Magnetic nanoparticles in composite materials and devices

Snorri Ingvarsson

Technology in Society…, March 19 2004

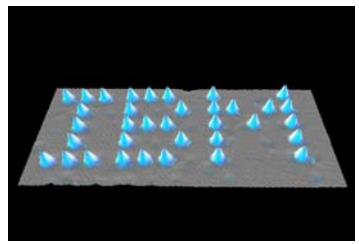
Research Division,
Yorktown Heights, NY

Nanoparticles?

- Nanoparticles are particles (typically crystals of inorganic elements) for which the largest characteristic dimension is ~1-100 nm (1nm = 10^{-9} m = 0.000000001 m).

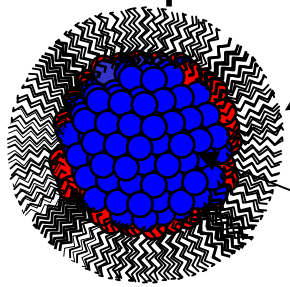
~100 μm = 0.1 mm

Human hair



Xe on Ni (110)

Nanoparticle



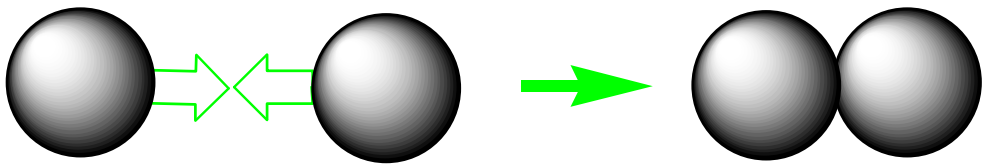
Ligand

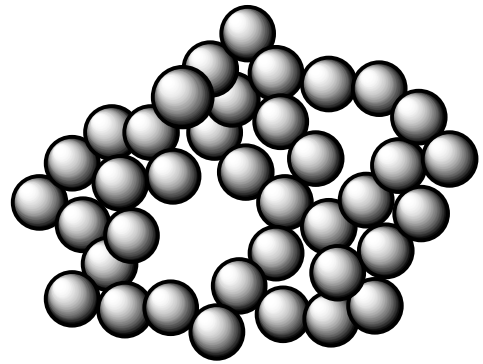
Atoms that form the spherical nanocrystal core.

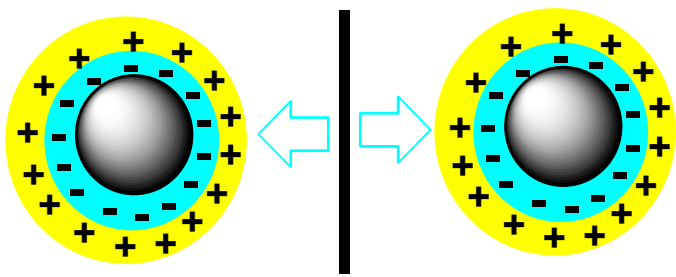
- They are sticky little things that adhere to anything (including each other)!
  Remedy: Coat them with “ligand” molecules.

Nanoparticle Stabilization

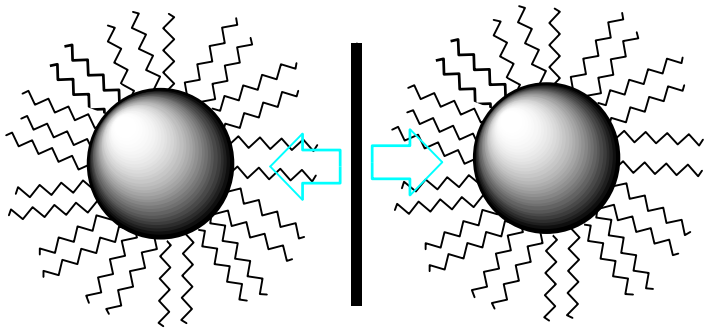
van der Waals
Magnetic Dipoles
Electric Dipoles







Electrostatic Repulsion

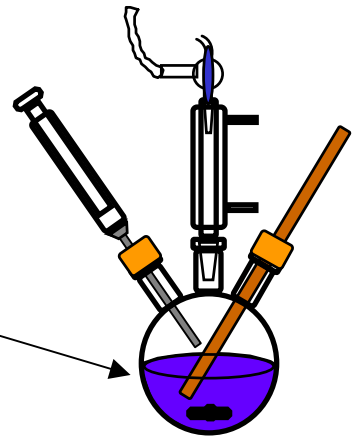


Steric Repulsion

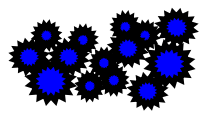
Monodisperse magnetic nanoparticle

Solution phase synthesis:

Dicobalt octacarbonyl, $Co_2(CO)_8$
Phenyl ether
Tributylphosphine
Oleic acid



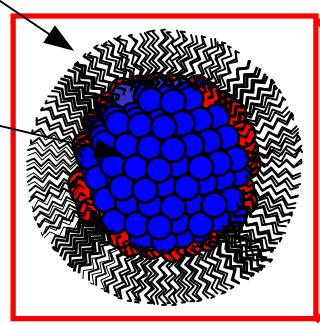
200 ˚C

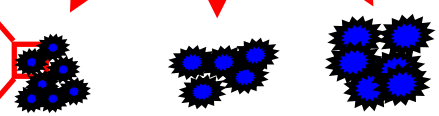


Size selective precipitation

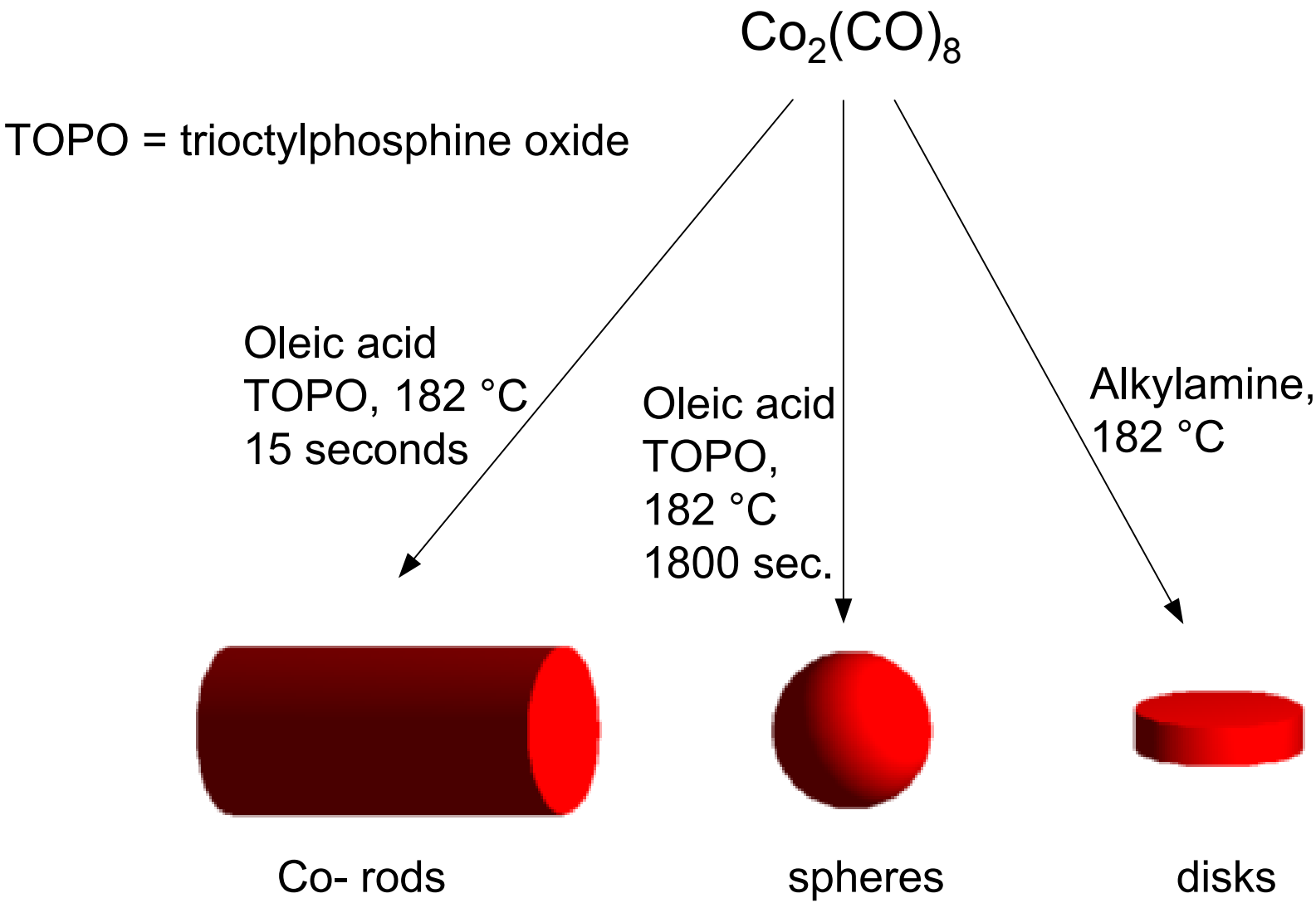
Ligand: Oleic acid

Co-nanocrystal core

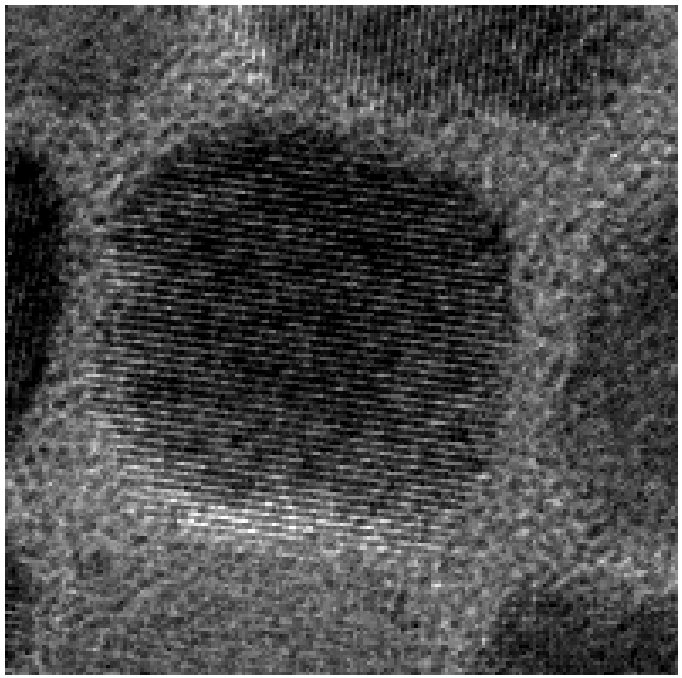


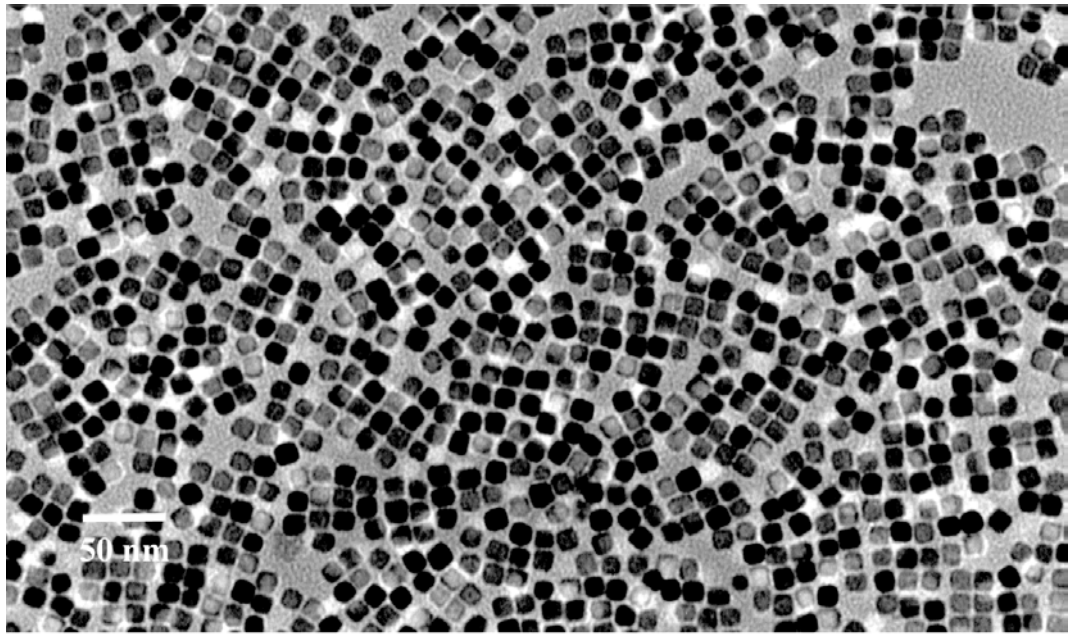


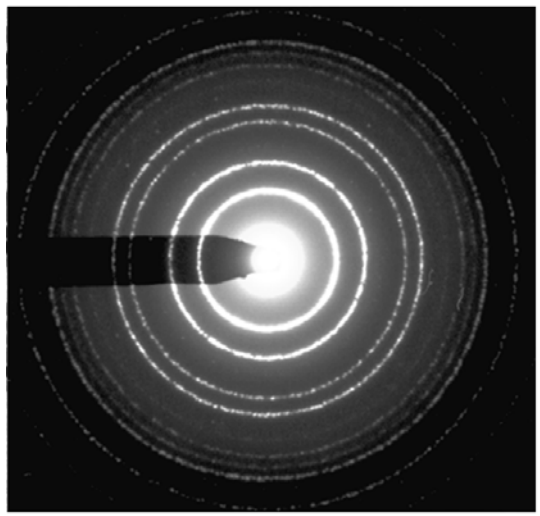
Ligand controlled morphology

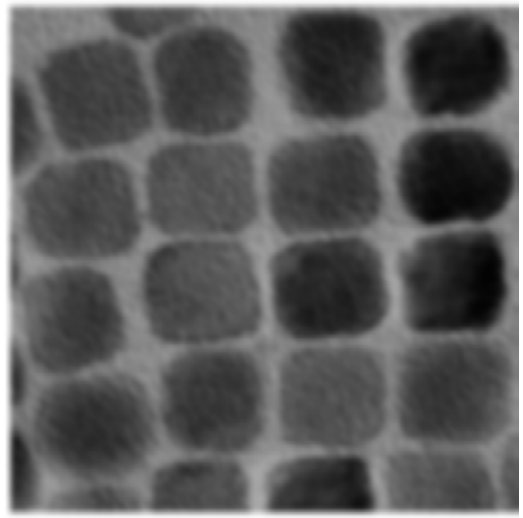


12 nm $SrTiO_3$ for Strontium titanium isopropoxide

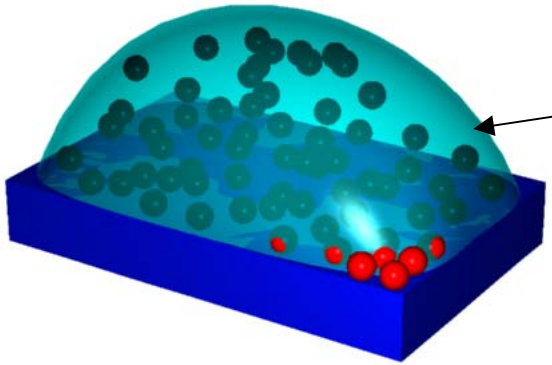






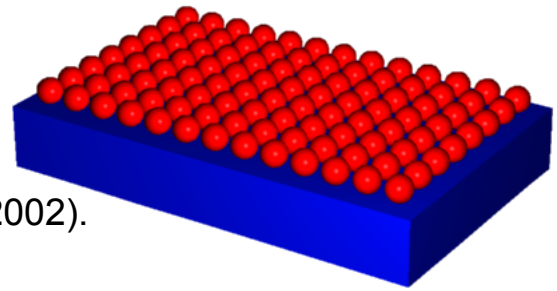


Self-assembly

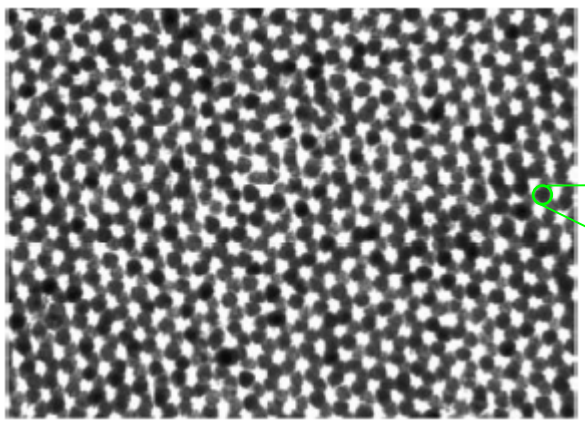


Under controlled evaporation particles self-assemble...

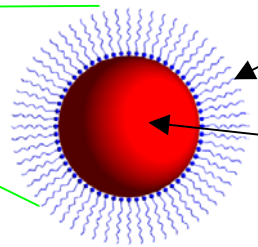
...into regular 2D (or 3D) arrays.



See e.g.: S. Sun *et al.,* J. Am. Chem. Soc. **124**, 2884 (2002).



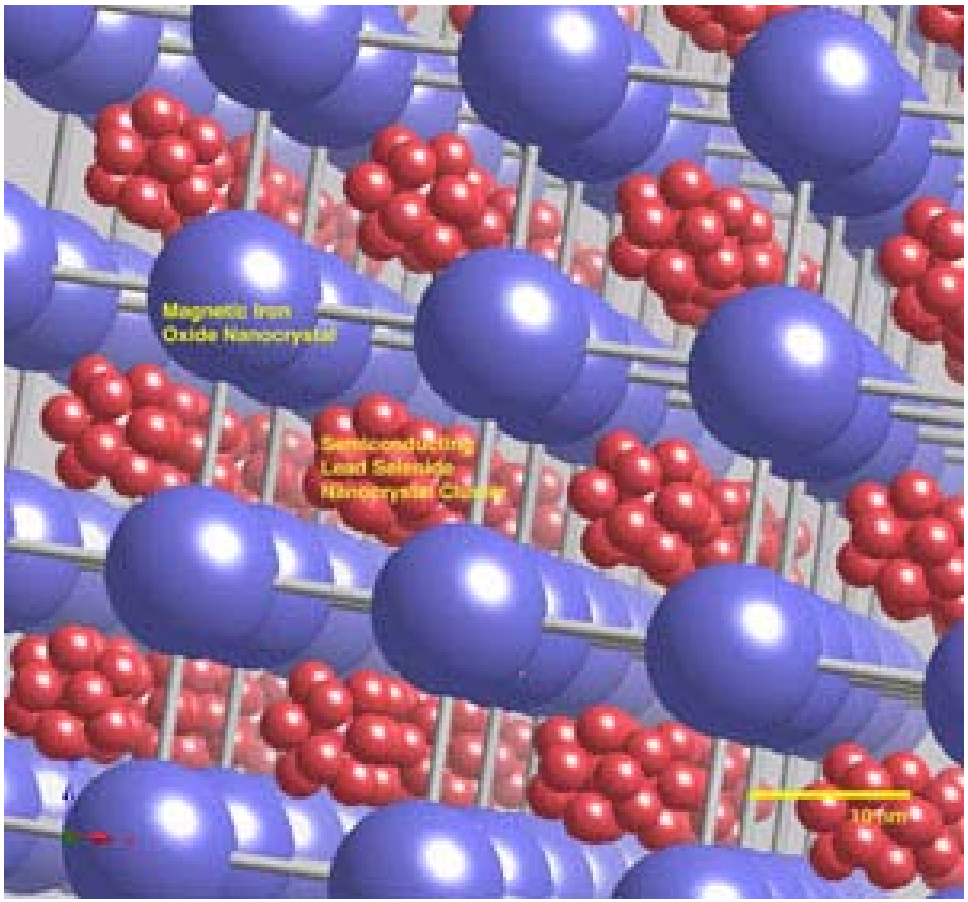
TEM of self-assembled array of 5 nm diameter Co particles with 2nm Oleic acid. [Woods *et al.* Phys. Rev. Lett. 87, 137205 (2001)]



Ligand: Oleic acid, 2 nm.

Co-nanocrystal. Diam. 3-12 nm.

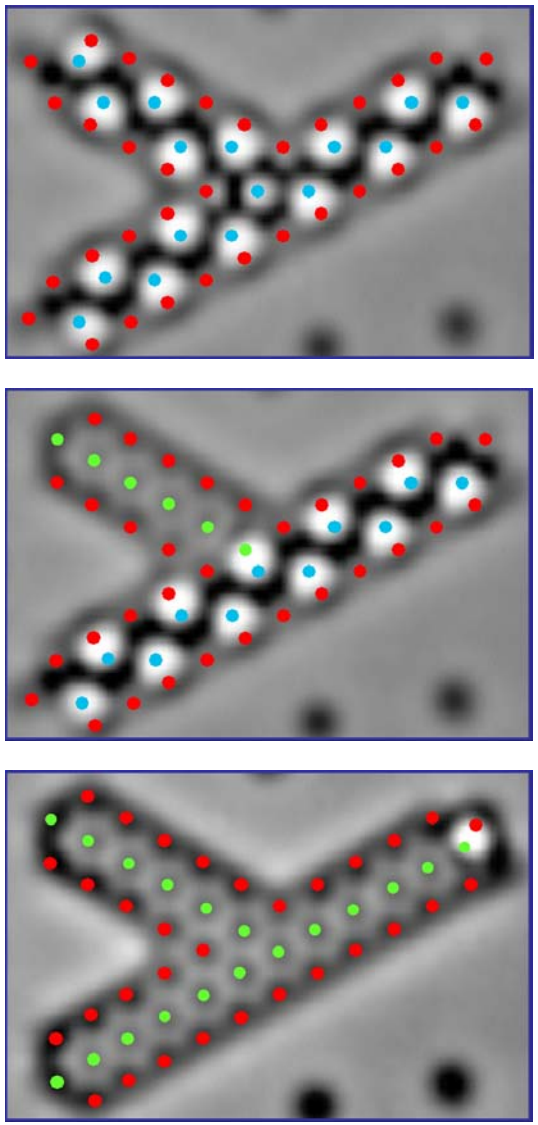
Why the sudden interest in NPs?



- **Monodisperse particles.**
- **Self-assembly:**
  - Can get “defect free” perfect lattices.
  - Can deposit films 1 monolayer thick…
  - …and monolayer by monolayer on top of that!
  - Can even grow *2 element 3D crystals!*

    (See: F. Redl *et al.,* Nature, **423**, 968 (26 June 2003).)

Molecular cascades computers!



From research.ibm.com

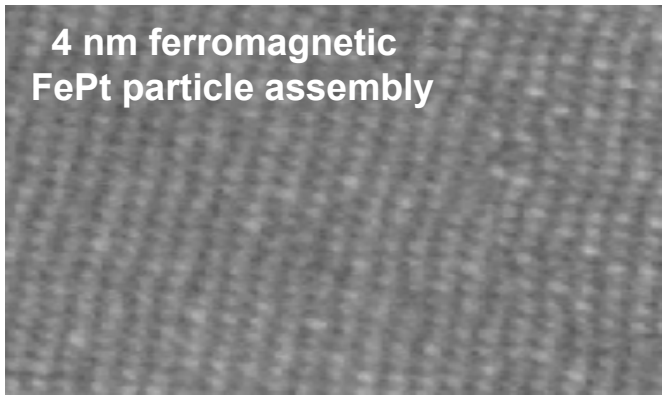
CO-molecules on Cu-surface. In an STM you can set up cascades that perform logic functions.

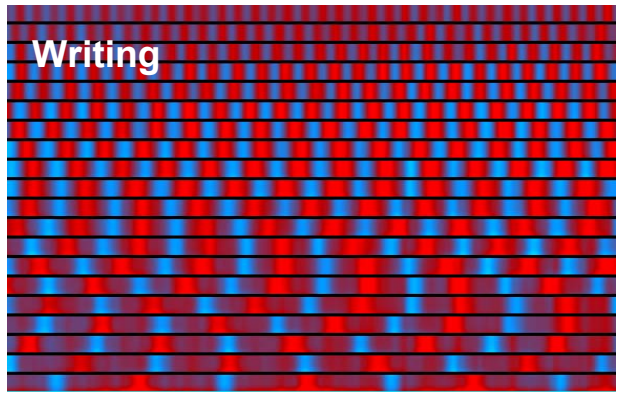
The example on the left is an AND gate, inputs on the left and outputs on the right.

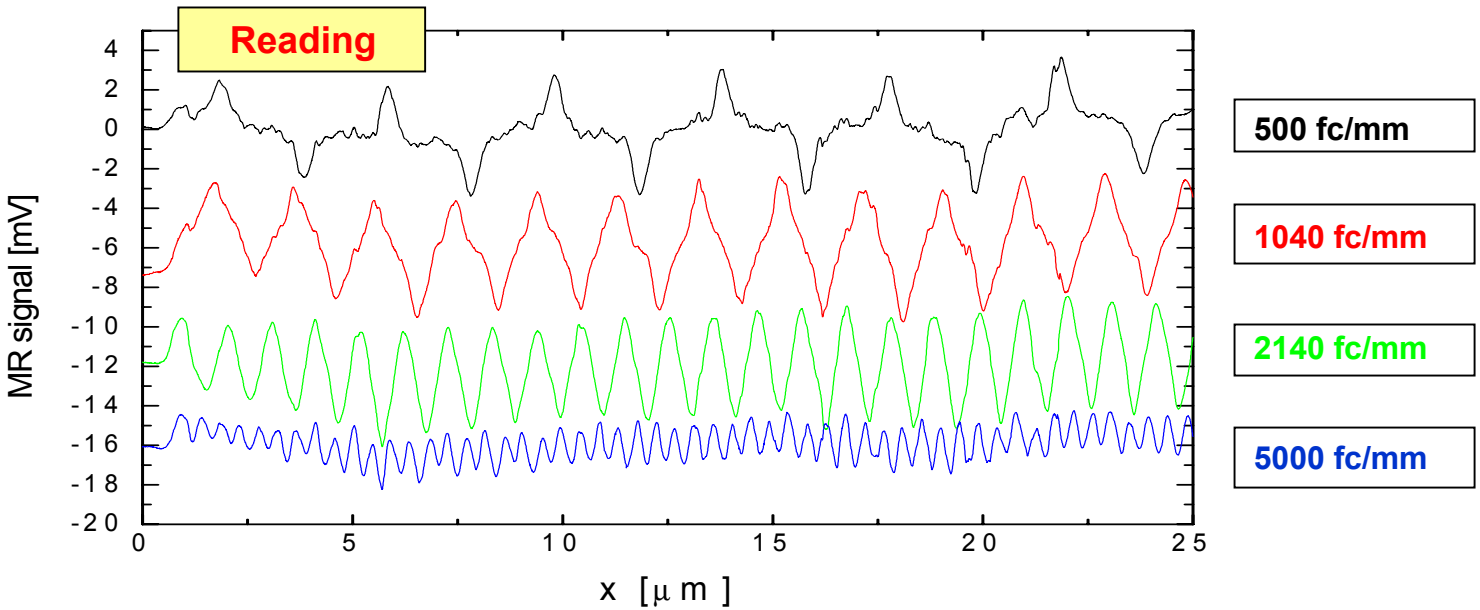
STM and e-beam (reading and writing with individual “needles”) is impractically slow, not scalable. Great for research purposes, not for industry.

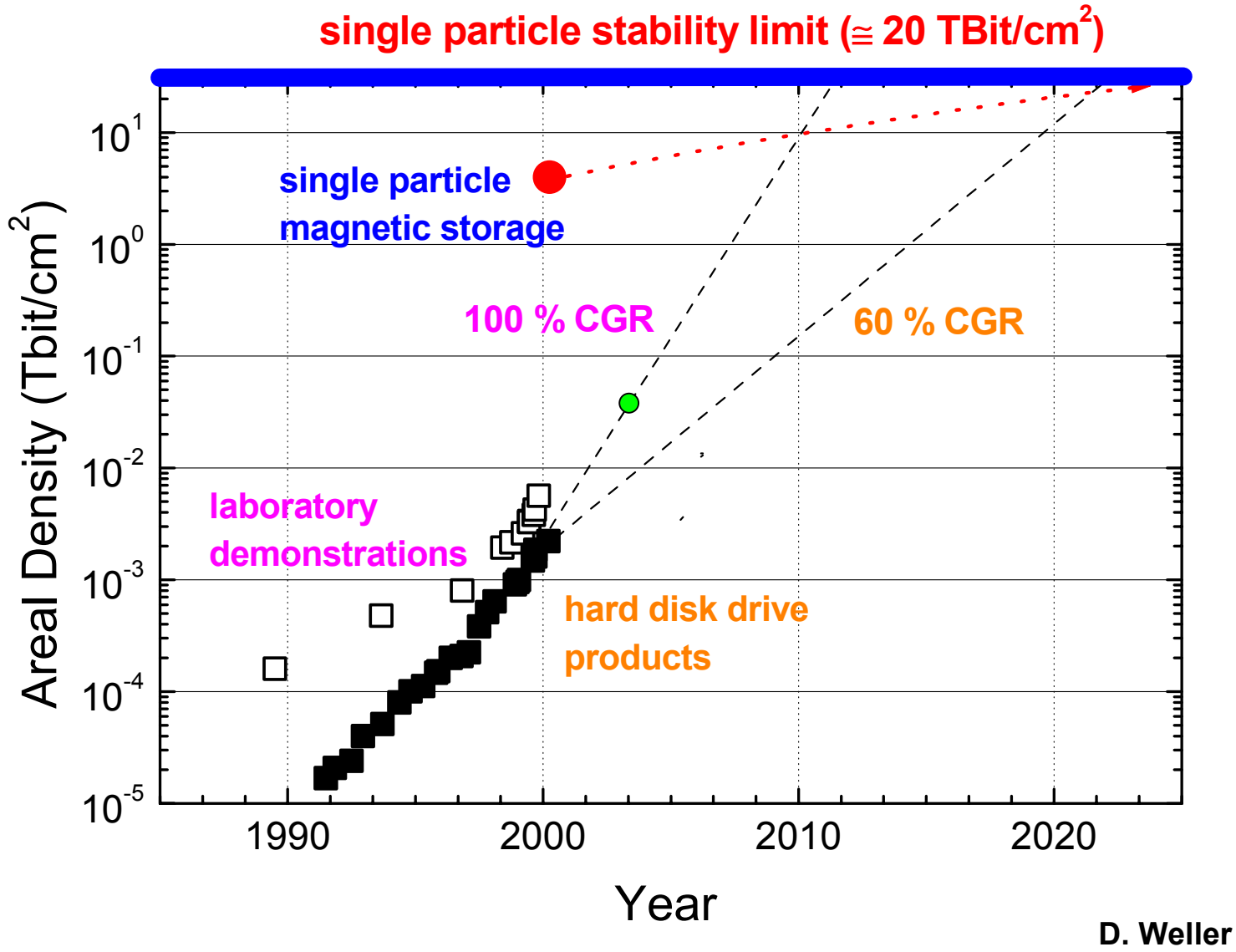
Preliminary Recording

(A. Moser, D. Weller)



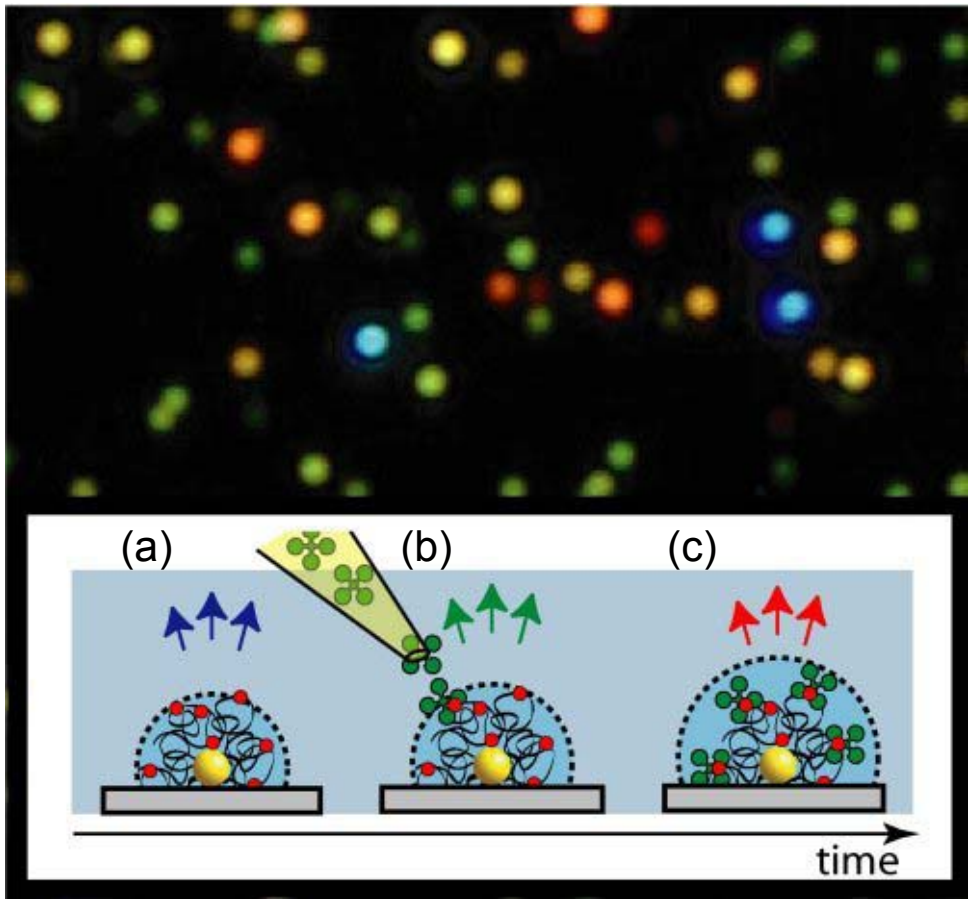





single particle stability limit (≅ 20 TBit/cm²)
single particle
magnetic storage
100 % CGR
60 % CGR
laboratory
demonstrations
hard disk drive
products
Areal Density (Tbit/cm²)
Year
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
1990
2000
2010
2020

D. Weller

Biosensors: Surface plasmons

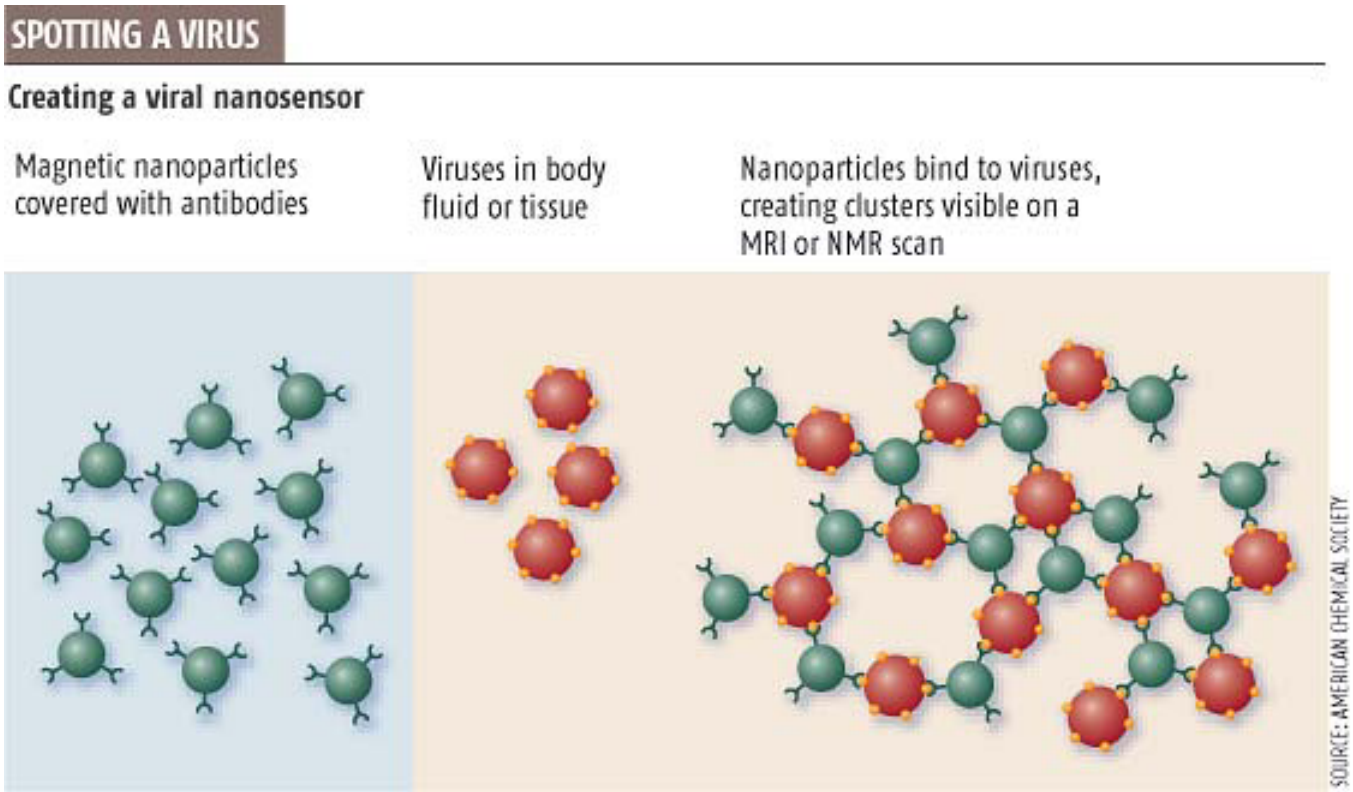


From Nanotechweb.org, July 2003

Wavelength of scattered light depends on dielectric surroundings.

(a) A single 40 nm Au nanoparticle functionalized with biotin-BSA molecules.
(b) Solution injected with the protein streptavidin.
(c) Streptavidin bound to biotin on Au-surface.

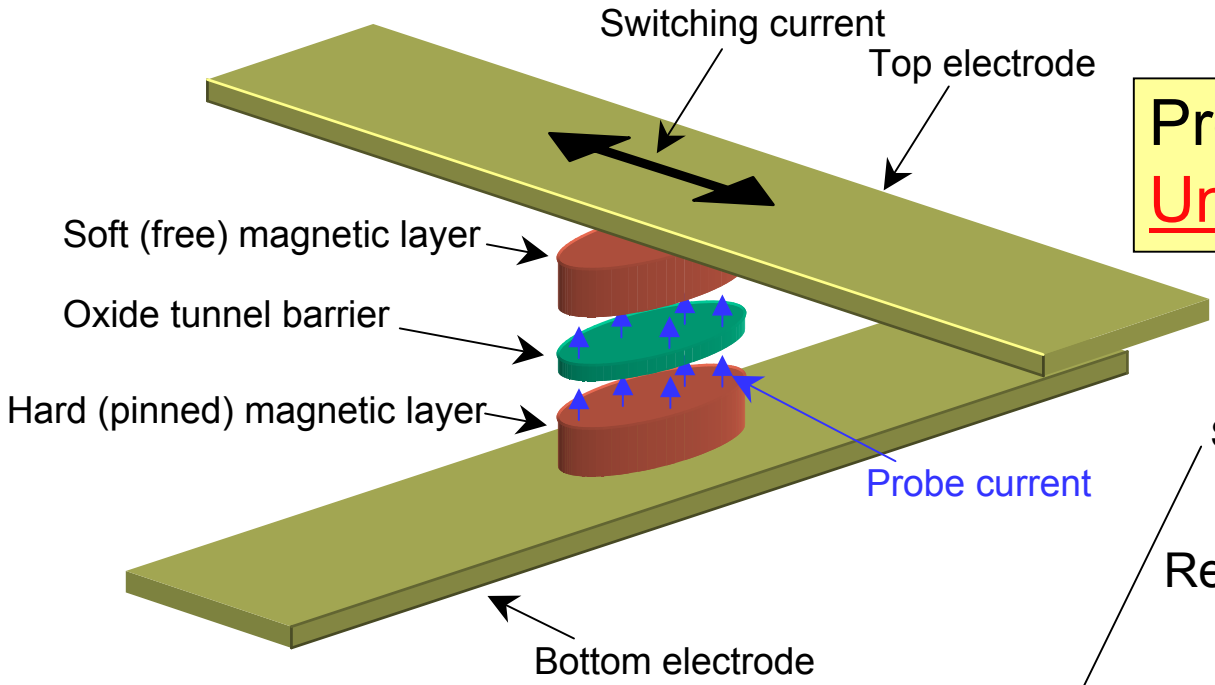
Sticking viruses to nanoparticles



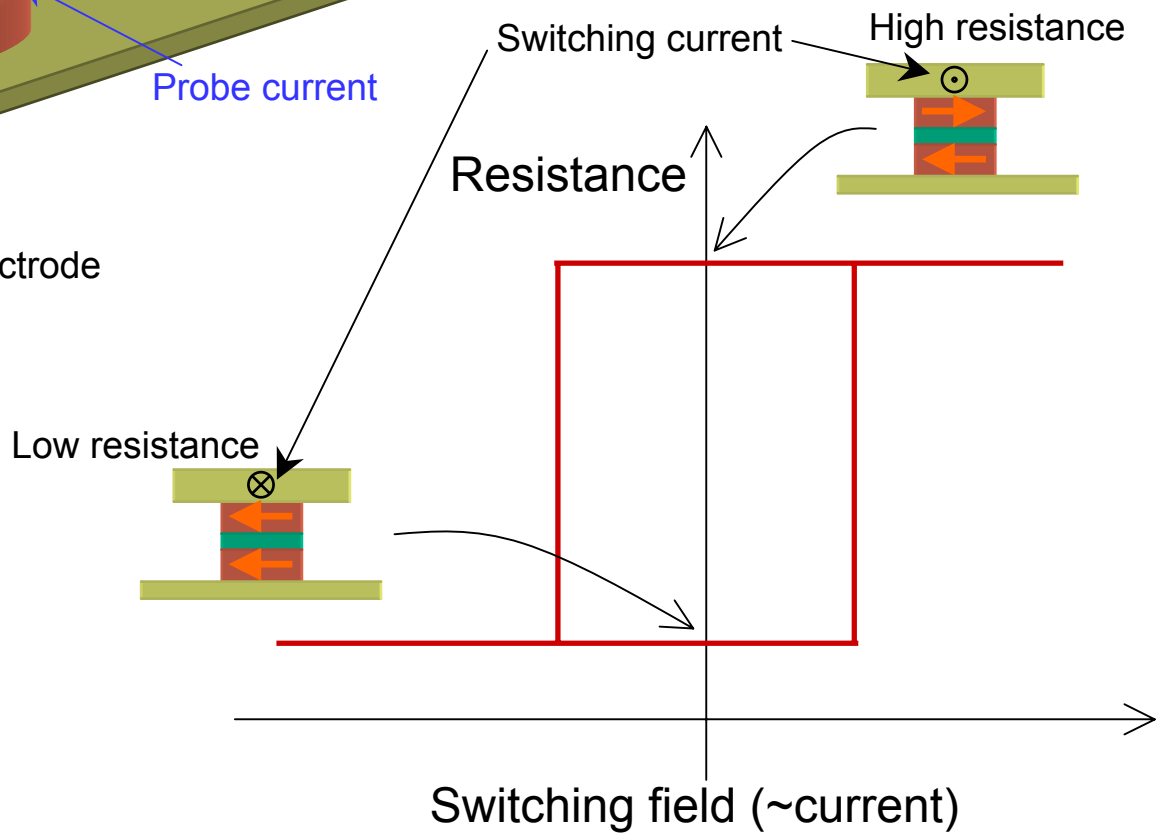
From New Scientist, August 2003

Iron oxide nanoparticles coated with dextran (a sugar), to which antibodies easily attach.

Magnetic tunnel junction memory



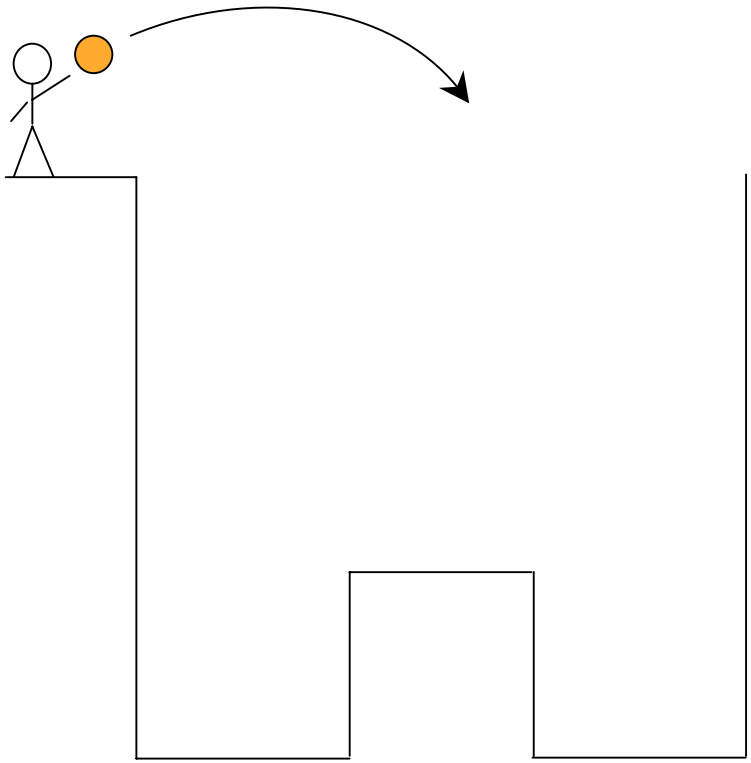
Problem 1:
Underdamped dynamics.



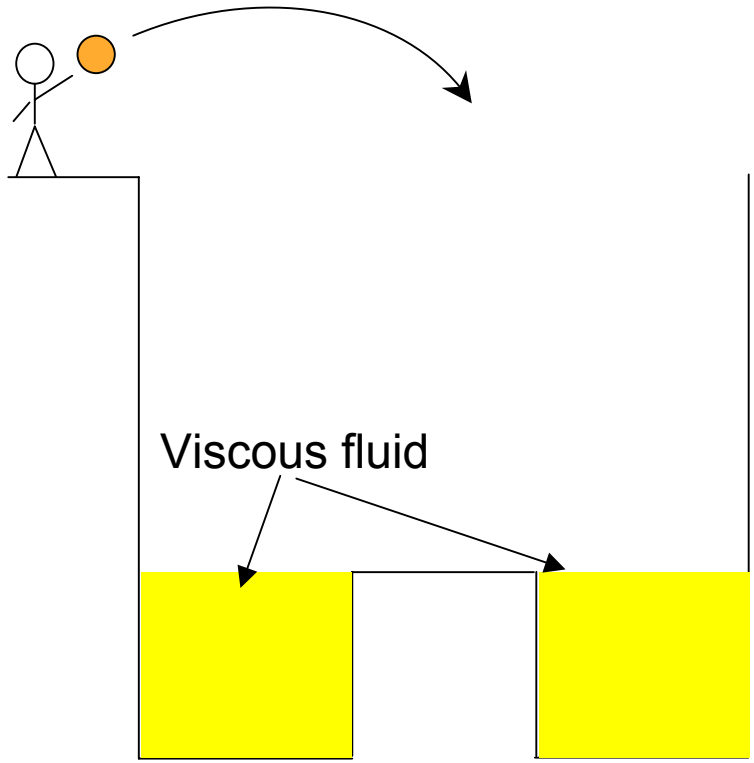
Magnetoresistance:

$$\frac{\Delta R}{R_{low}} \approx 0.2 - 0.5$$

Underdamped dynamics 101:

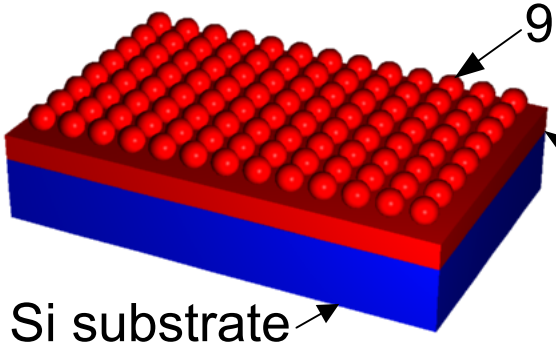


No good. Ball bounces back and forth.



Good. Ball ends up in the slot you aimed for.

Increased damping with particles



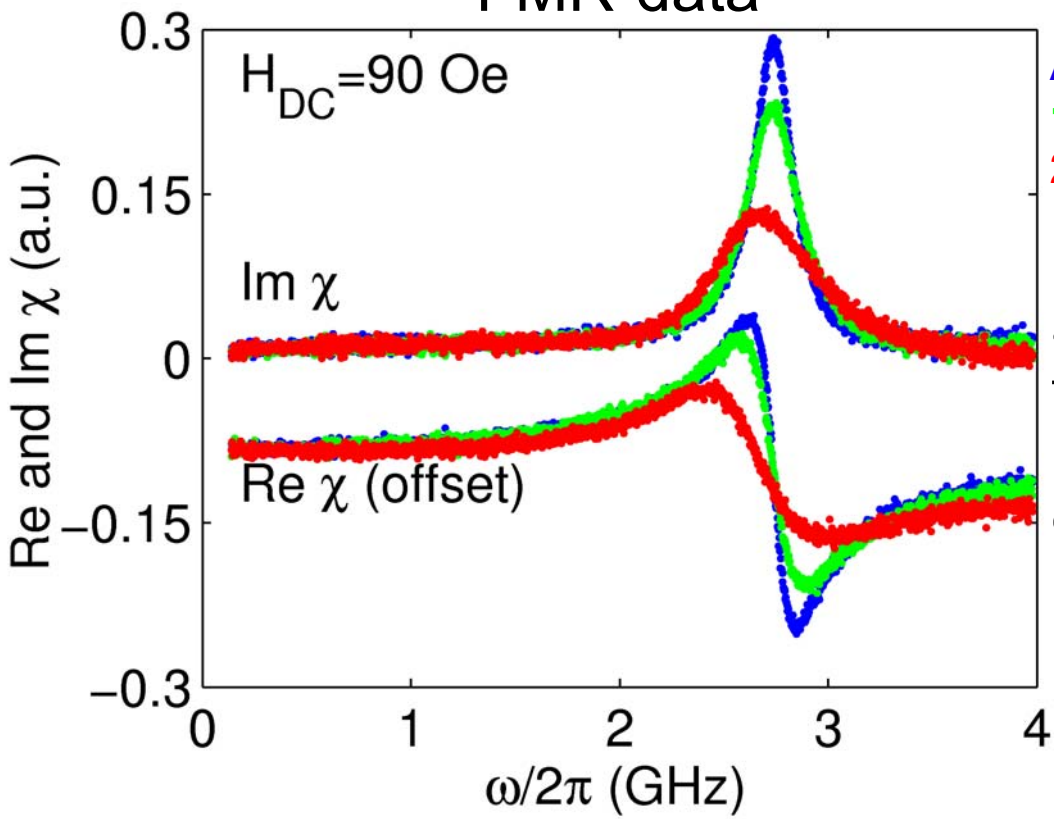
9 nm diam. εCo (D077) nanoparticle array.

Separated by 2-5 nm of polymer, *no exchange* coupling.

Permalloy ($Ni_{81}Fe_{19}$): 30 nm thick,
1.8 mm diameter disk.

Si substrate

FMR-data



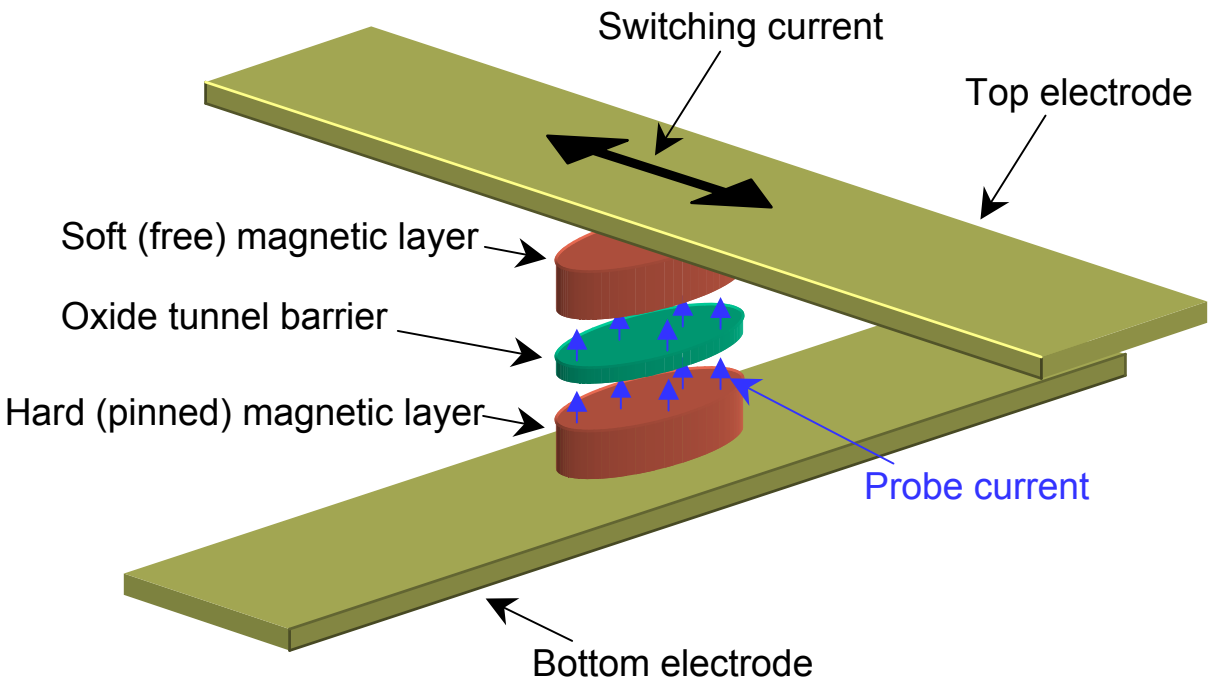
As-grown NiFe-disk
1st particle deposition
2nd particle deposition

Resonance broadens and shifts to lower frequencies as more particles are deposited.

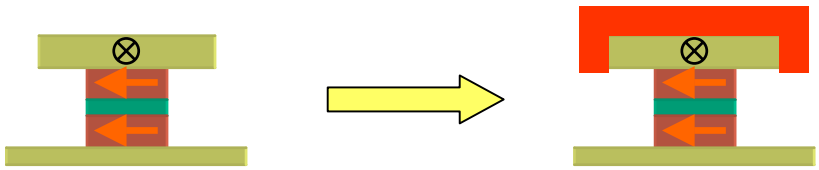
200% increase in damping!

Problem 2:
Large electrical currents cause heating.

- Bit is more stable if anisotropy is large…
- …**but** requires a higher switching field/current.
- That means increased heating…there's too much of that in computers already!

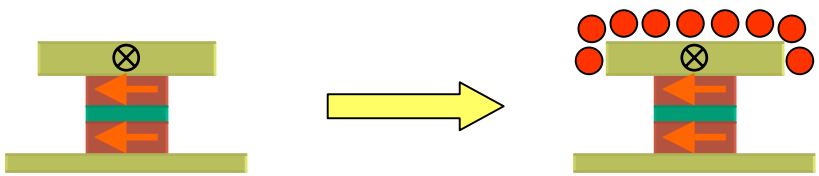


Magnetic liners



Increases field.

Magnetic poles disturb.
Usually some hysteresis.



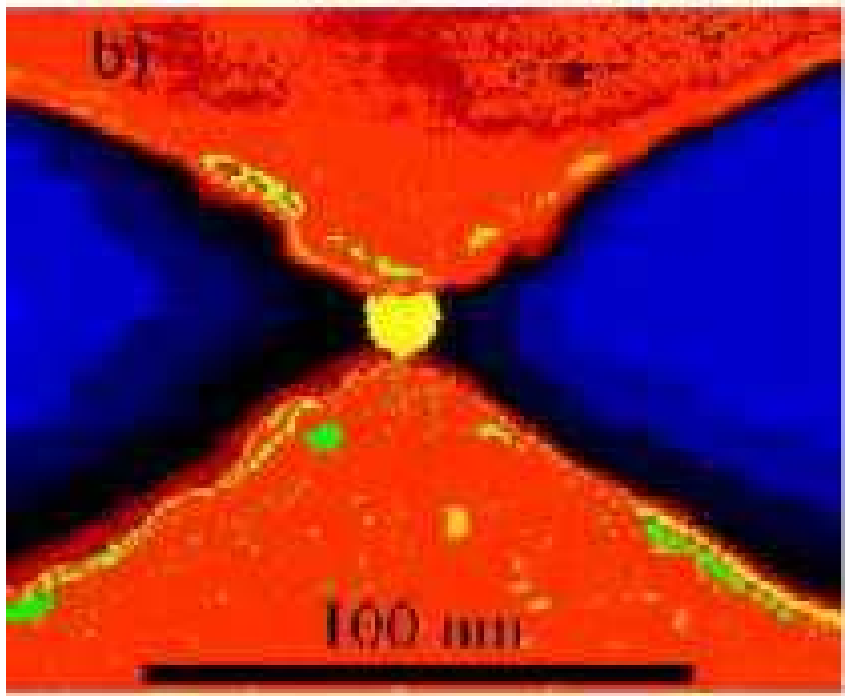
Increases field.

No magnetic poles.
No hysteresis.

Unique magnetic properties of nanoparticles provide a *significant improvement* over other liners.

Iðntæknistofnun-Háskóli Íslands

"***Trapping and characterization of an individual nanoparticle***".



A 20 nm diameter Pd nanoparticle trapped between two Pt electrodes patterned on top of a Si/SiN substrate. (From A. Bezryadin et al., *Appl. Phys. Lett.* **71**, 1273–1275 (1997)).

Future: Stretch *molecules* across such a gap, venturing into molecular electronics. Collaborate with theory groups at Háskóli Íslands.

What does nanotechnology bring us?

New research tools.

Composite materials.

New devices, gadgets.

Opportunity to explore and to do things we weren't able to do before.

Some nanoparticle (NP) applications

Magnetic NP:

- Harder permanent magnets (i.e. larger coercivity).
  Hao Zeng *et al.* Appl. Phys. Lett., **80**, 2583 (2002).
- Contrast agents in MRI imaging.
- Bioconjugated nanoparticles in medicine. Attach to cancer cells. Destroy cancer cells? Antibodies that viruses stick to.
- Purification of cells and biomacromolecules from complex mixtures.
- High frequency (radio freq.) electromagnetic properties.
  Ingvarsson *et al.* 2 patent applications.

Magnetic and other NP:

- Catalysts (A/V ~ 1/d).
- Seeds for C-nanotubes.
- Self-assembled quantum dots. C. B. Murray *et al.* J. Am. Chem. Soc. **115** (1993).
- Size-tunable infrared electro-luminescence (1000 – 1600 nm) in PbS nanocrystals embedded in semiconducting polymer.
  L. Bakueva *et al.*, Appl. Phys. Lett., **82**, 2895 (2003).
- Electro-optical and magneto-optical applications.
- Biosensors. (Surface plasmons in Au e.g.).
- Paper preservation (aging) with Calcium Hydroxide NPs.