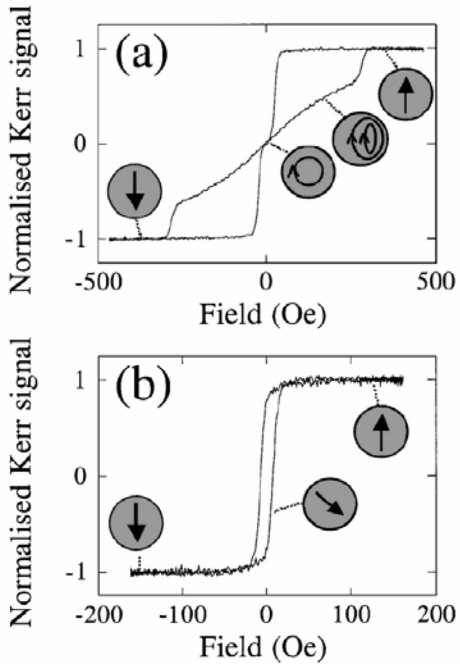
Energy barriers for switching

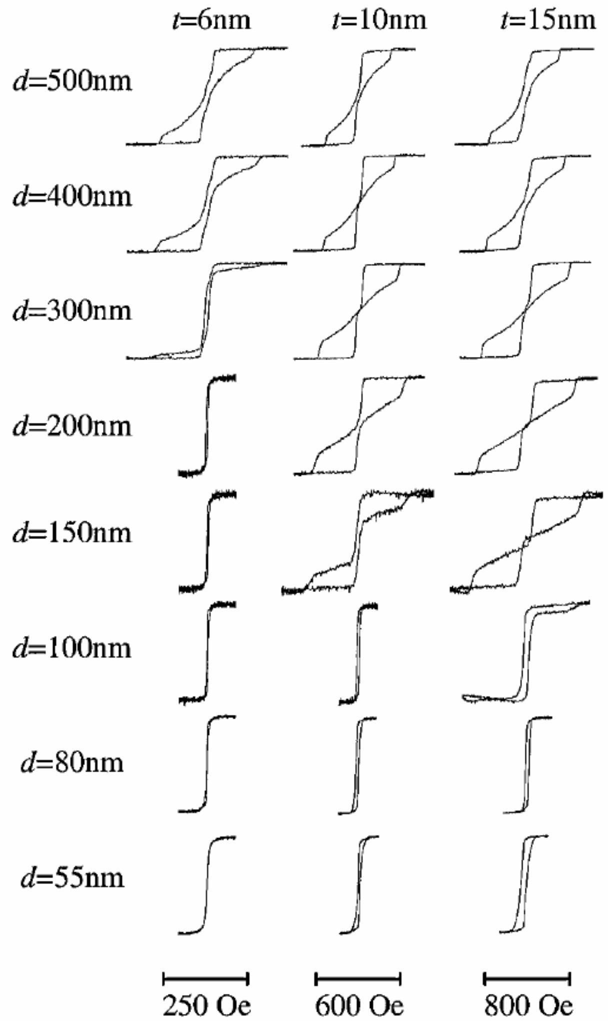


M. Karolak, B. Baxevanis, and E. Y. Vedmedenko

Magnetization reversal of magnetic disks

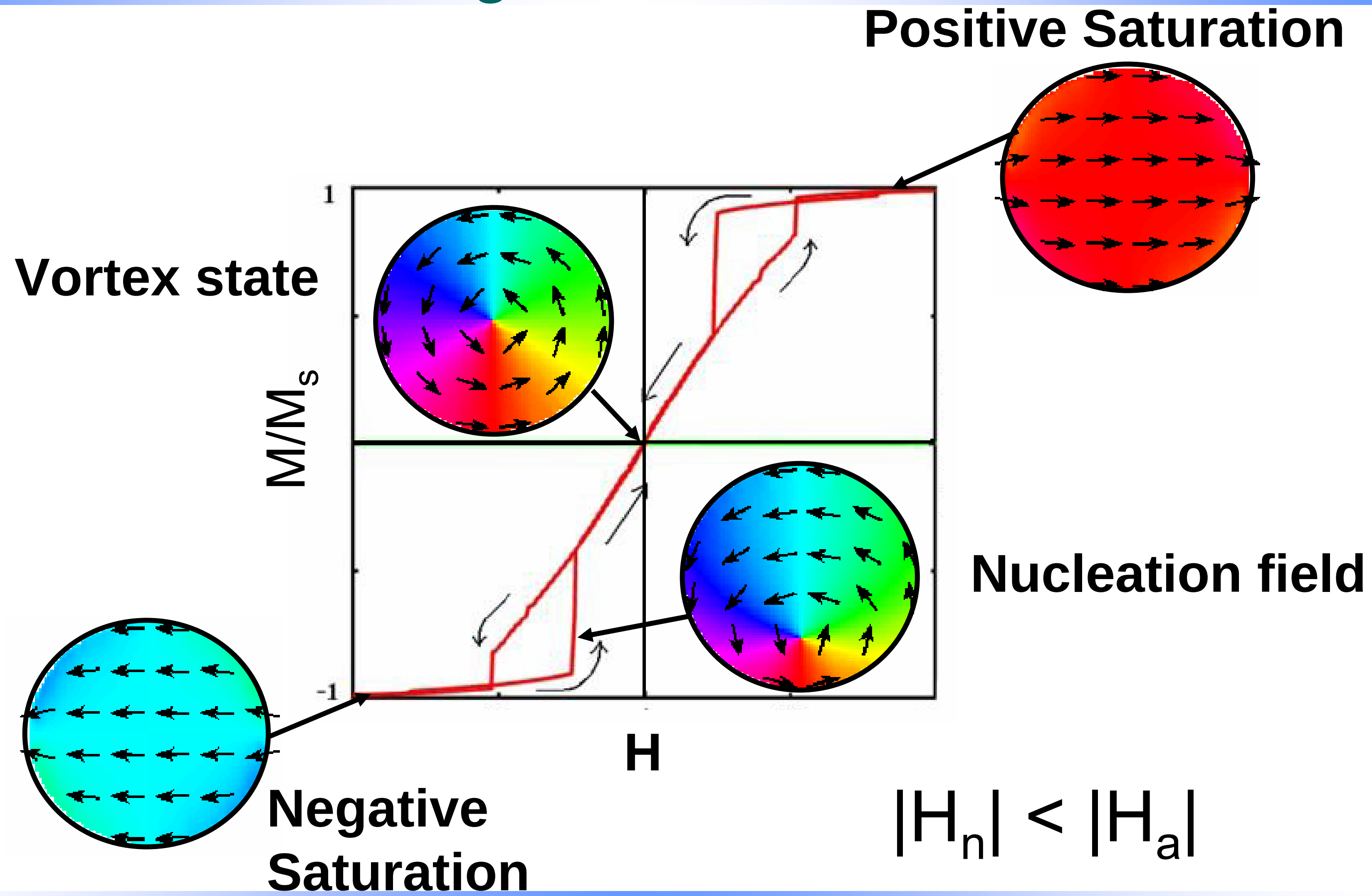






R.P. Cowburn et al. PRL 83, 1042 (1999),
R.P. Cowburn PRB 65, 092409 (2002)

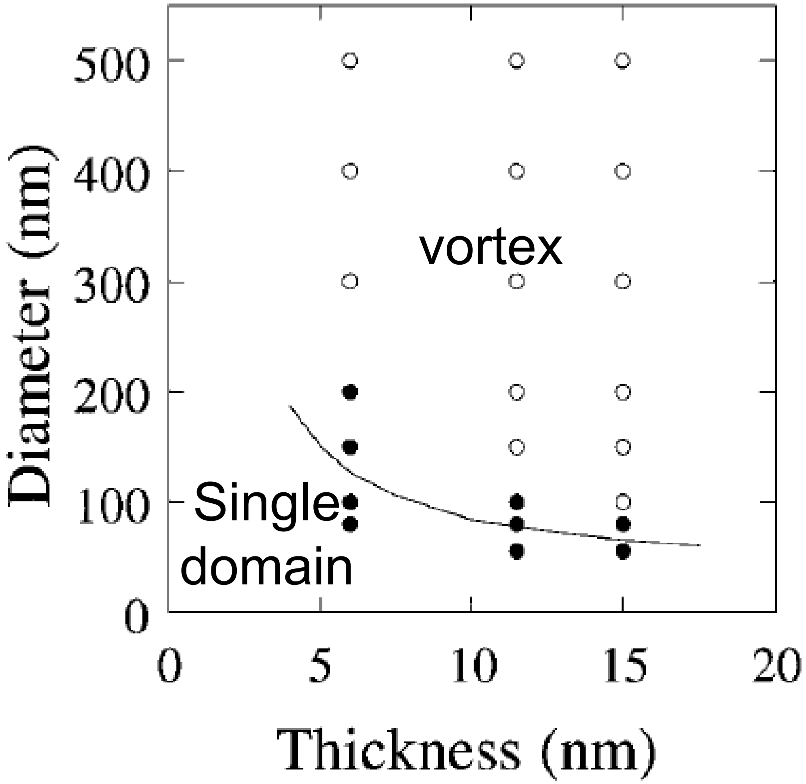
Magnetization reversal of magnetic dots



$|H_n| < |H_a|$

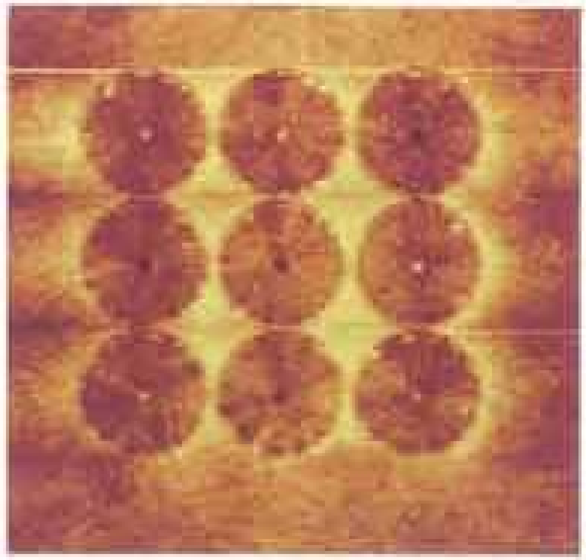
Vortex state and phase diagram

Phase diagram



R. Cowburn et al

Vortex core



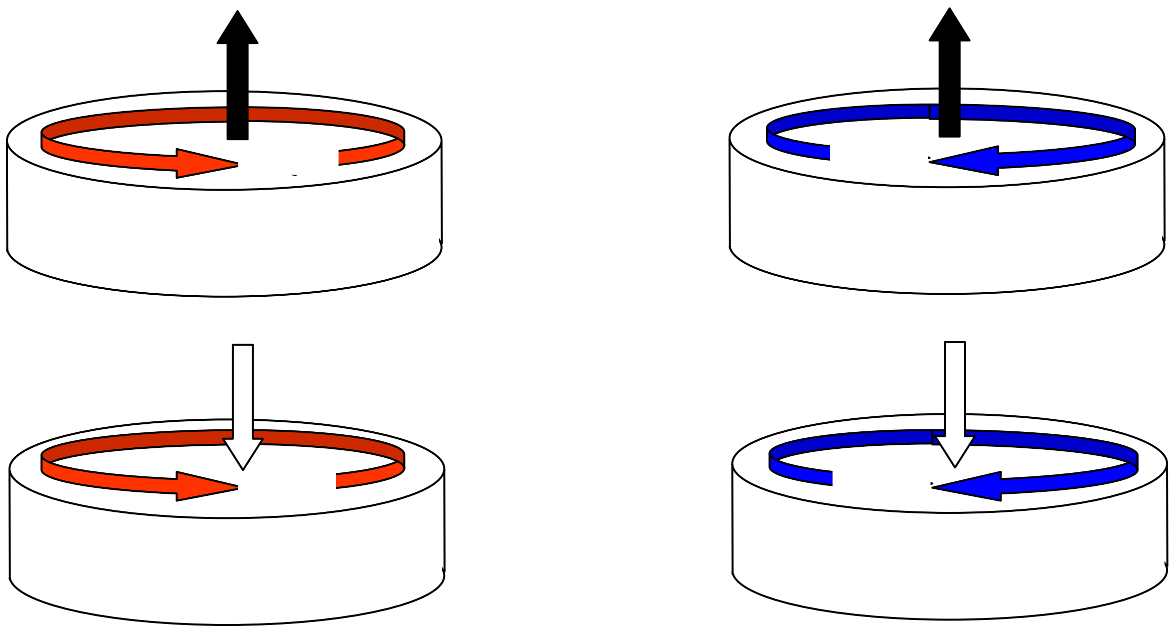
T. Shinjo et al.

M. Rahm et al.

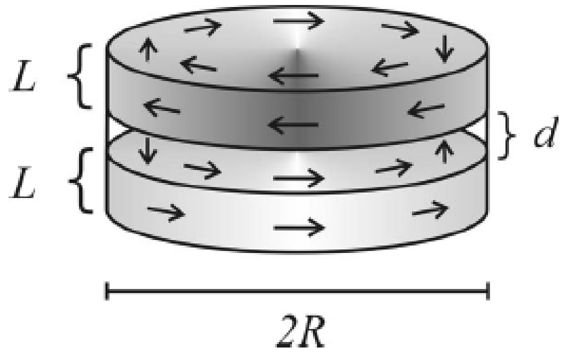
Chirality and polarity

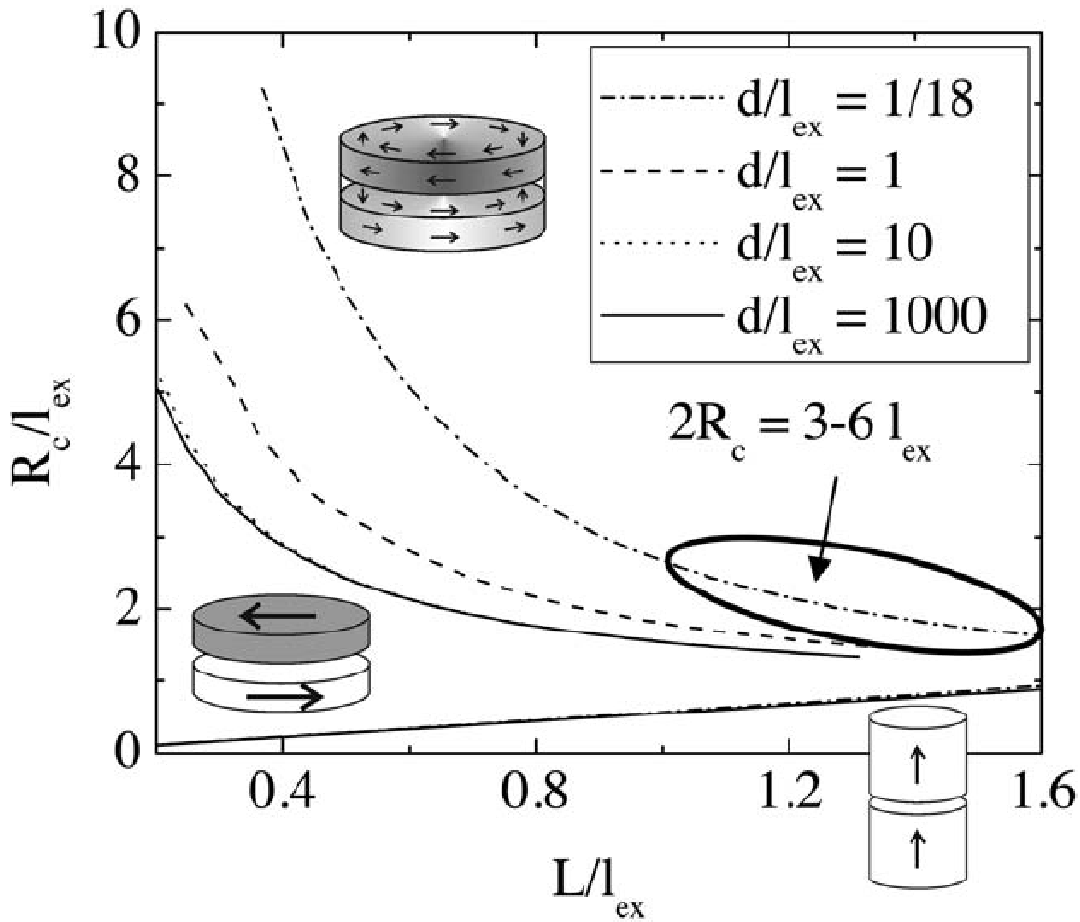
→ degrees of freedom = 4 instead of 2

→ higher density for storage devices



Coupling of magnetic disks

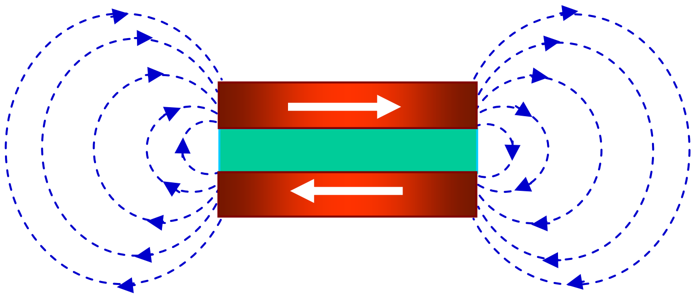




K.S. Buchanan et al. PRB **72**, 134415 2005

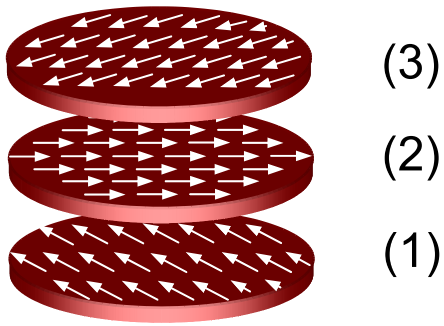
Dipolar coupling in the perpendicular direction

AF-coupling



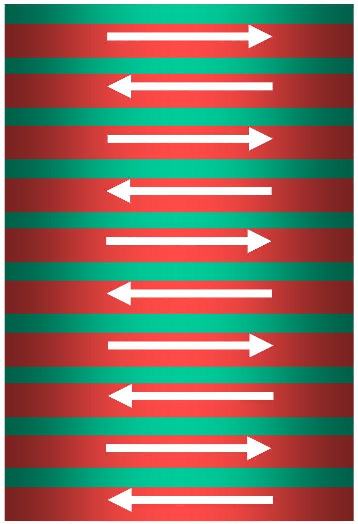
$$\theta = \pi$$

Spin helix



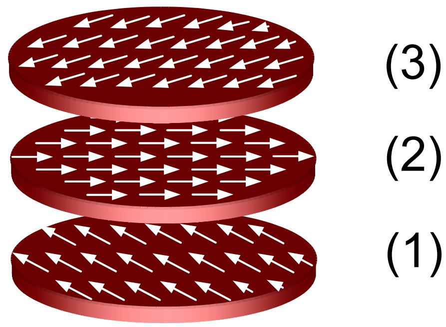
$$\theta = \frac{2\pi}{3}$$

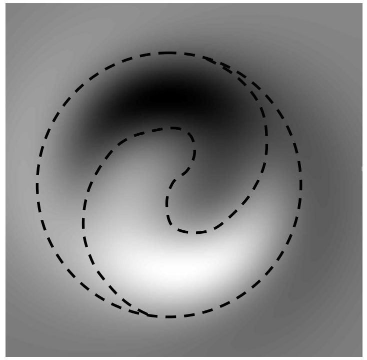
AF-spin chain



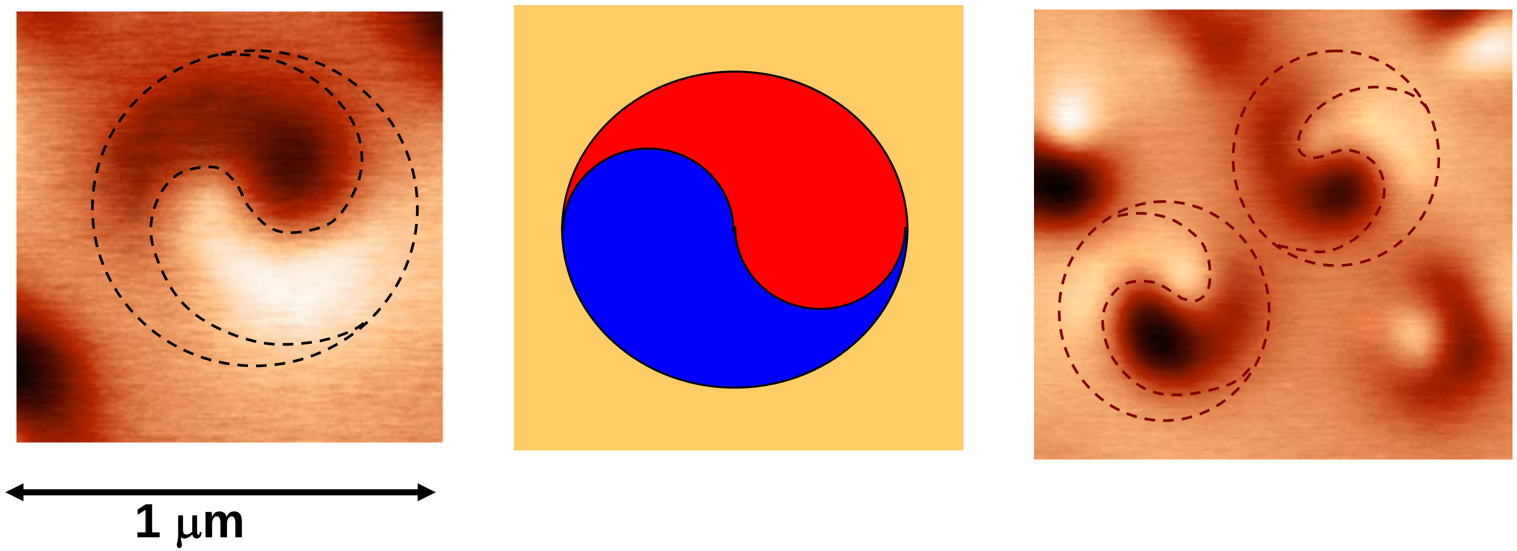
$$\theta = \frac{(n-1)\pi}{n}$$

MFM contrast of spin helix





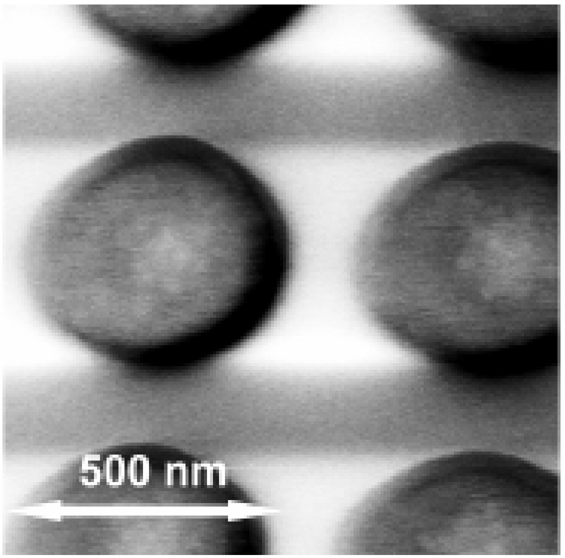
Simulated MFM contrast



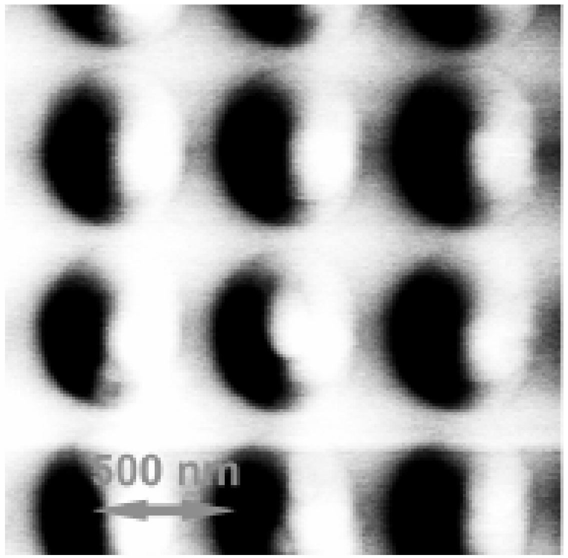
A.A. Fraerman et al. submitted

pin chain of 10 double layers

MFM contrast

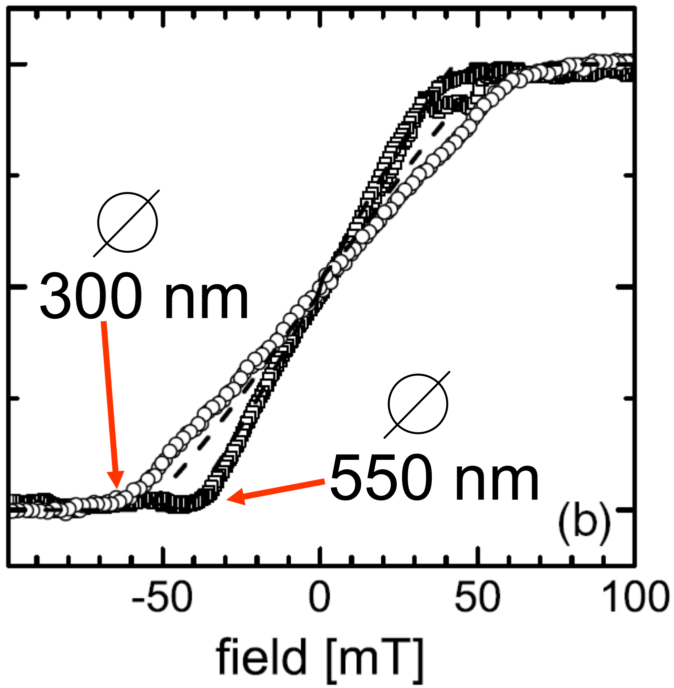


Remanence



30 mT

MOKE



M. van Kampen et al. J. Phys. Condensed Matter **17**, L27 (2005)

Thank you for your attention !