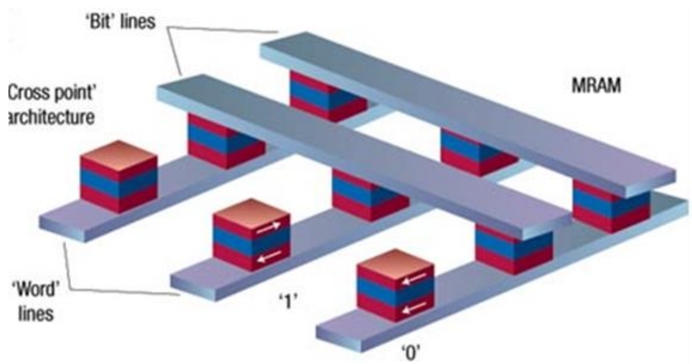
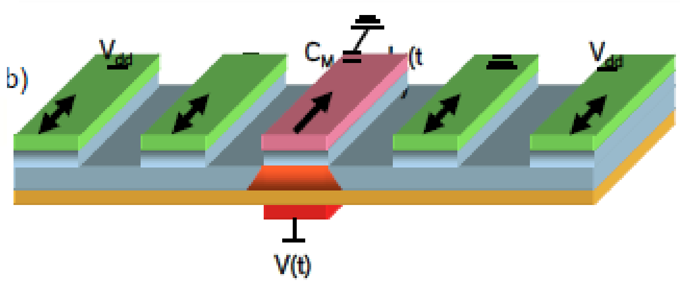
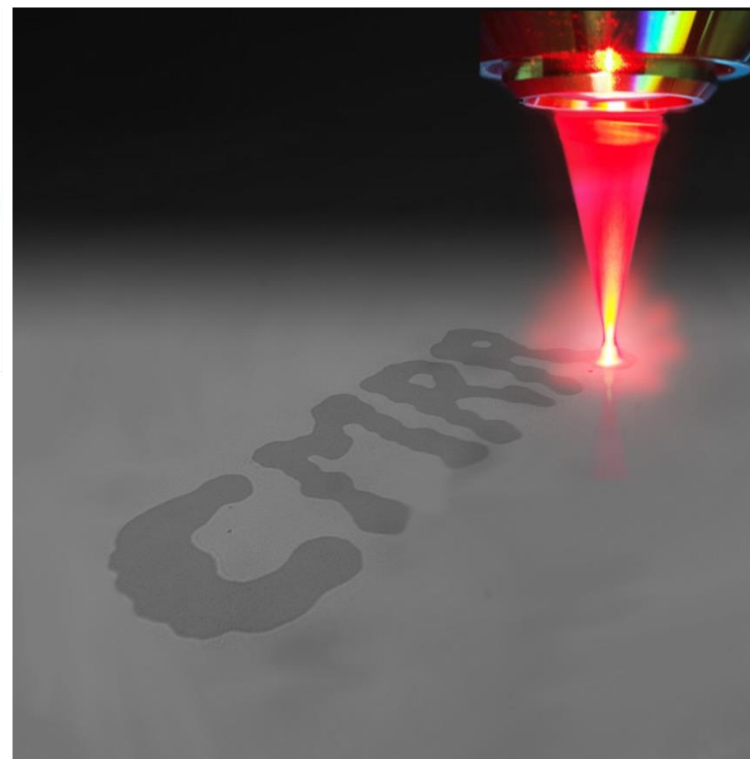
Bits of the Future: Emergent Physics for Advanced Magnetic Information Technologies

Eric E. Fullerton
Center for Magnetic Recording Research
University of California, San Diego







Bits of the Future: Emergent Physics for Advanced Magnetic Information Technologies

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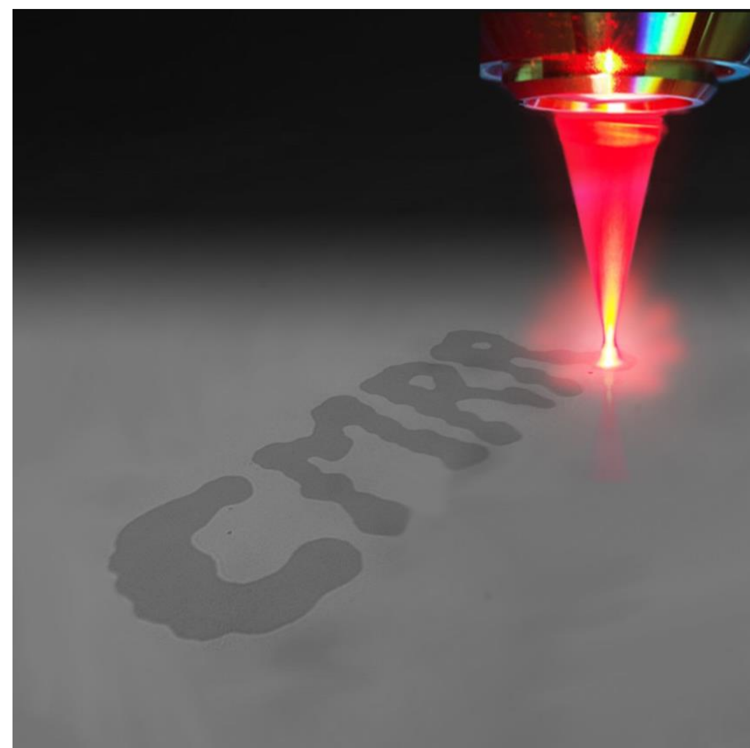
- A bit of history and introduction
- All-optical control / storage
- Current control / memory
- Conclusions and outlook

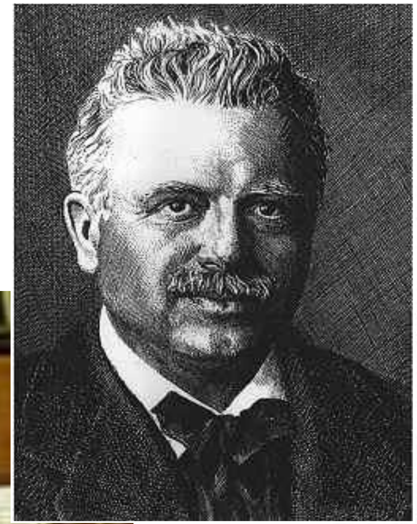


UCSD

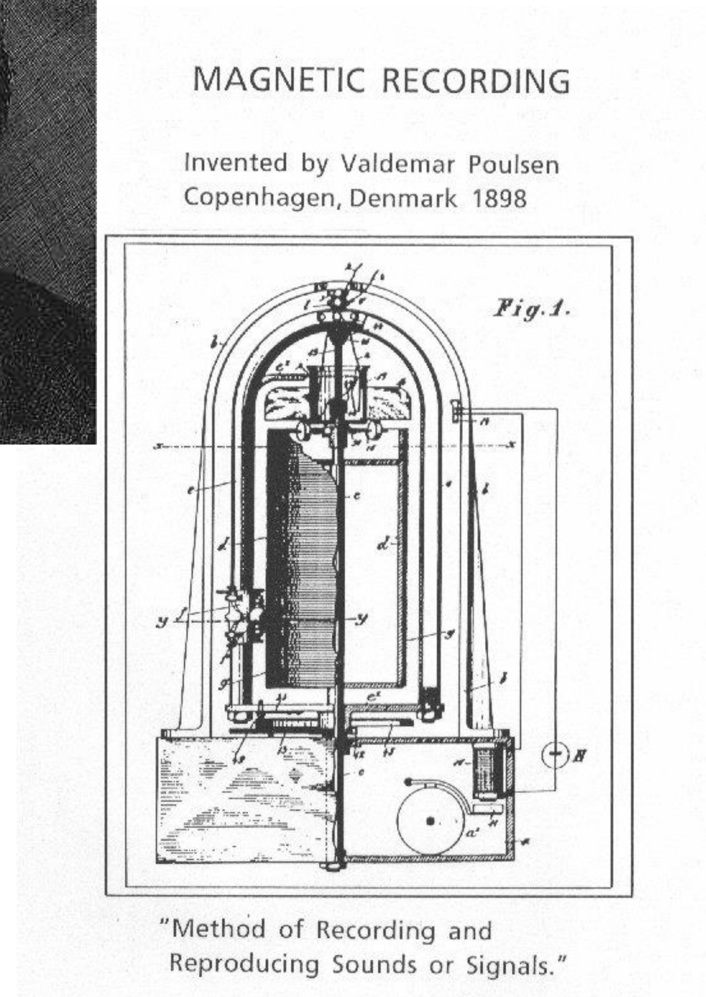
First magnetic recording 1898

Magnetic Recording Invented

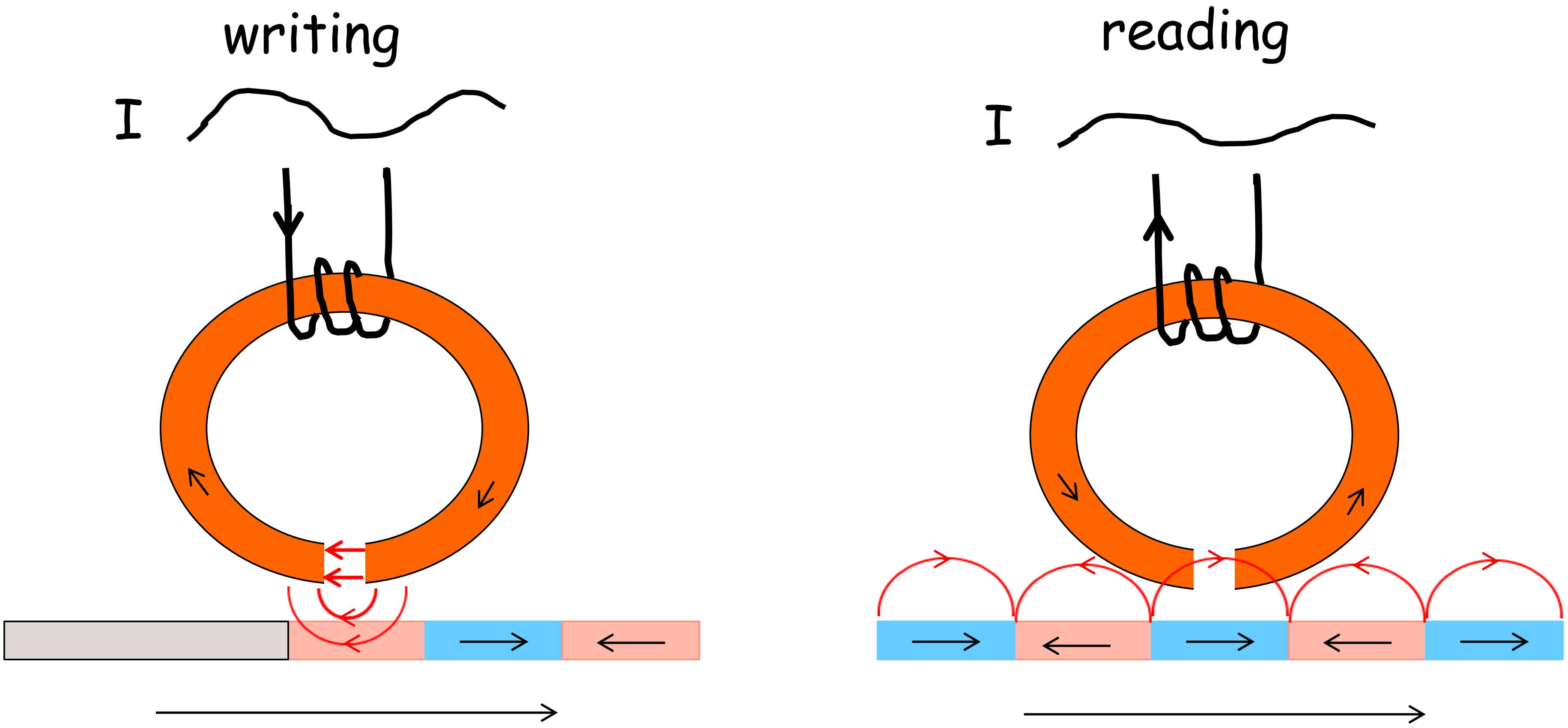
Valdemar Poulsen



Valdemar Poulsen's wire recorder from 1898
(Danish technical museum www.tekniskmuseum.dk)



Magnetic recording



Killer applications

patent

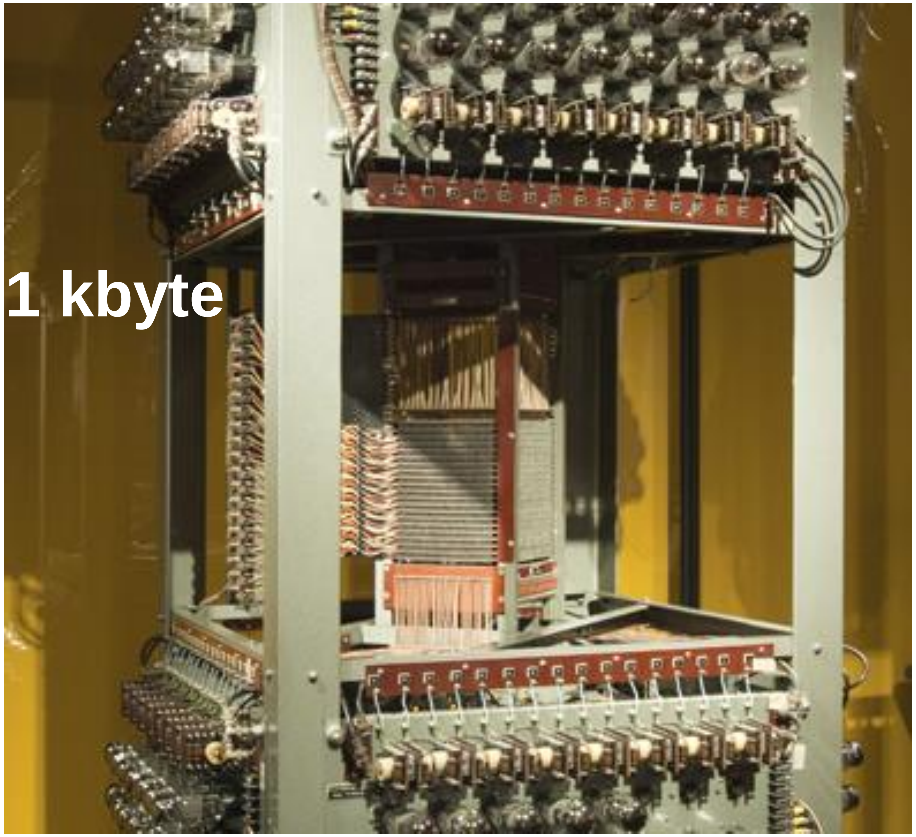
The invention is of great importance for telephonic purposes

phone communications can be received by the apparatus when the subscriber is absent, whereas upon his return he can cause the communications to be repeated by the apparatus.

If, for example, the message, "The subscriber is not at home at present, but will return at four o'clock, at which time please ring again," is fixed to the steel wire

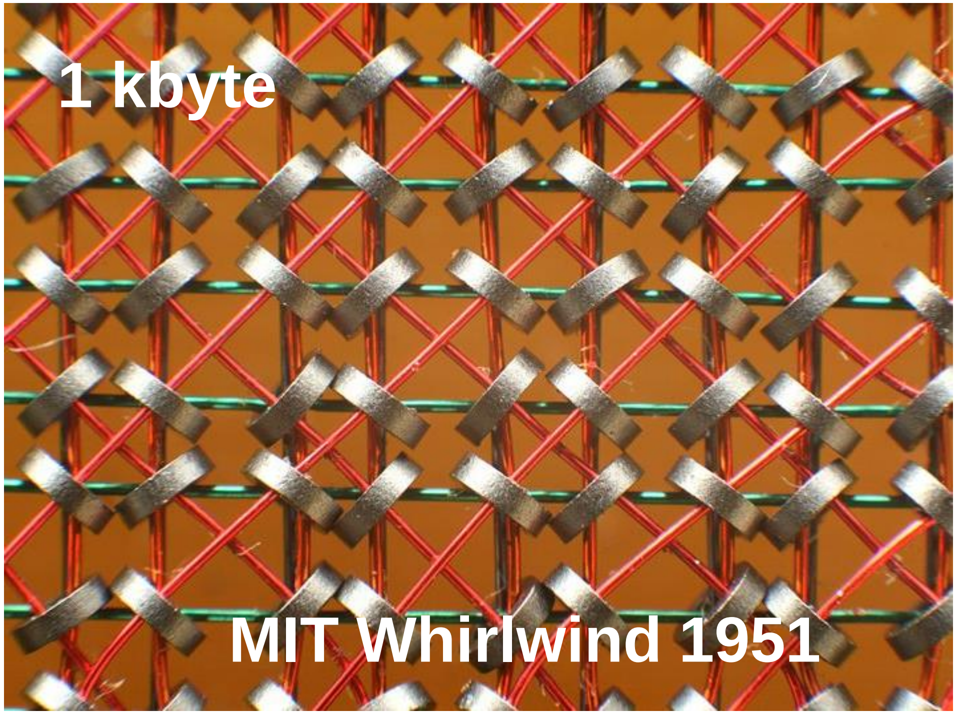
Digital magnetic storage/memory

RAMAC 1956



MIT Whirlwind 1951

Digital magnetic storage/memory



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

Cell Size: 1 mm^2
Access time: 10 microseconds
Destructive read
Cost: $1/bit

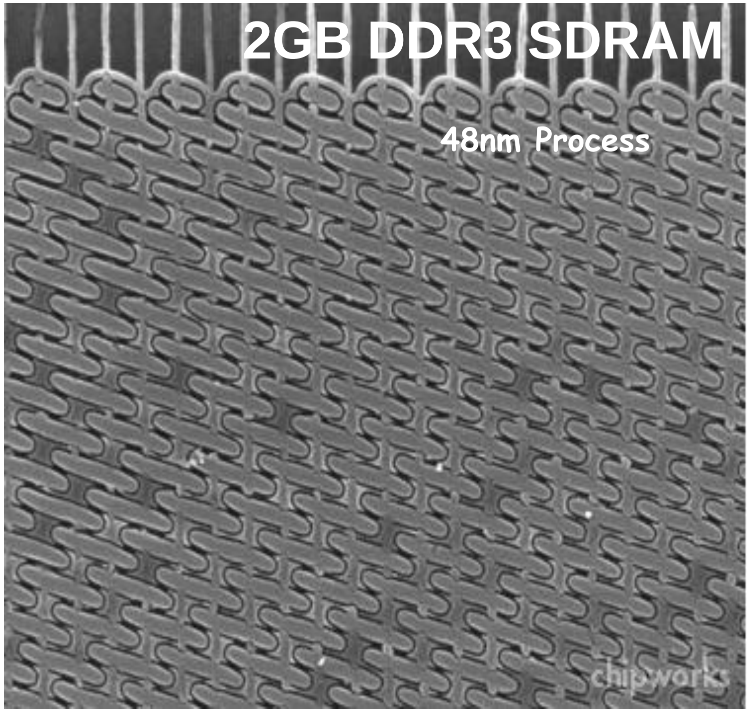
Current storage/memory

500 Gbyte mobile drive

1 x 2.5”
glass disk

630 Gbits/in^2 (3x10^8)
1.4 Gbits/s (2x10^4)
Non-volatile
$0.15/Gbyte

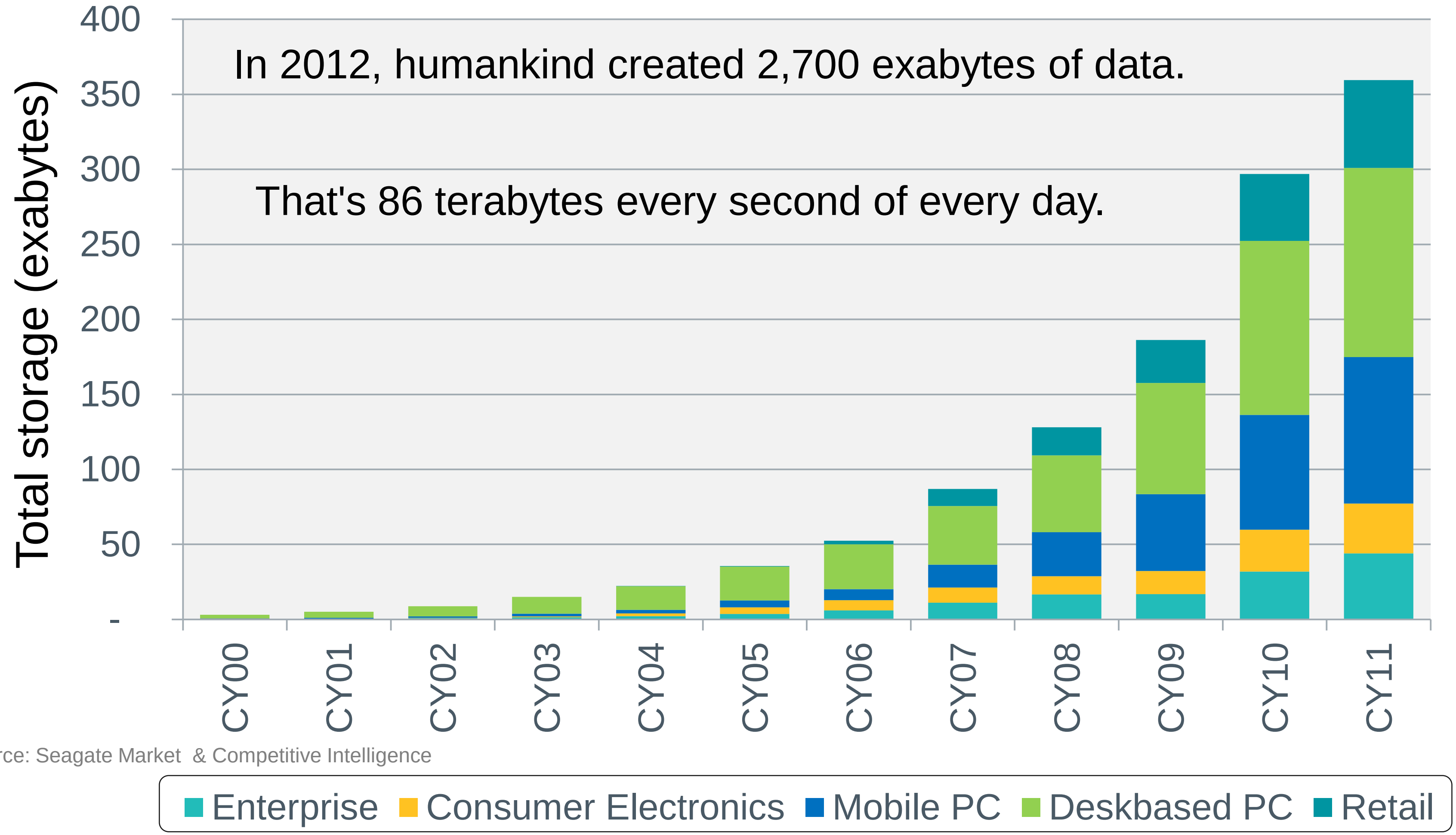
Samsung 2011



Cell Size: 0.0092 μm^2 (~10^8)
20 nanoseconds (~10^3)
Volatile
Cost: $0.25/gigabit

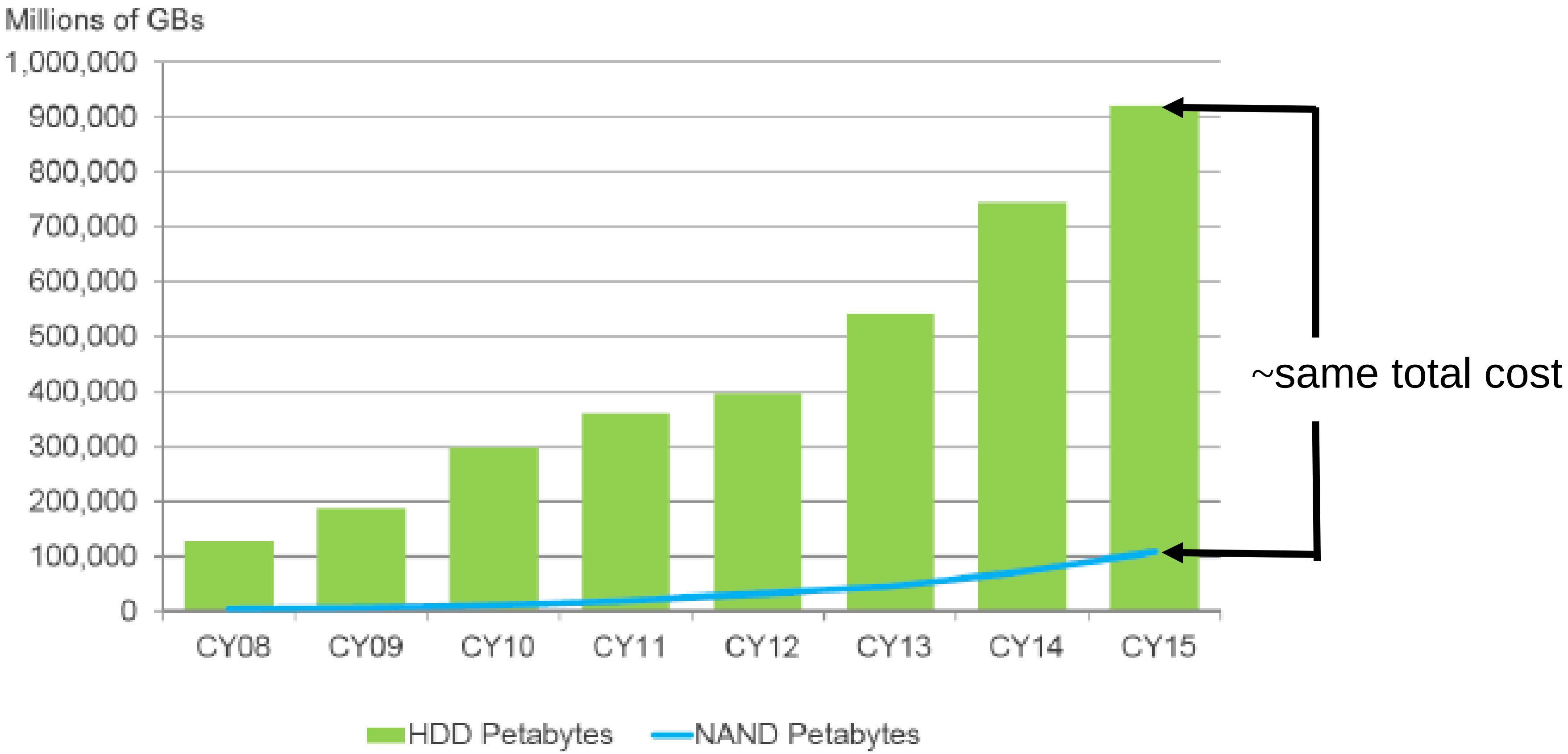
Total hard-drive capacity

Exabyte = 1 million terabytes or 1 billion gigabytes or



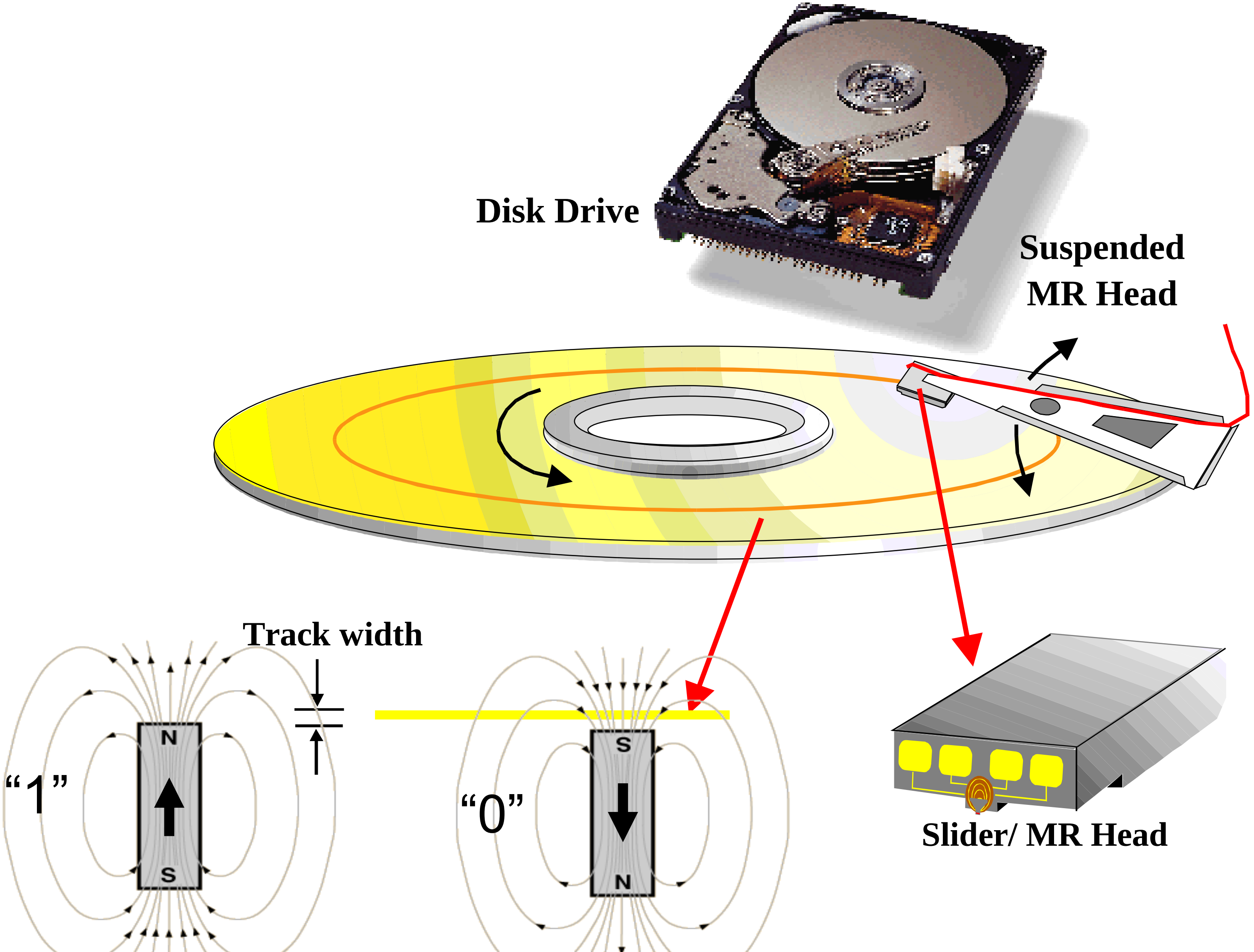
Source: Seagate Market & Competitive Intelligence

Hard-drives vs. solid state drives

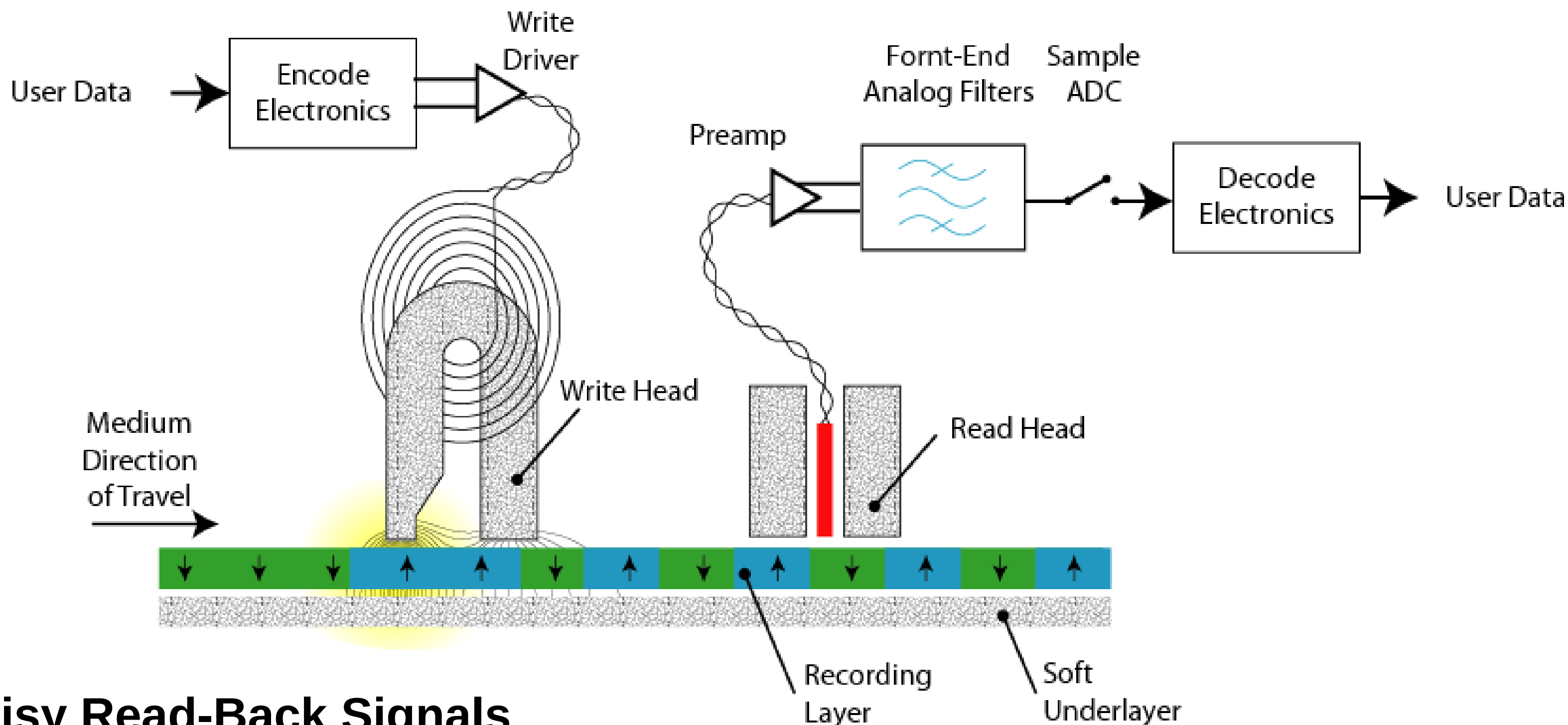


Source: Seagate Market & Competitive Intelligence

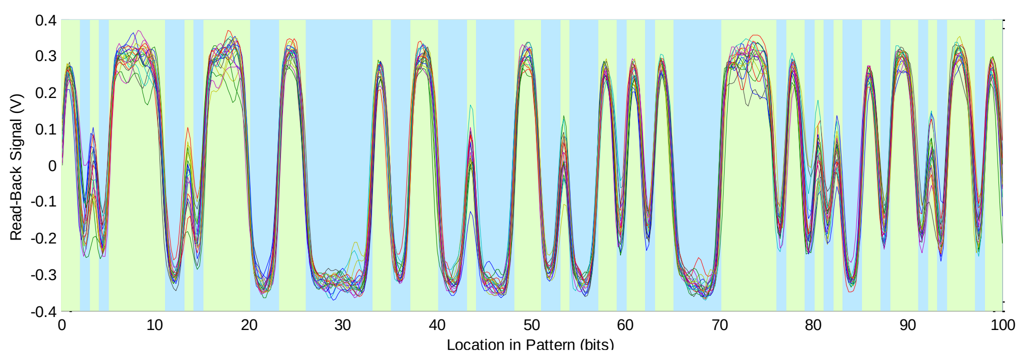
Disk drive basics



Magnetic recording



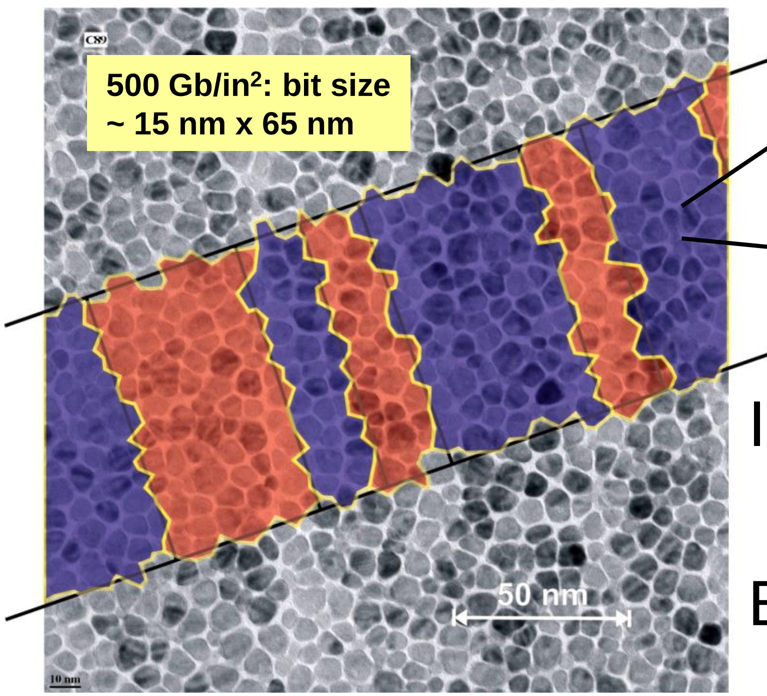
Noisy Read-Back Signals

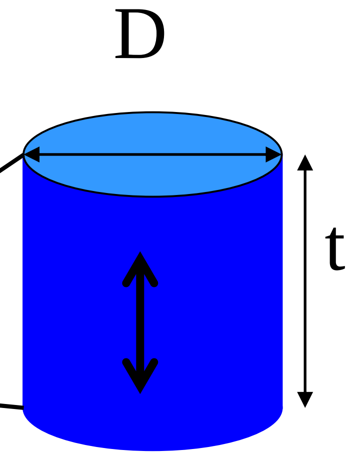


Media and the superparmagnetic effect

The edges of each recorded bit follow the grain boundaries

→ transition noise





M_S, K_U, V

Energy=$K_U V$

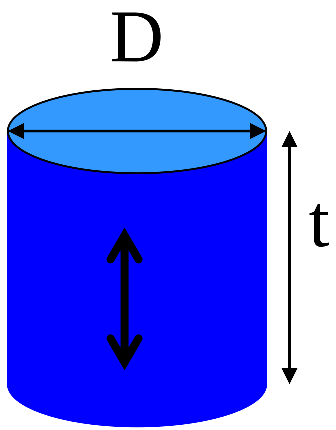
Independent grains SNR ~ $\sqrt{N}$

want small V

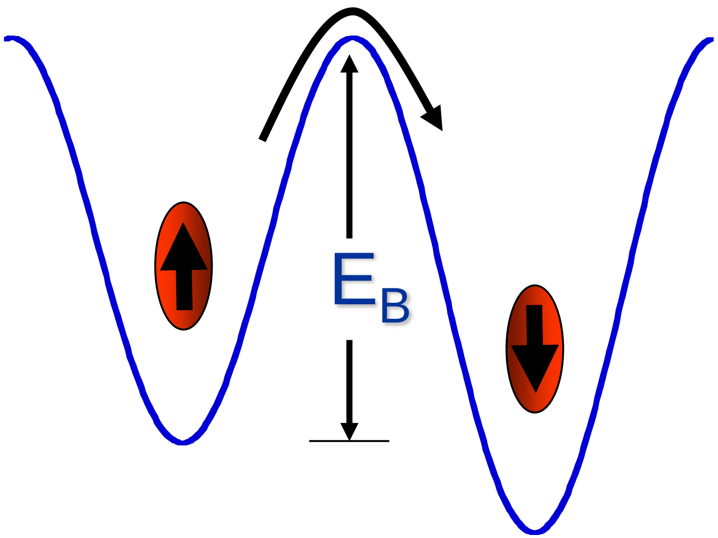
Energy/grain $K_U V > 50 k_B T$

→Scale media microstructure together with rest of recording system

Media and the superparmagnetic effect



K_U, M_S
Energy ~ $K_U V$



$\tau \sim \tau_0 \exp(E_B/k_B T)$

0.1 ns

$K_U V = 100\ k_B T$ ***τ > age of the universe***

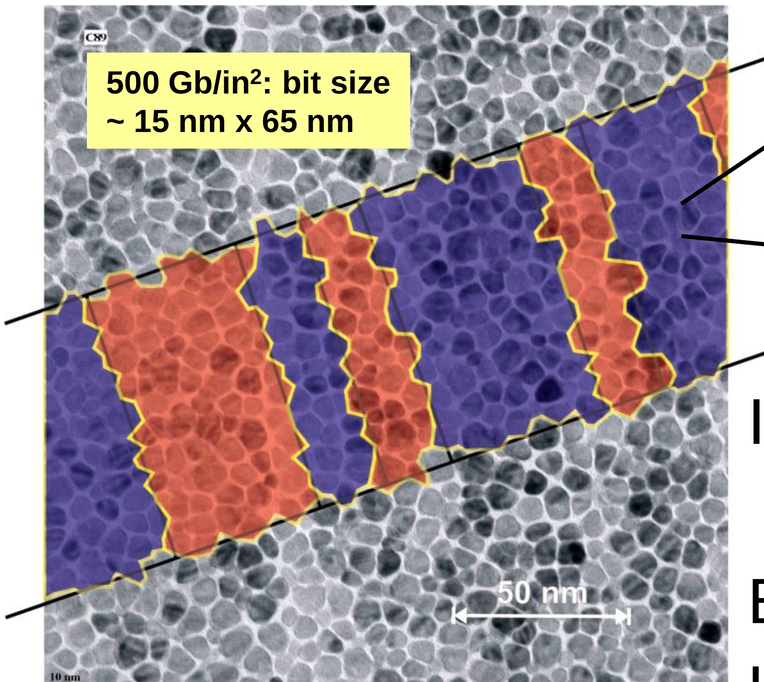
$K_U V = 45\ k_B T$ ***τ ~ 10 years***

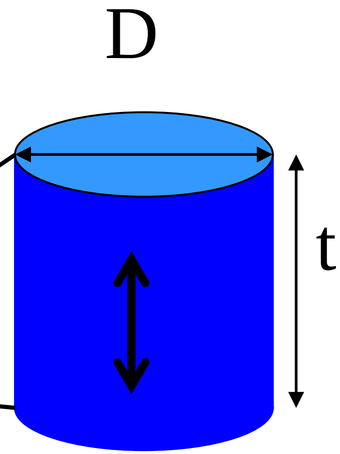
$K_U V = 25\ k_B T$ ***τ ~ 7 seconds***

Media and the superparmagnetic effect

The edges of each recorded bit follow the grain boundaries

→ transition noise





M_S, K_U, V

Energy=$K_U V$

Independent grains SNR ~ $\sqrt{N}$

want small V

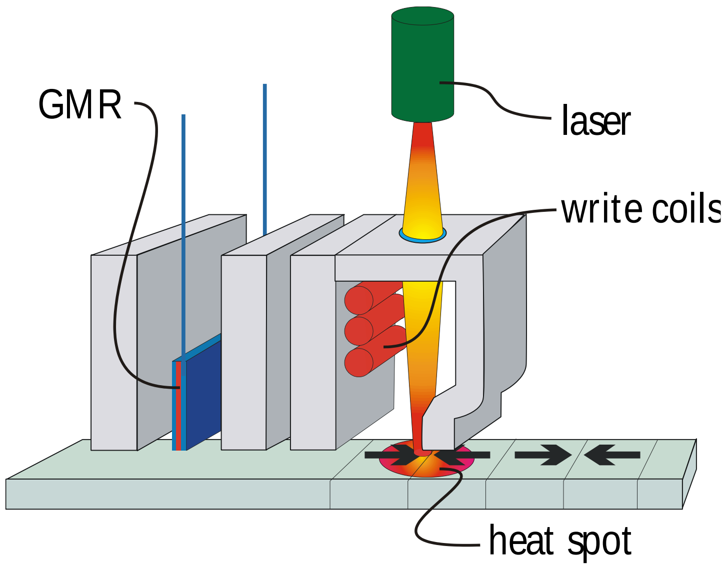
Energy/grain $K_U V > 50 k_B T$

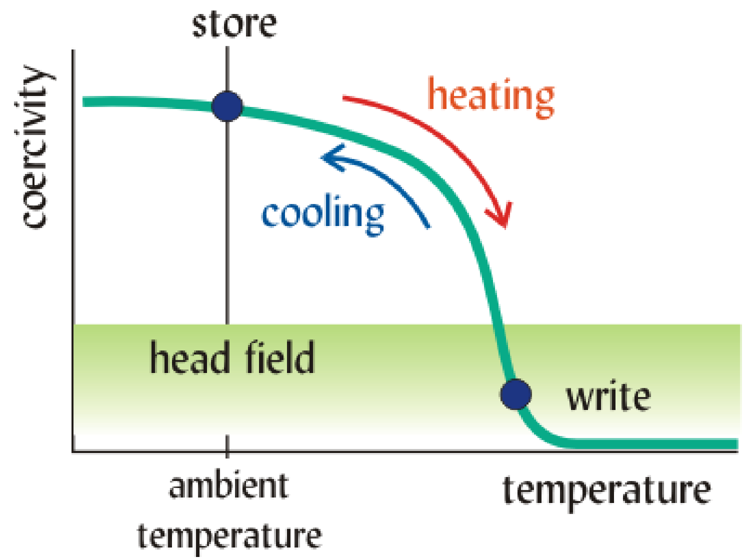
$H_C = K_U / M_S < H_{\text{write-head}}$

→Scale media microstructure together with rest of recording system

Competition for reading, writing and storing data: superparamagnetic effect

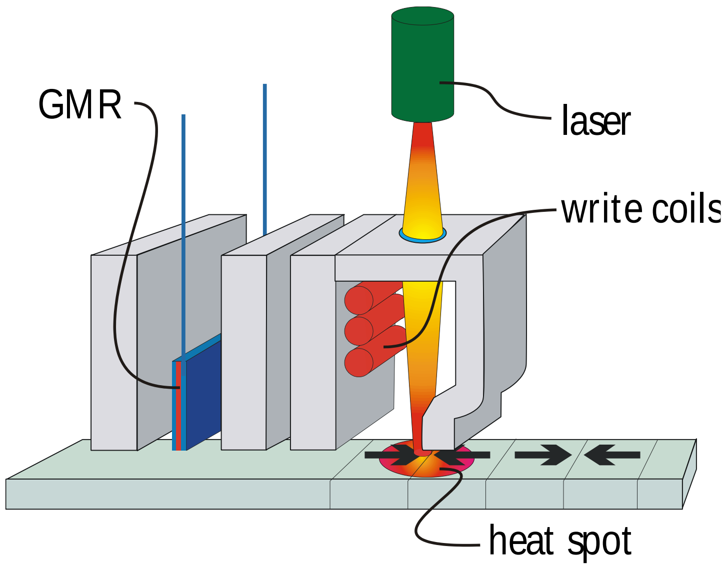
Heat-assisted recording

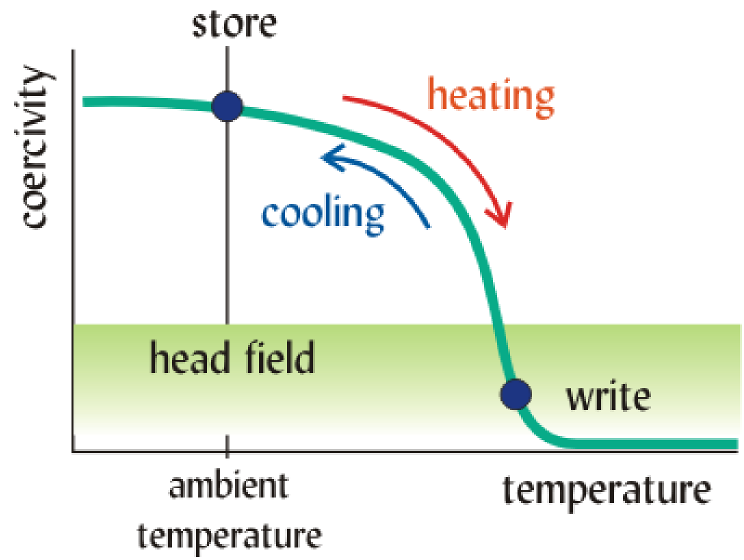


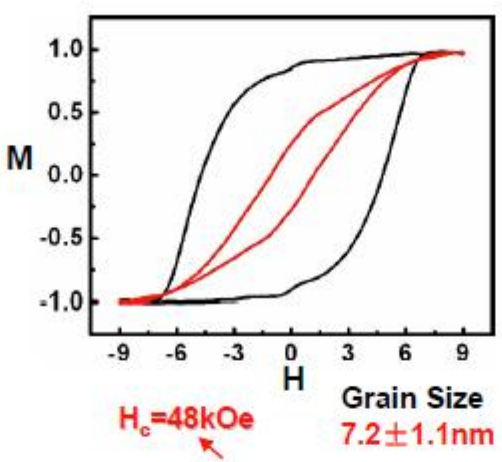


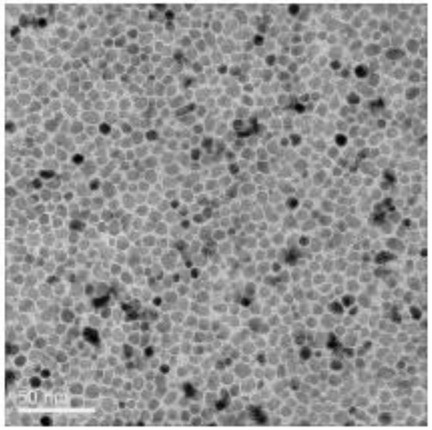
- <50-nm heat spot, ~300 °C rise/cool in 1 ns integrated into a head
- A magnetic media w/ high K_U, small grains and high dH_K/dT
- A head-disk interface (i.e. lubricant) that can handle repeated heating

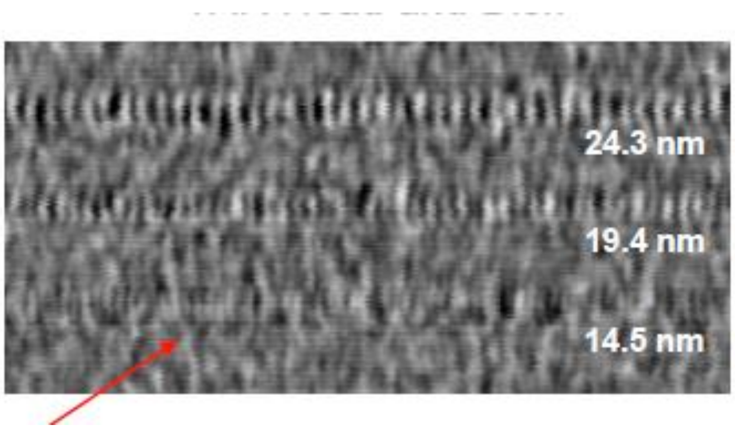
Heat-assisted recording









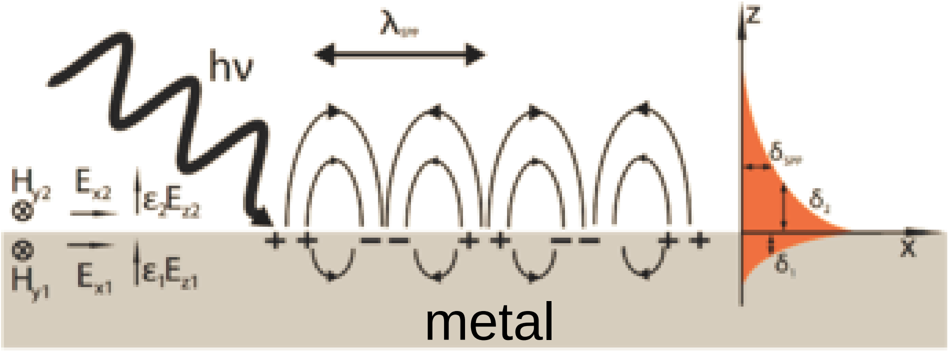


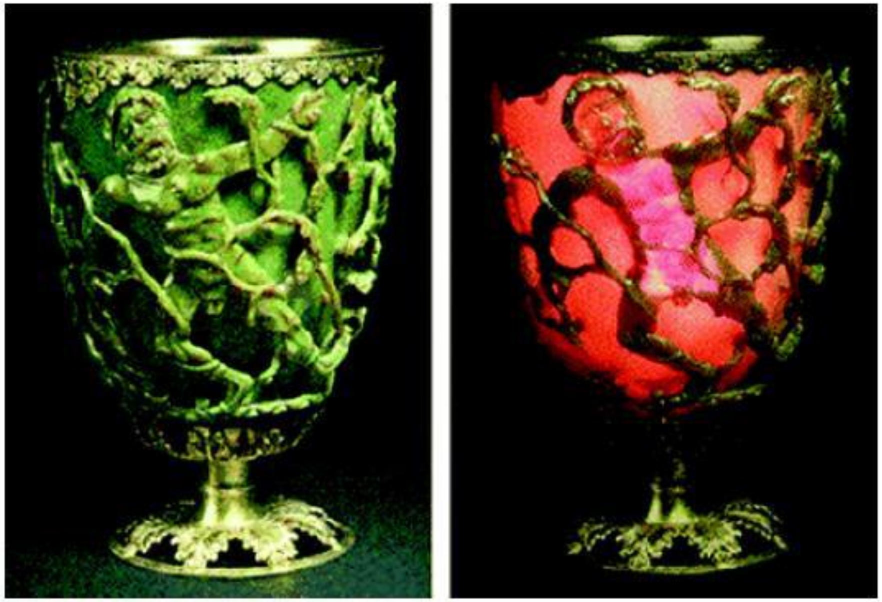
IEEE Trans. Magn. **47**, 4062-4065 (2011)

HGST San Jose

Plasmonics

Surface plasmons

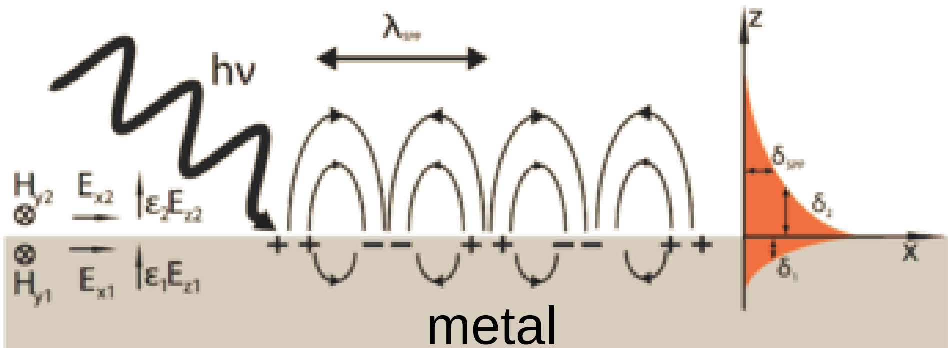


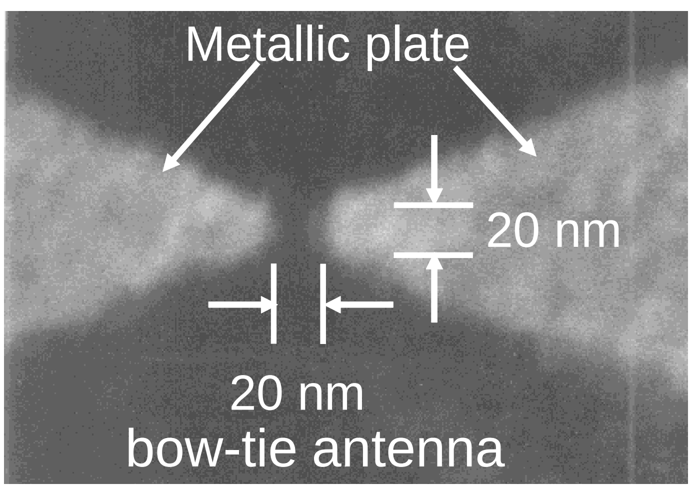


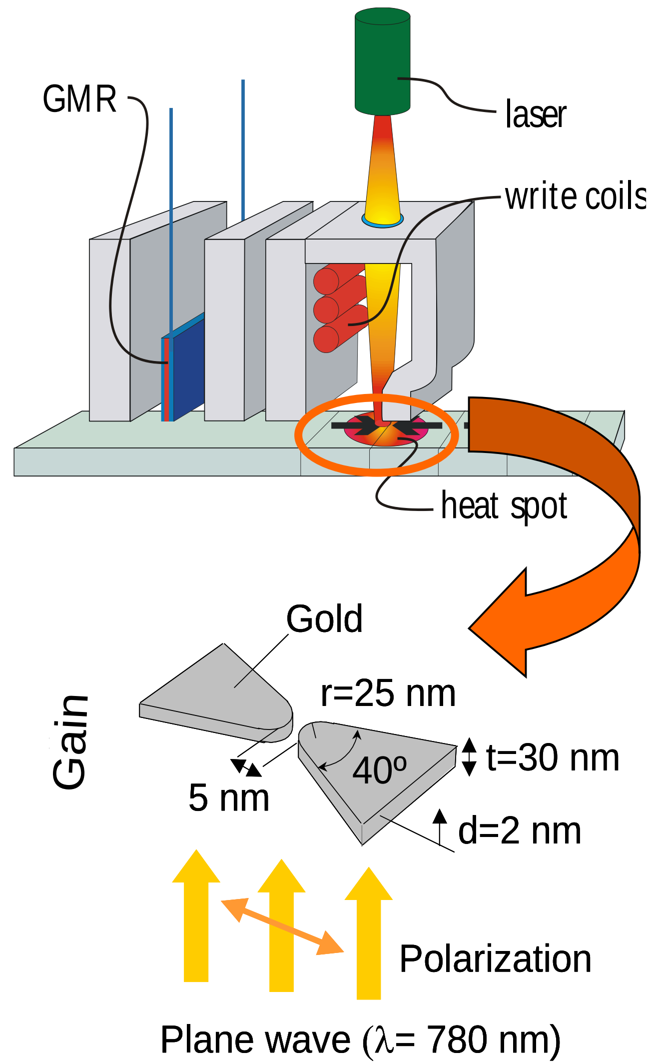
Lycurgus Cup - 4th Century Roman

Plasmonics

Surface plasmons

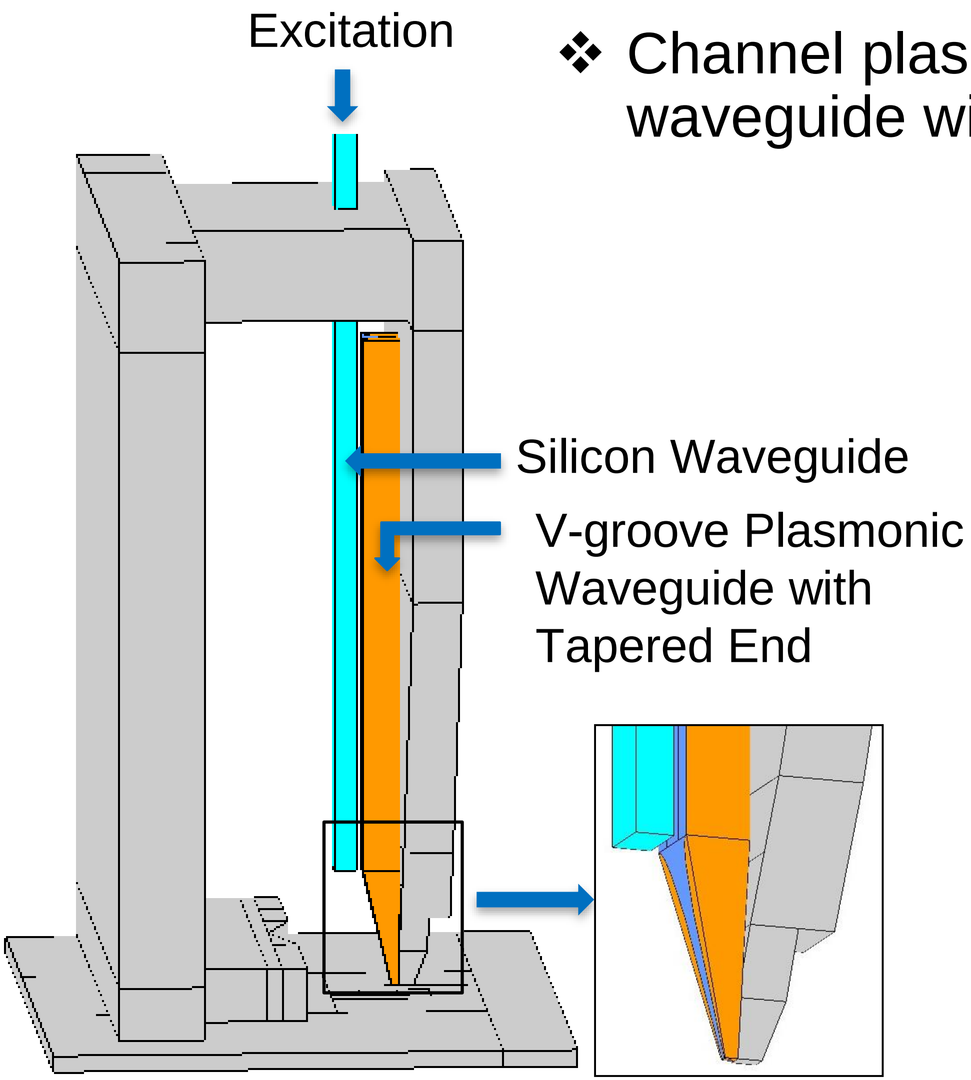


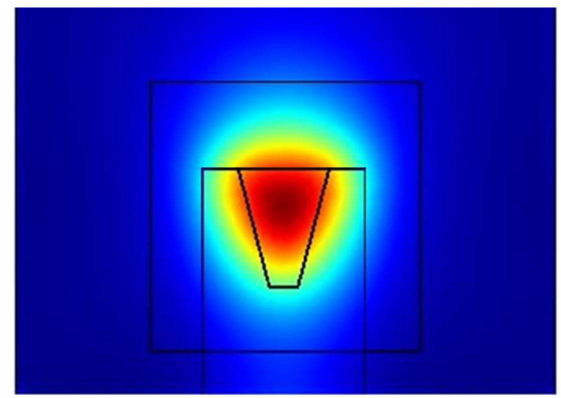




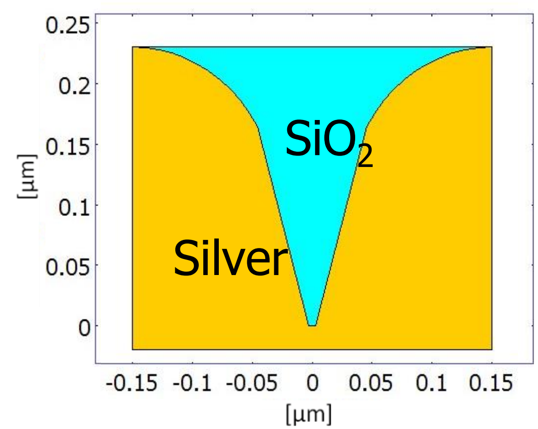
Advanced optical guides

- Channel plasmon polariton (CPP) waveguide with V-groove





FWHM: 31nm x 32nm
Efficiency with silver: 20%

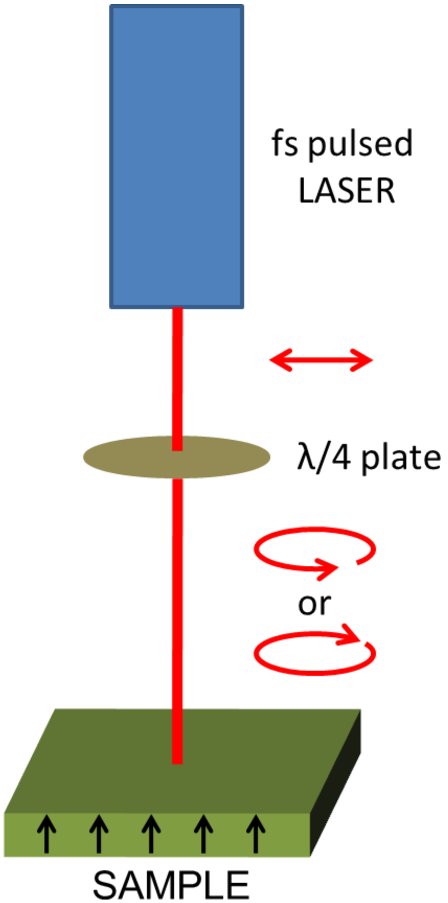


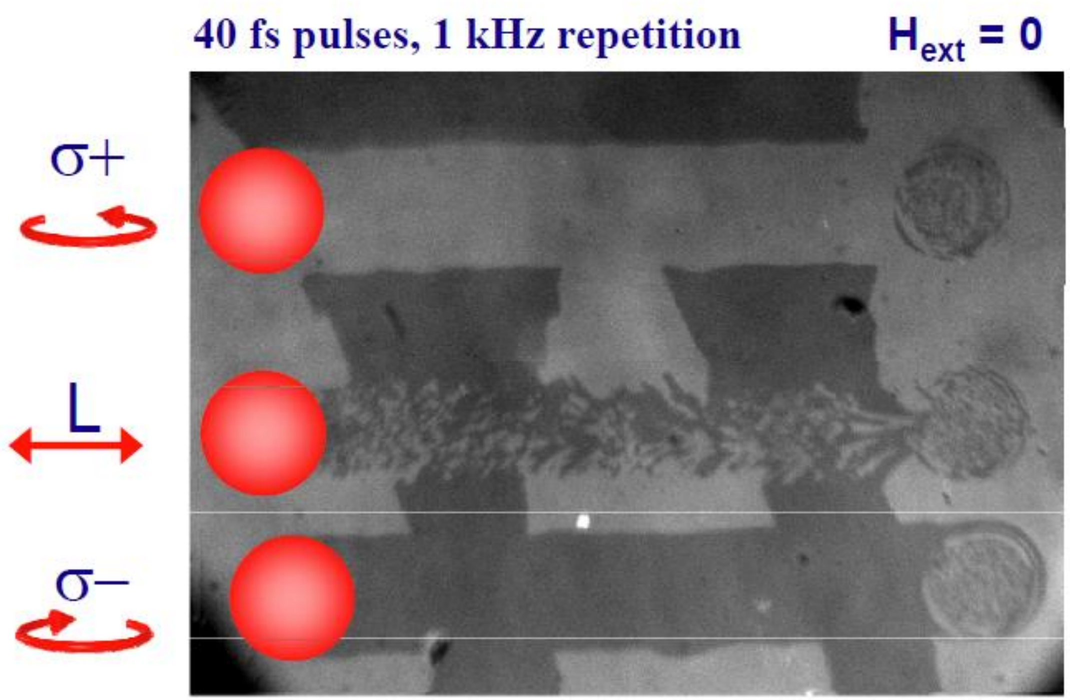
V. Lomakin

All-optical recording?

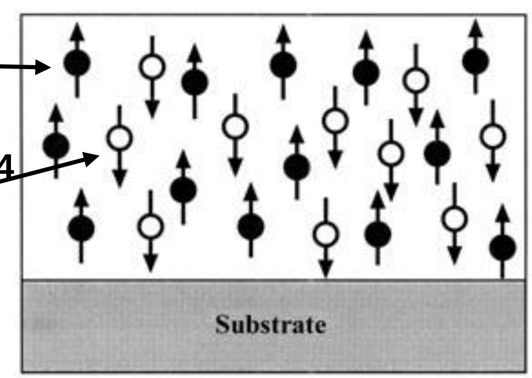
Directly control magnetism with light?

All-optical recording?





20 nm thick $Gd_{22}Fe_{74.6}Co_{3.4}$



C. D. Stanciu et al., PRL (2007)
Kirilyuk, Kimel, Rasing, Rep. Prog. Phys. **76**, 026501 (2013).

All-optical switching (AOS)

What are the origins?

- Is GdFeCo unique?
- Is heat required?
- Is it an ultra-fast process?
- Is angular momentum of the light important?

For applications

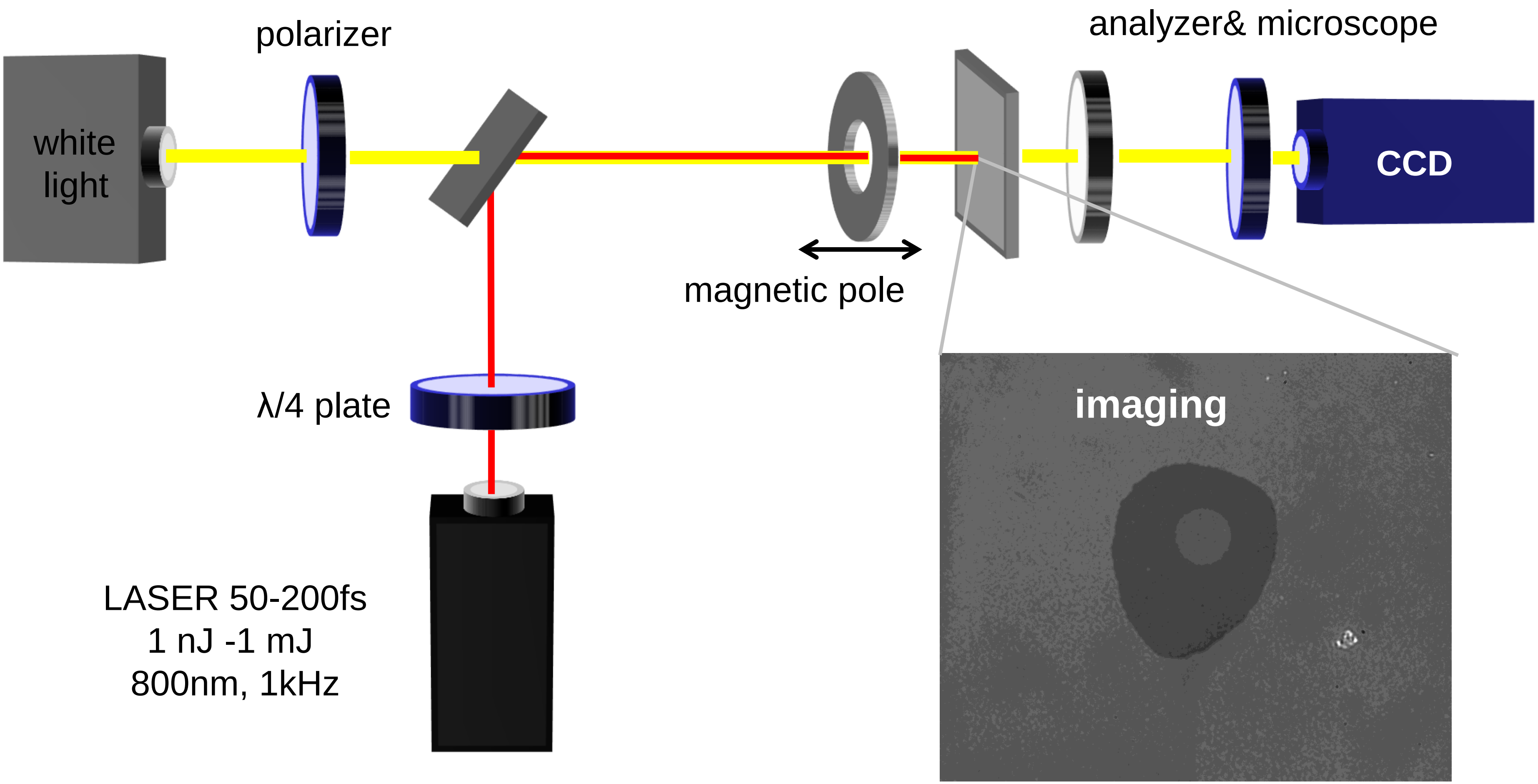
- Higher anisotropy
- Ferromagnetic recording media

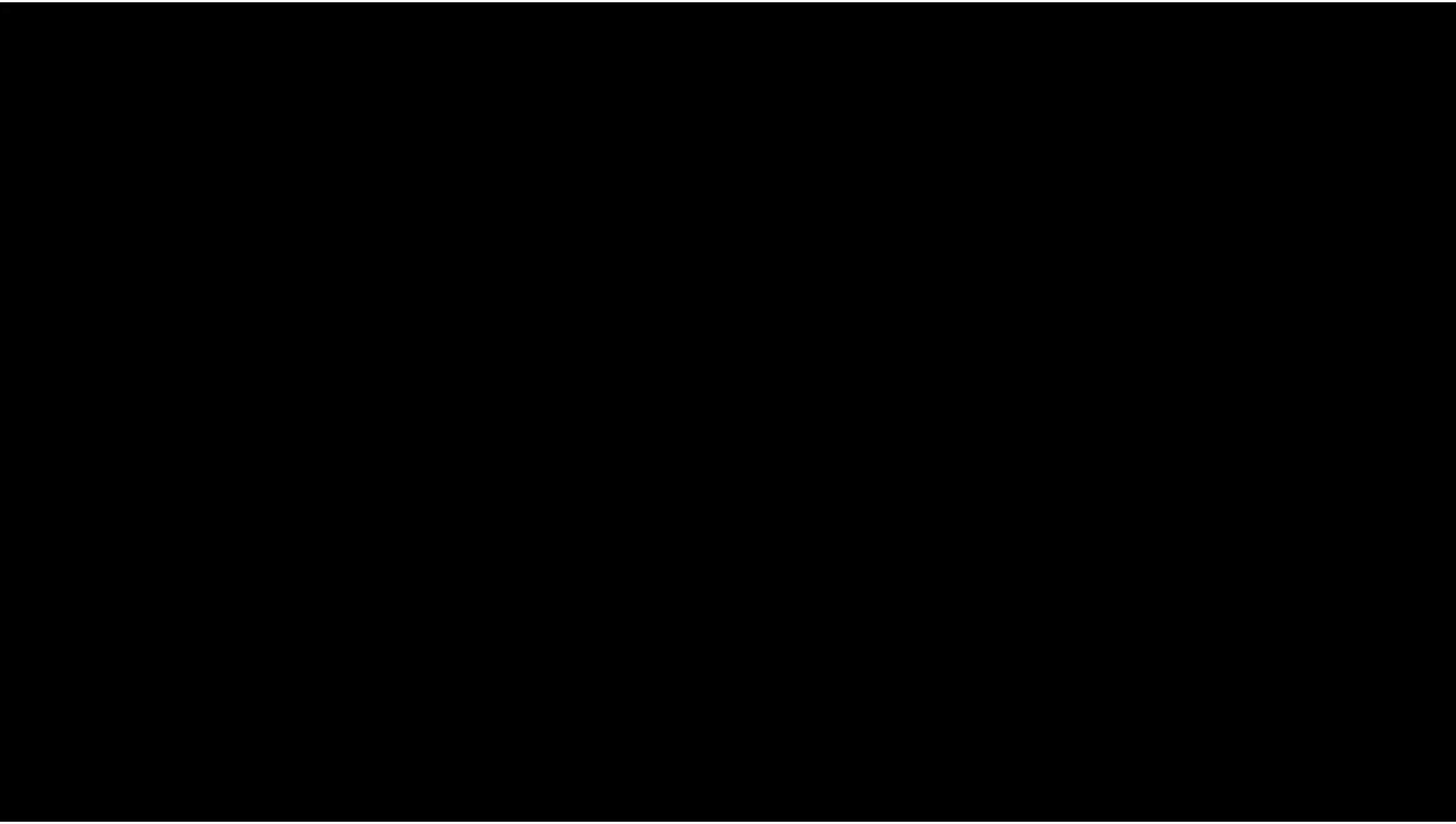
Materials study of AOS

Broaden the materials space: >1000 samples

- **RE-TM alloys and multilayers**
- **Heterostructures**
- **Nanostructures**

UCSD experimental facility



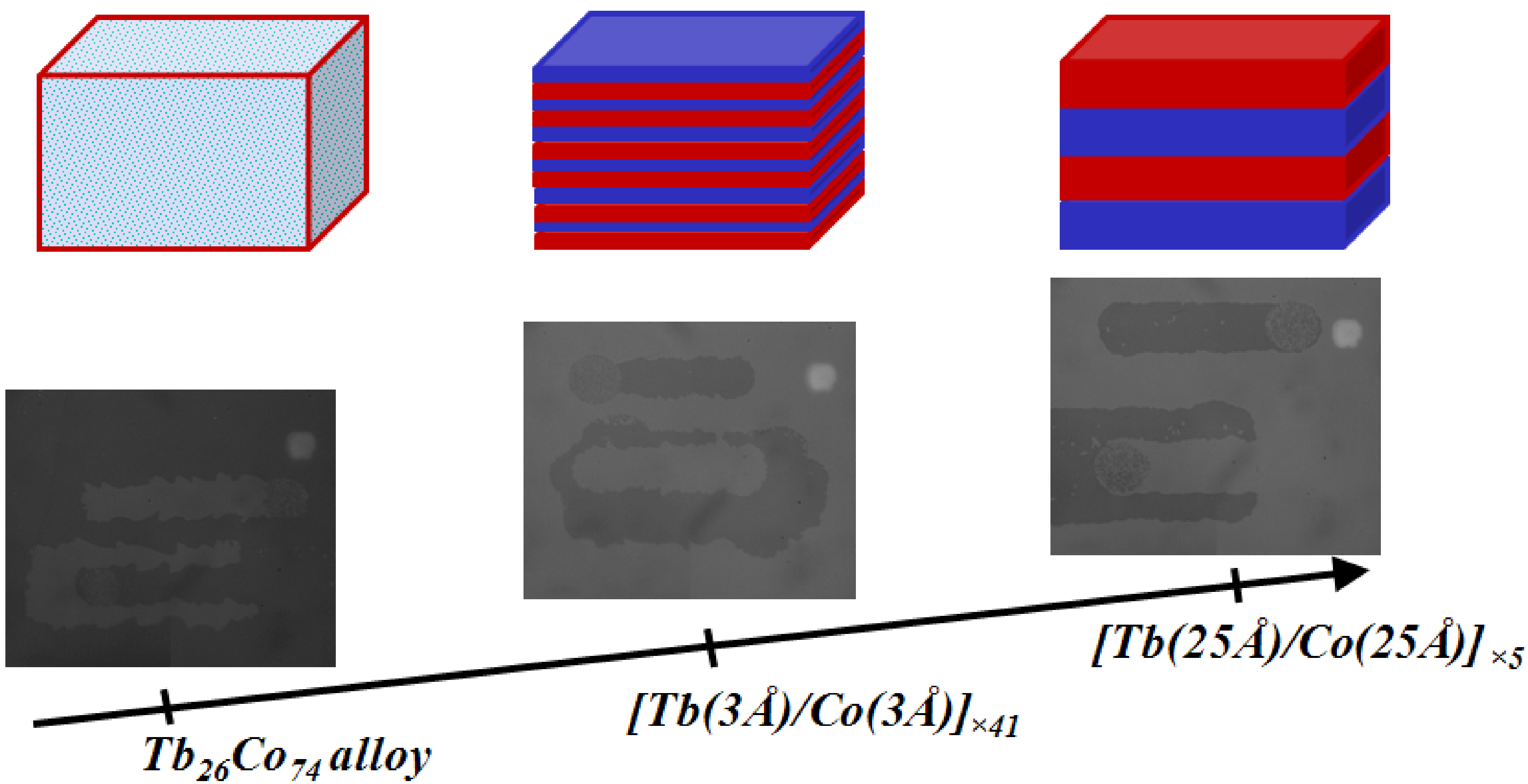


TbCo film

Materials study of AOS

*Lanthanide series

lanthanum	cerium	praseodymium	neodymium	promethium	samarium	europium	gadolinium	terbium	dysprosium	holmium	erbium	thulium	ytterbium
57	58	59	60	61	62	63	64	65	66	67	68	69	70
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
138.91	140.12	140.91	144.24	[145]	150.36	151.96	157.25	158.93	162.50	164.93	167.26	168.93	173.04



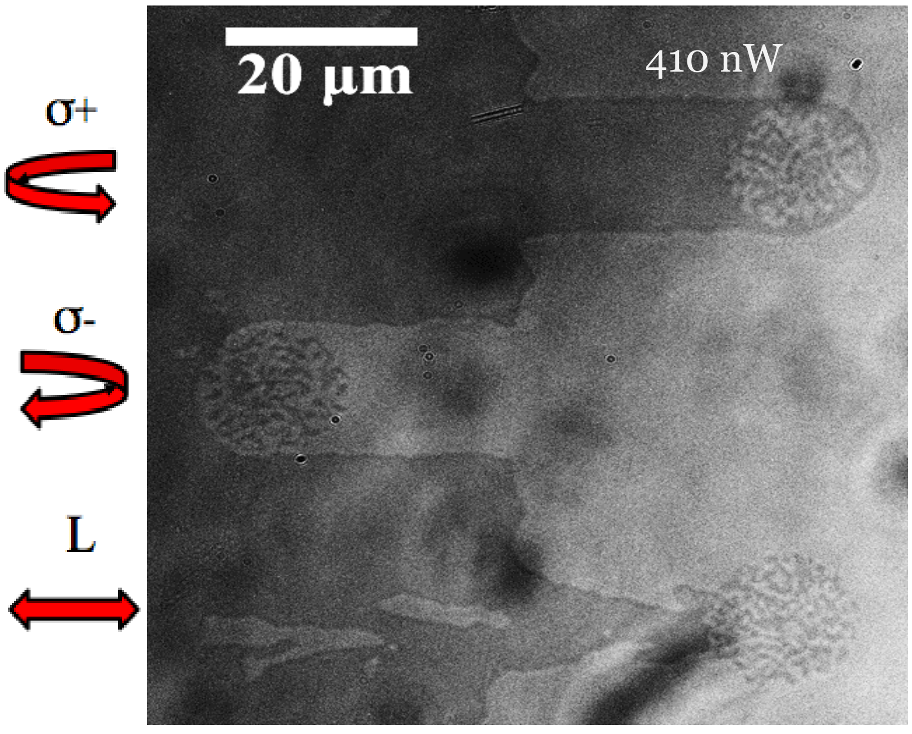
All-optical switching

Rather general property of ferrimagnets

Nature Materials **13**, 286-292 (2014)

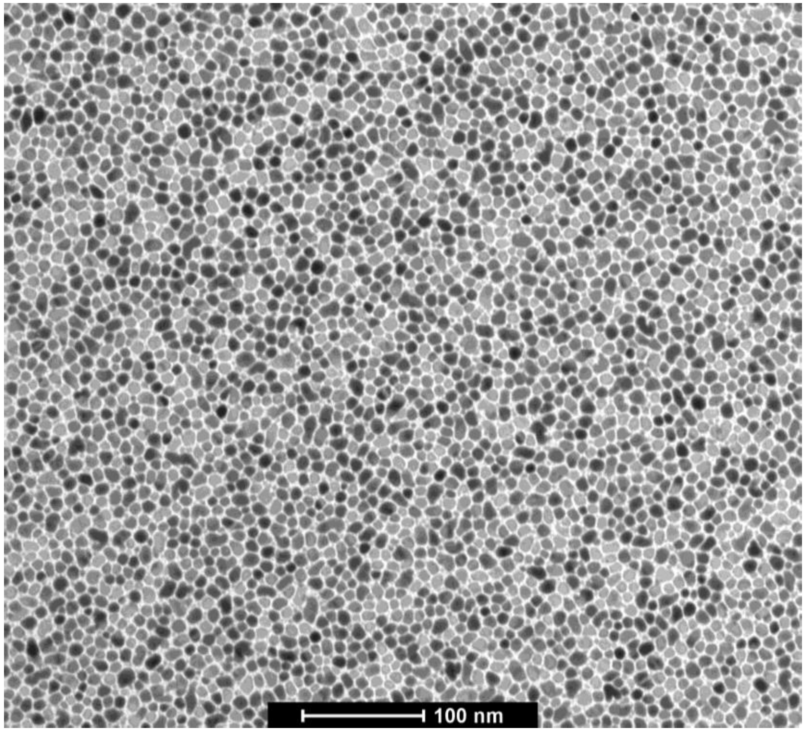
Can it also work with ferromagnets?

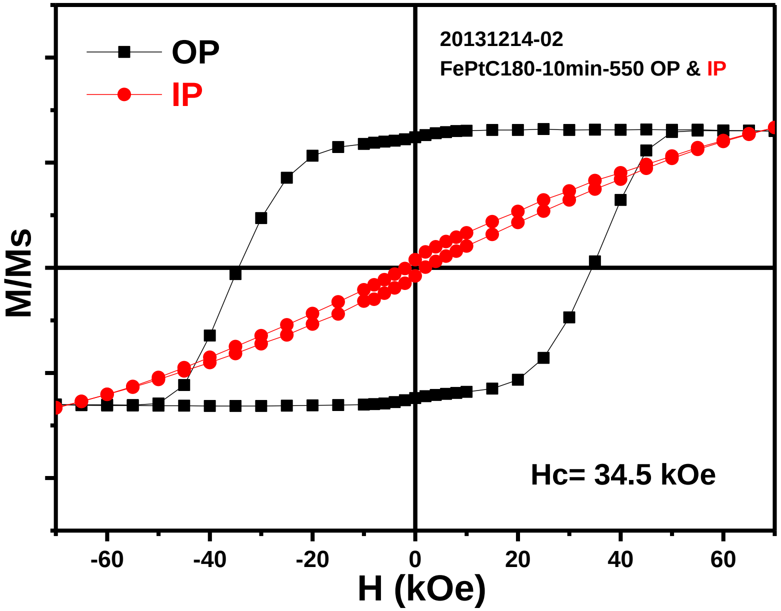
Can it work with magnetic recording media?



Ferromagnets

15-nm FePt-C and FePtAg-C granular films



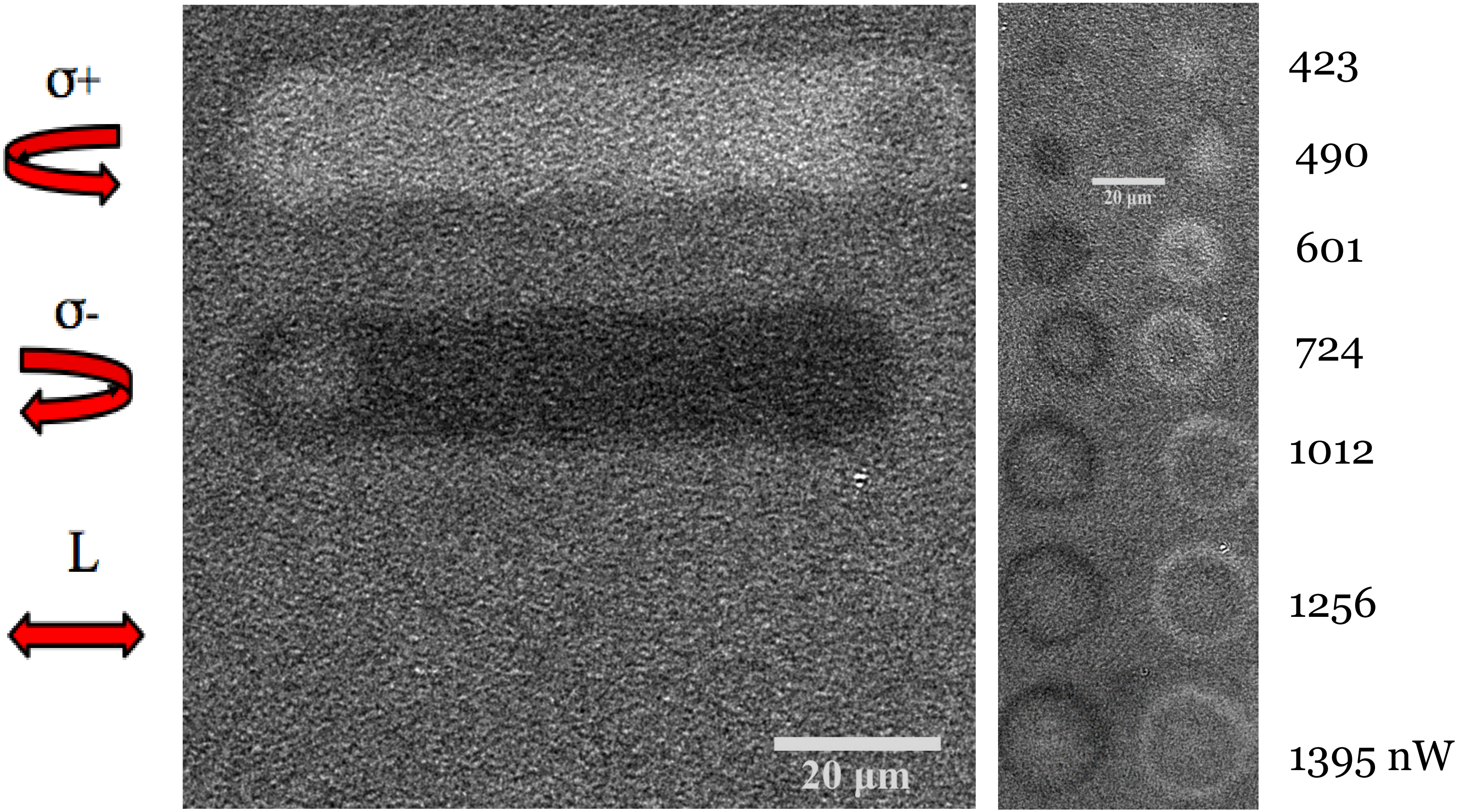


8 nm grains with 11 nm separation

Varaprasad *et al*., IEEE Trans. Magn, **49**, 718-722 (2013).

Ferromagnets

15-nm FePt-C granular films



Ferromagnetic AOS

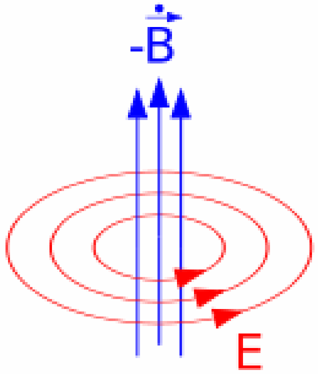
Heating by the laser near T_C

+

Magnetic field/Angular momentum from a laser beam

Inverse Faraday effect

$$\vec{H}_{eff} = \frac{\varepsilon_0}{\mu_0}\alpha\left[\underbrace{\vec{E}(\omega)\times\vec{E}^*(\omega)}_{circular\ polarization}\right]$$



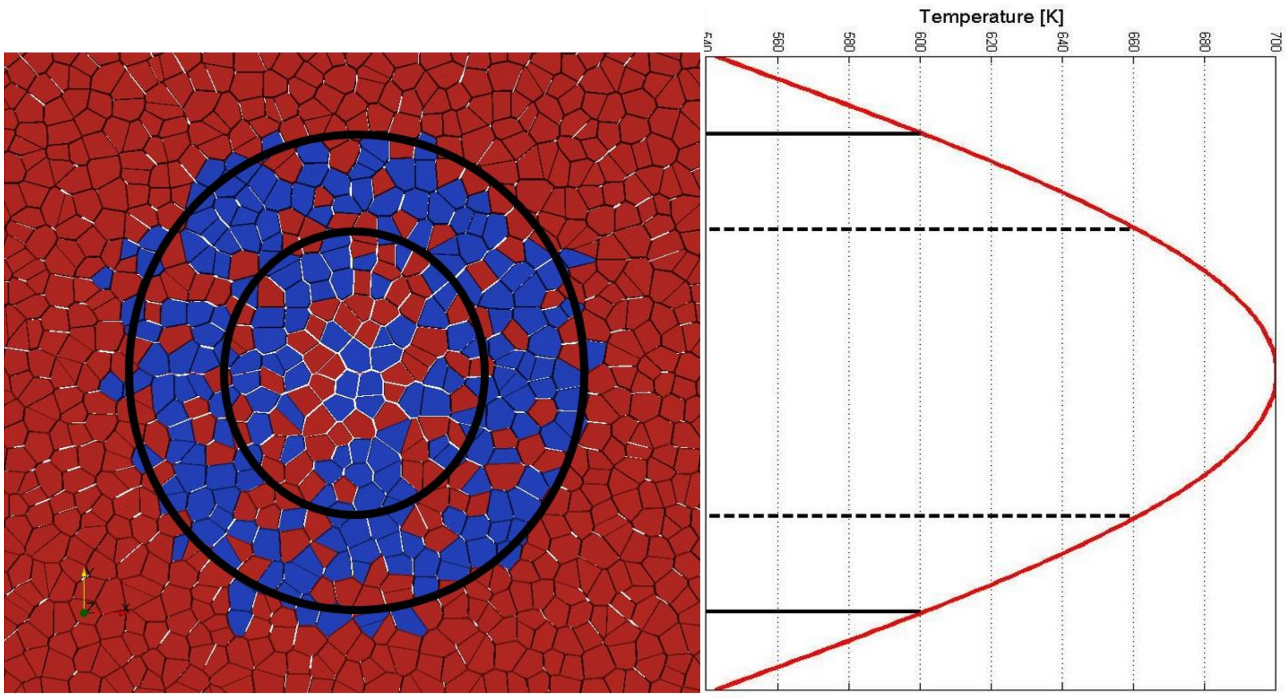
+

Suppression of domain formation during cooling
thin film, high anisotropy and/or low M

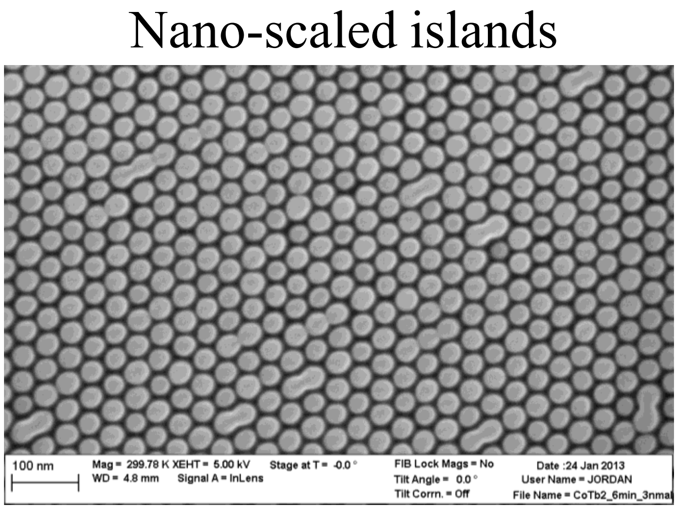
Landau–Lifshitz–Bloch simulations

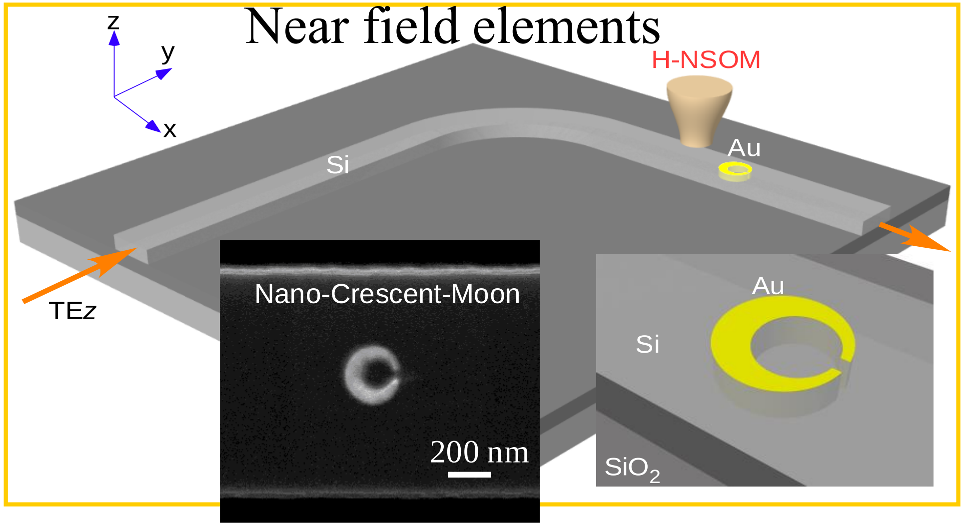
Marco Menarini and Vitaliy Lomakin, UC San Diego

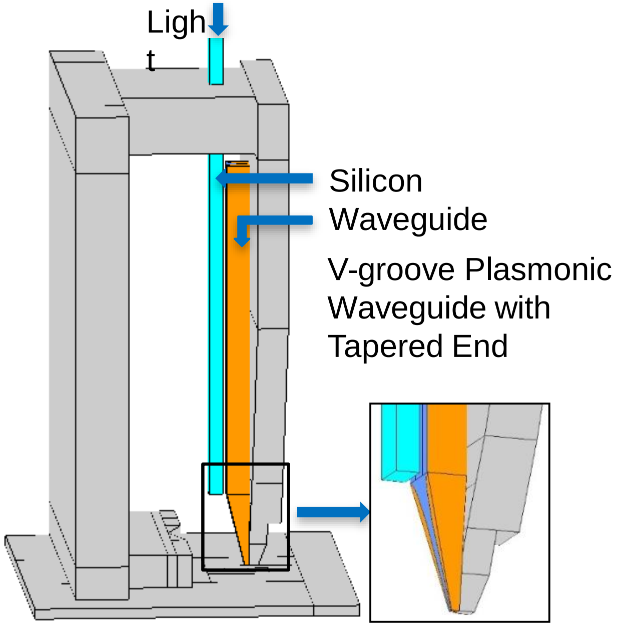
Landau-Lifshitz-Bloch simulations
Pulse Length 1ps with a pulse field intensity 2T
Maximum Temperature T=700 K and T_C=660 K

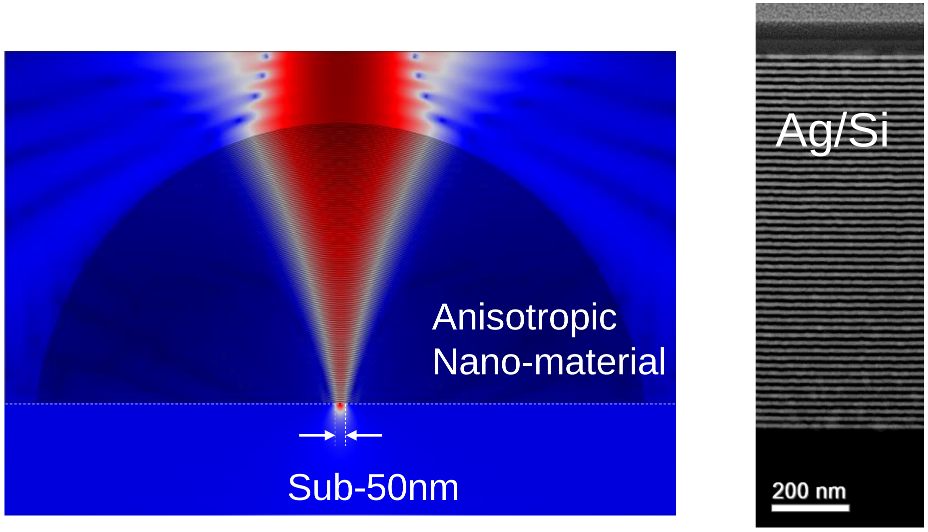


Future of all-optical switching?









Leveraging the hard drive for memory

Return of magnetism in memory and processing?

Advantages of magnetism

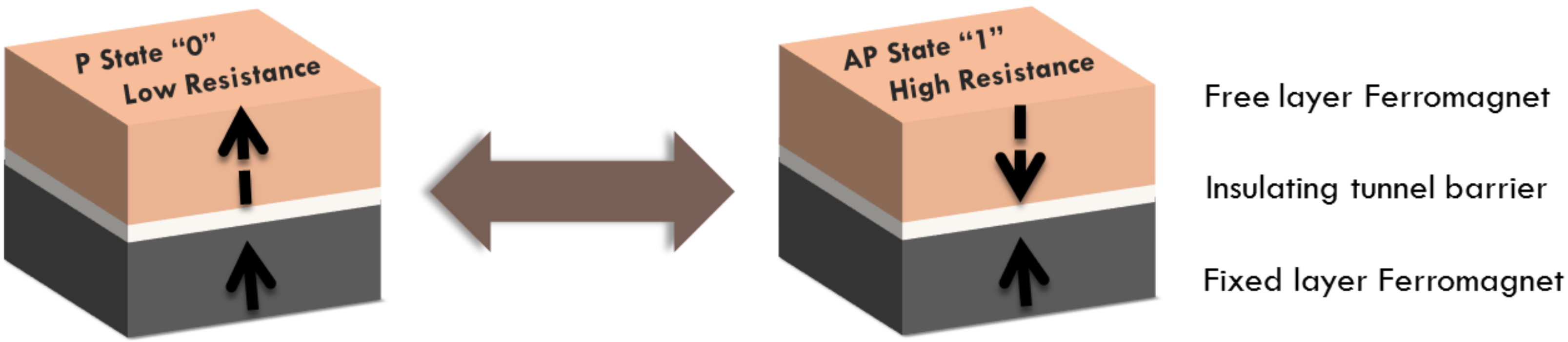
- Non-volatile ($E_B > 50\ k_BT$)
- Low energy $50\ k_BT = 0.2$ aJ

Performance and power issues in IT

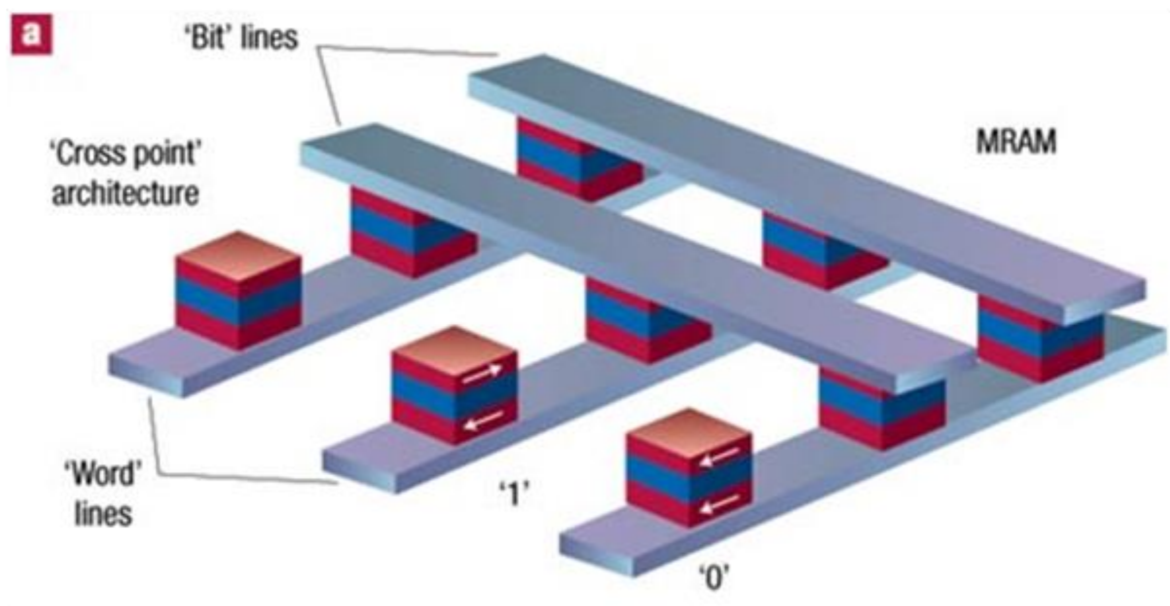
- Memory is a bottleneck (data-centric vs. compute centric)
- Hand-held devices are increasingly power limited
- computing and data centers dissipate Megawatts of power

- Opportunities for new non-volatile memories

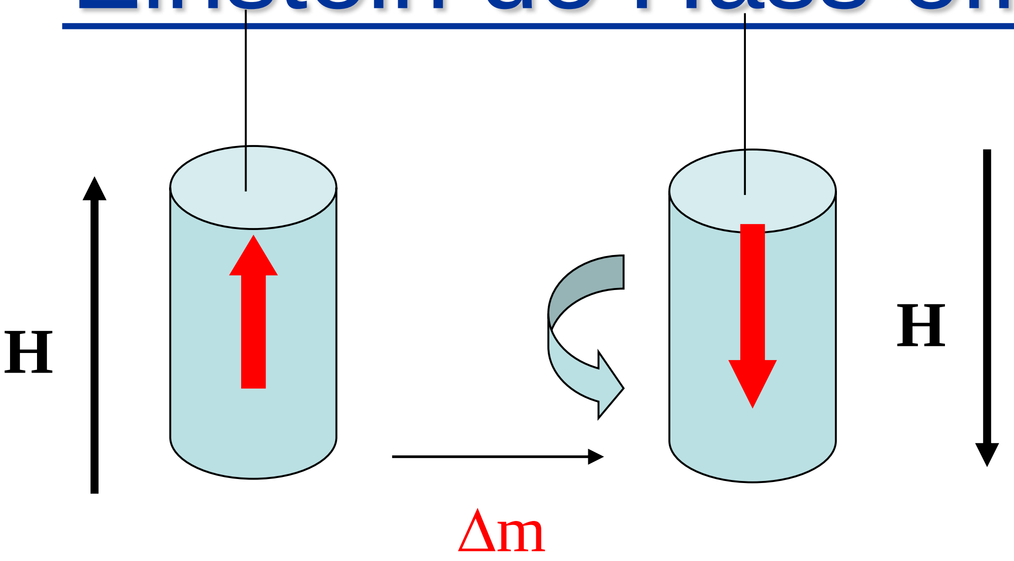
Magnetic RAM



Nobel Prize in physics in 2007



Einstein de Hass effect



$$\boxed{\Gamma = \frac{d\mathbf{L}}{dt}}$$

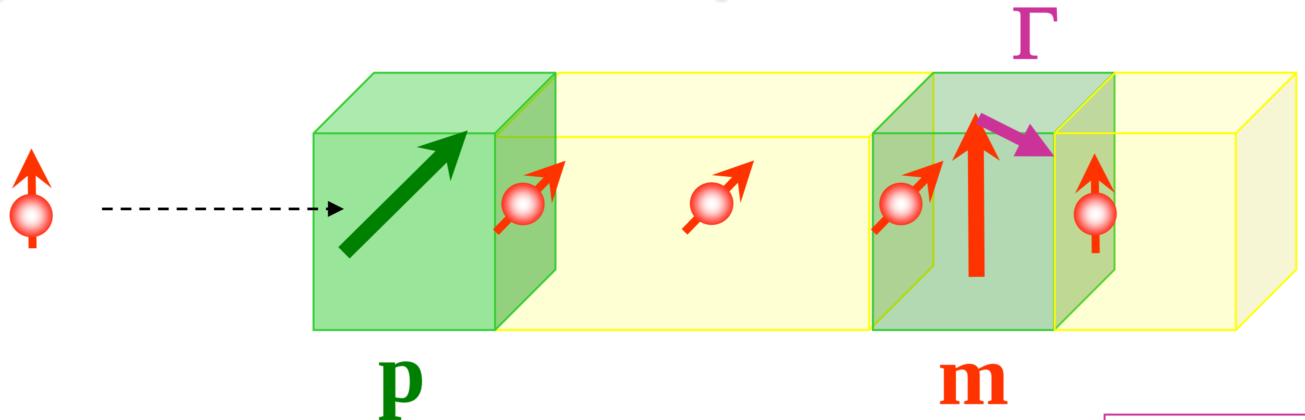
ΔL → Rotation

A. Einstein, W. J. de Haas, *Experimenteller Nachweis der Ampereschen Molekularstörme*, Deutsche Physikalische Gesellschaft, Verhandlungen **17**, pp. 152-170 (1915).

Proof of the existence of the Ampere molecular field

"how treacherous nature is, when you have to deal with it experimentally"

Spin transfer torques



$$\Gamma_m = \frac{d\mathbf{L}_e}{dt}$$

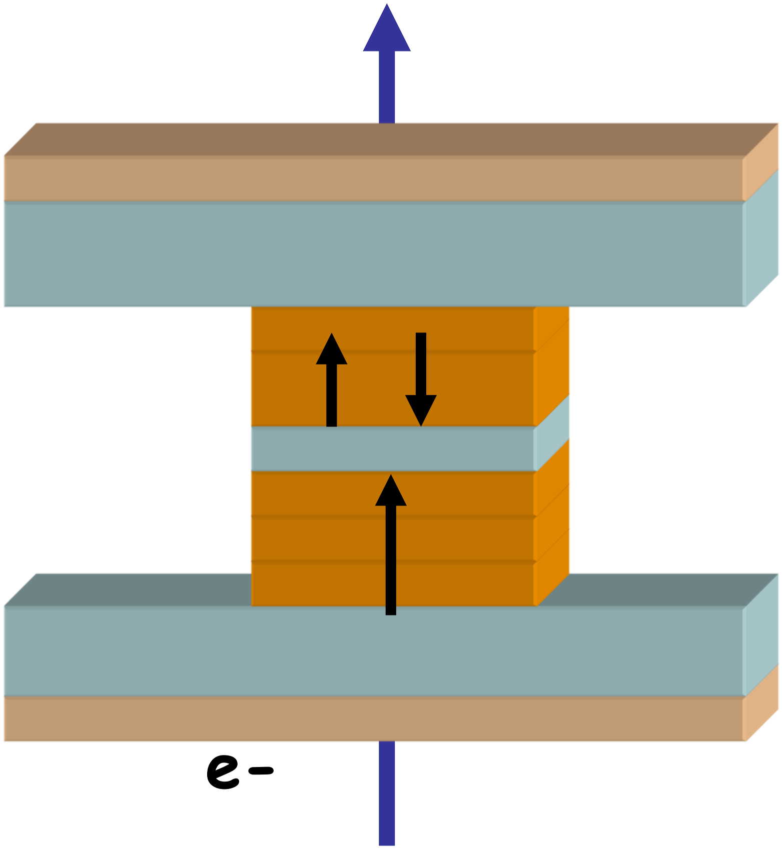
Angular momentum conservation
➔ spin transfer torques

J. Slonczewski, J. Magn. Magn. Mater. **159,** L1 (1996)
L. Berger, Phys. Rev. B **54,** 9353 (1996)

Katine *et al*., PRL **84**, 3149 (2000)

see J. Magn. Magn. Mater. **320** (2008)
articles on spin torque edited by Stiles and Ralph

Perpendicular anisotropy devices



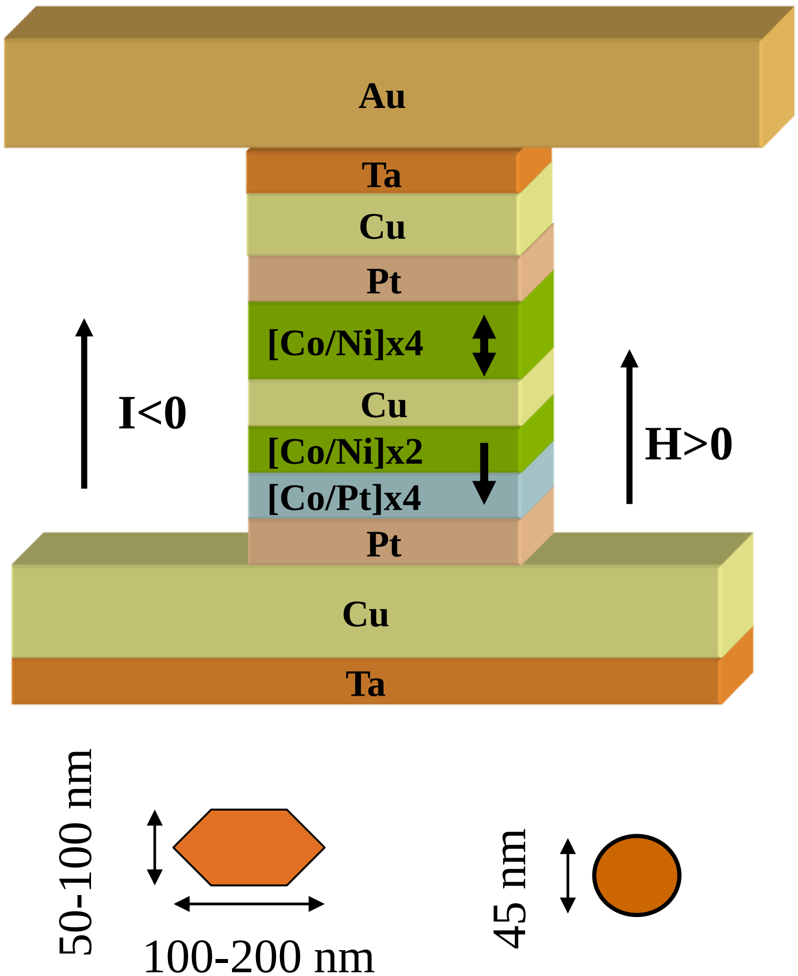
- Higher thermal stability
  - $E_B > 50\ k_BT$
- More efficient reversal
  - I_C scales with E_B

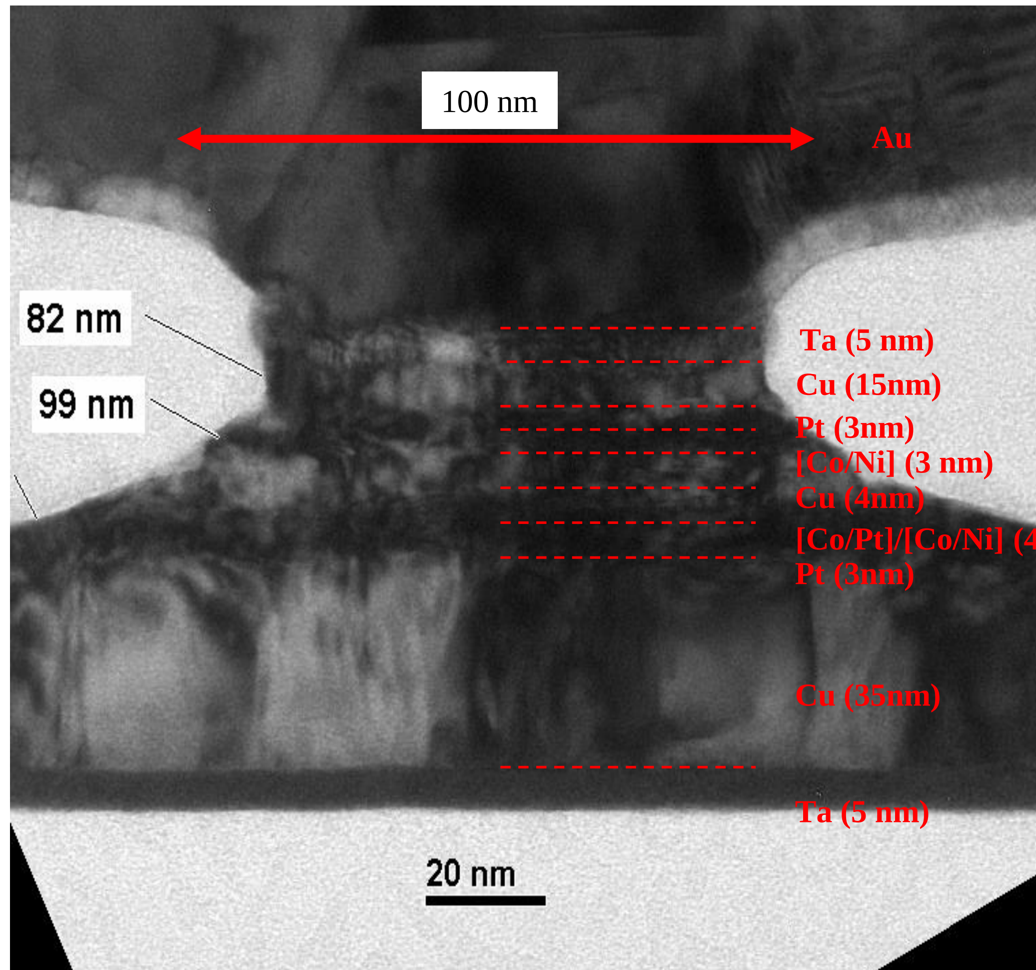
Mangin et al., Nature Mater. ***5****, 210 (2006)*

Perpendicular devices

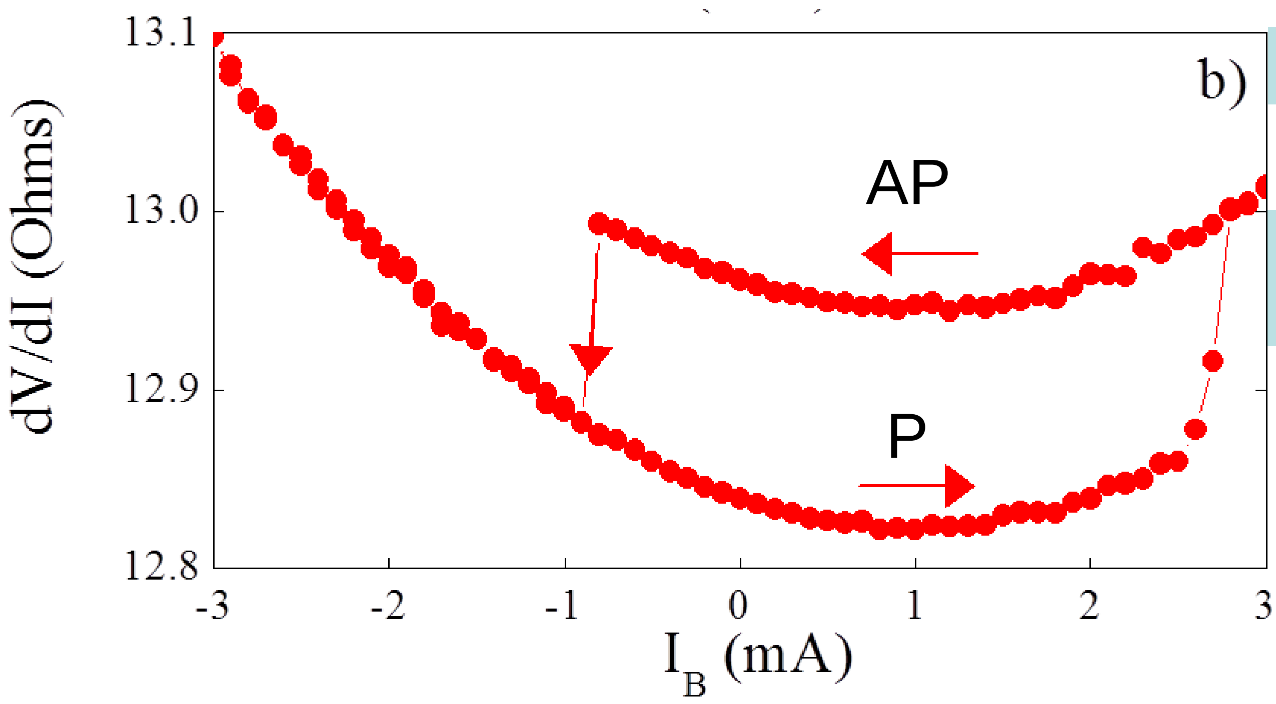
- Use of negative HSQ resist as a high fidelity mask

-~1000 devices/5 inch wafer: circles and hexagons from 45nm to 1500nm





Current reversal in 50x100 nm^2 devices



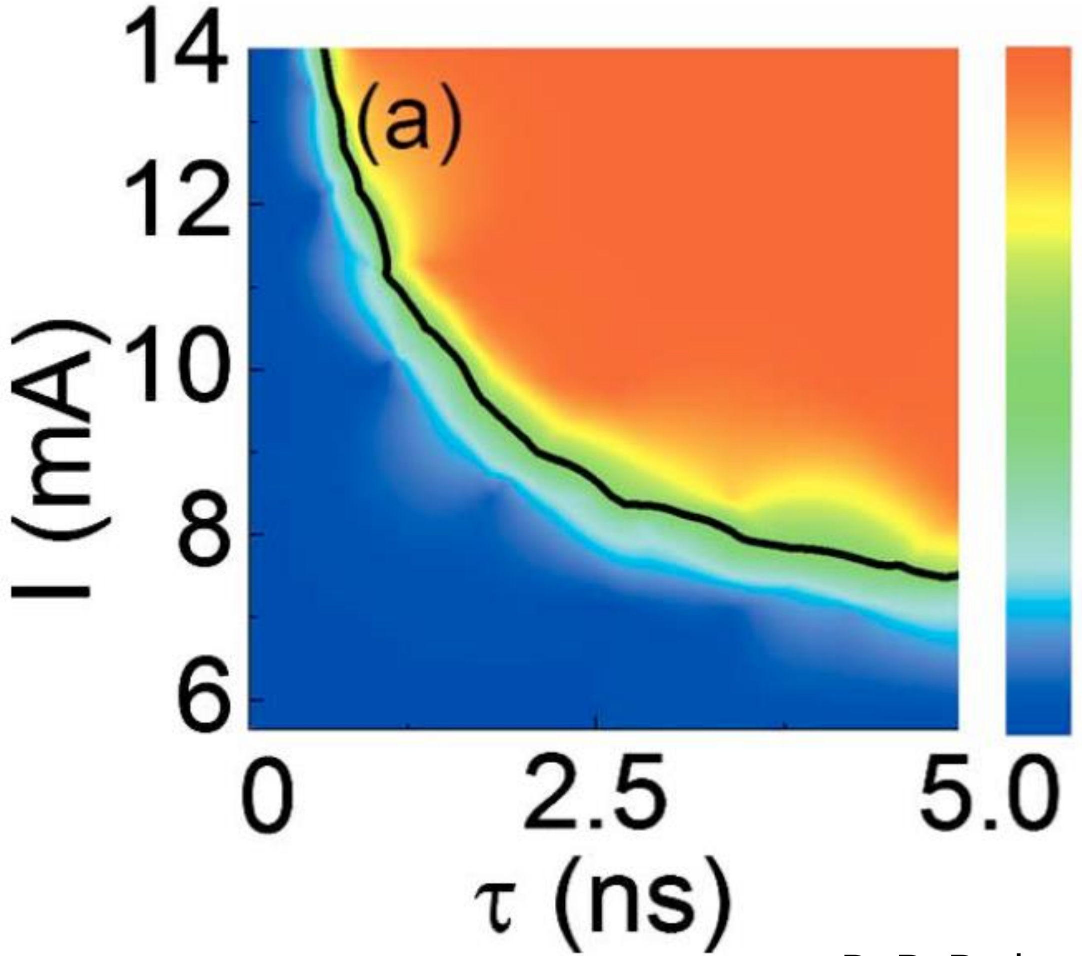
H_C = 2.65 kOe

$I_C^{AP\text{-}P}$ = -2.6x10^7 A/cm^2

$I_C^{P\text{-}AP}$ = 7x10^7 A/cm^2

Energy and time scales?

Time dependence and energy



$$1/\tau = A(I - I_{C0})$$

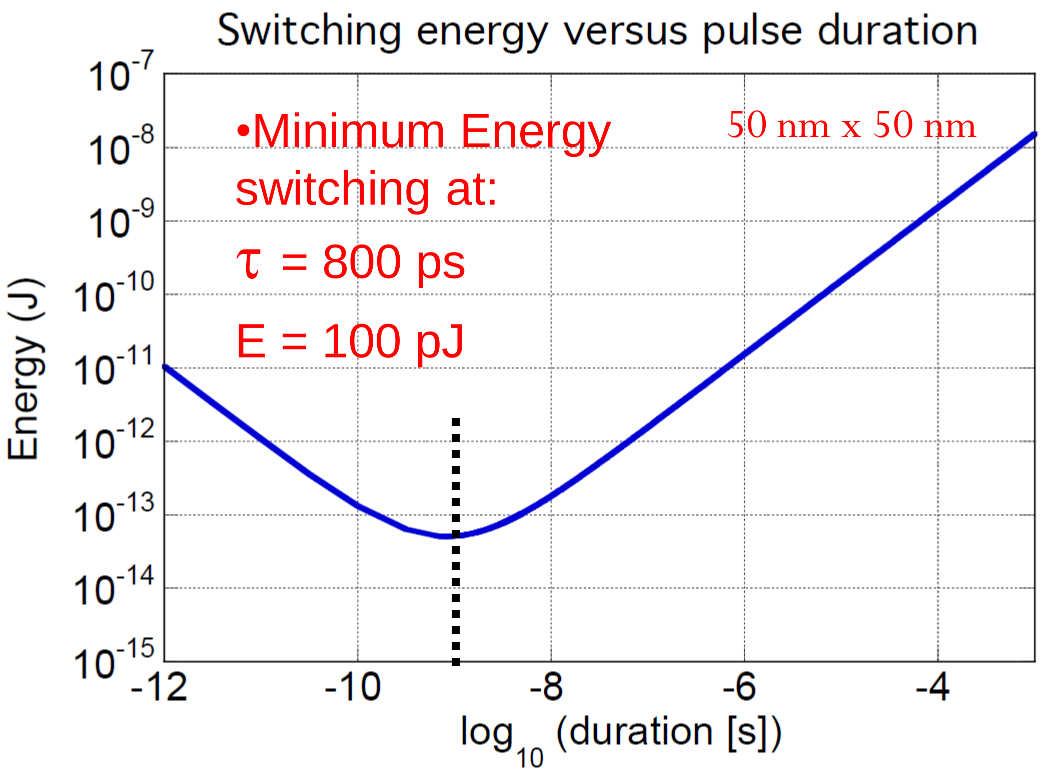
τ = reversal time
I = current
I_{C0} = critical current to counter damping
A = dynamics parameter

D. B. Bedau *et al*., Appl. Phys. Lett. **96**, 022514 (2010)
D. Bedau, App. Phys. Lett. **97**, 262502 (2010)
H. Liu, et al., Phys. Rev. B **85**, 220405 (2012)

Minimum energy

$$E = I^2 R\tau$$

$1/\tau = A(I - I_{C0})$



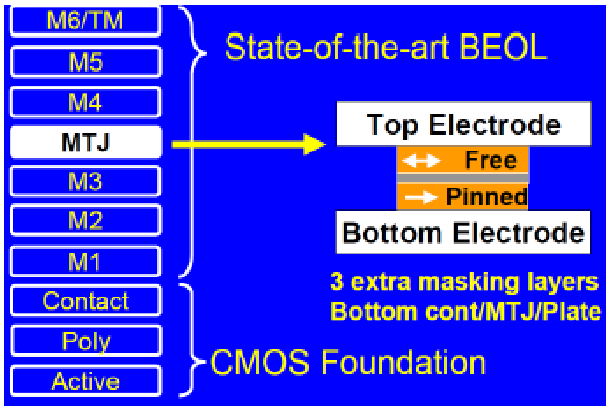
6×10^6 electrons

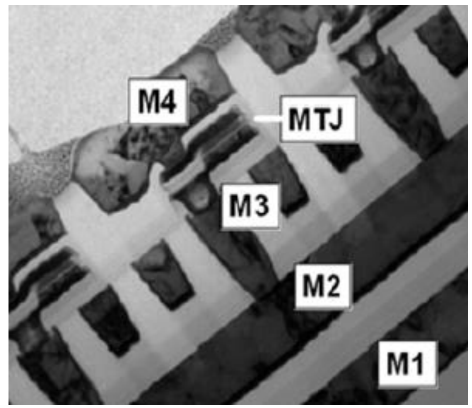
5×10^5 spins in the free layer

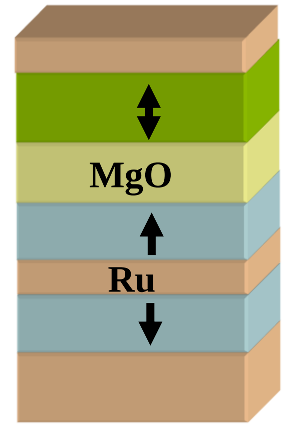
~14 electrons/spin

Energy in pulse is 5×10^5 times E_B

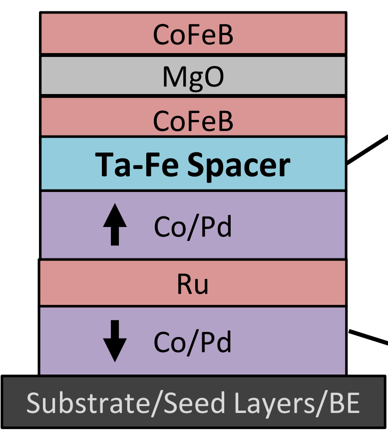
Perpendicular MRAM cells

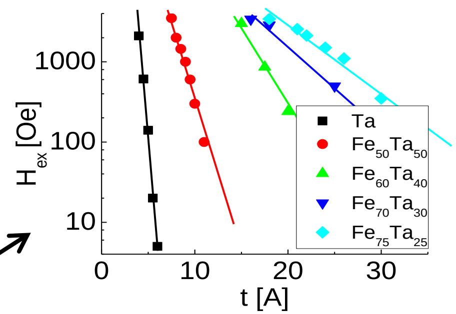




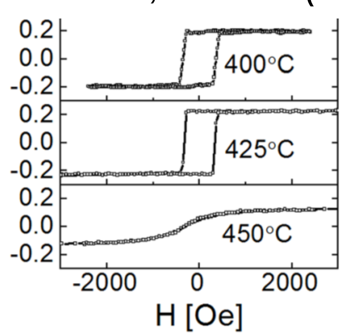


High anisotropy
$E_B > 50\ k_BT$ (30 nm)
High TMR
Low I_c and V_c
Symmetric I_c
Low read current
T_{ann} = 400 °C

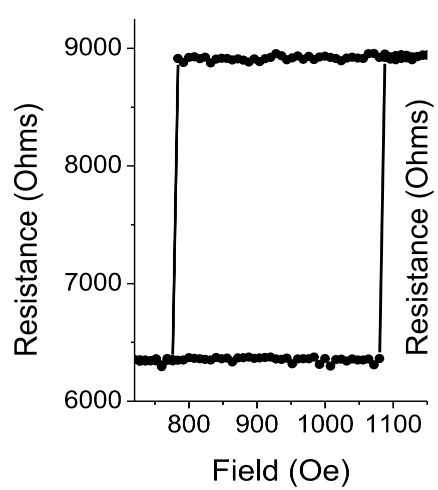


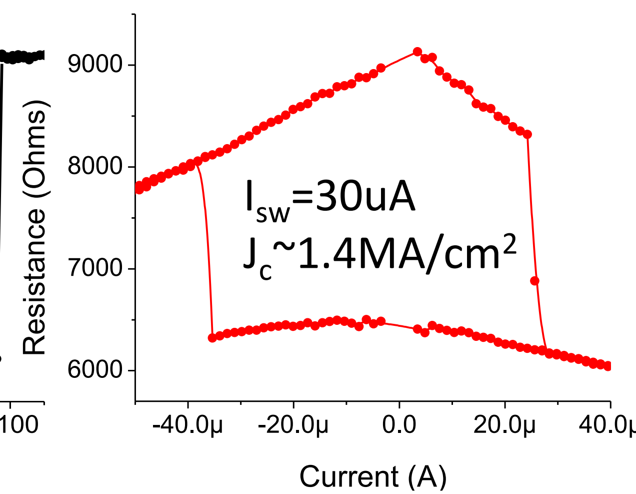


APL Mater. ***1****, 022102 (2013)*



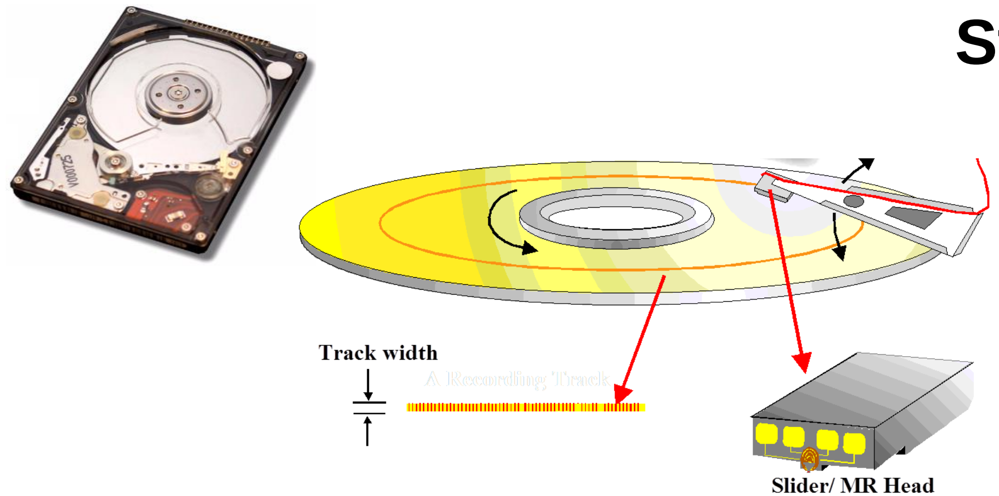
*Appl. Phys. Lett.****102****, 052405 (2013)*

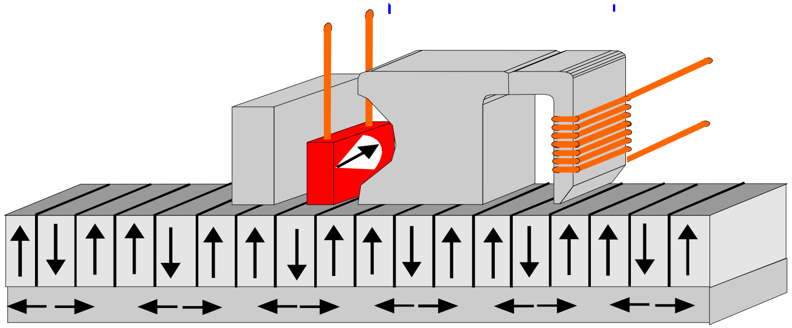




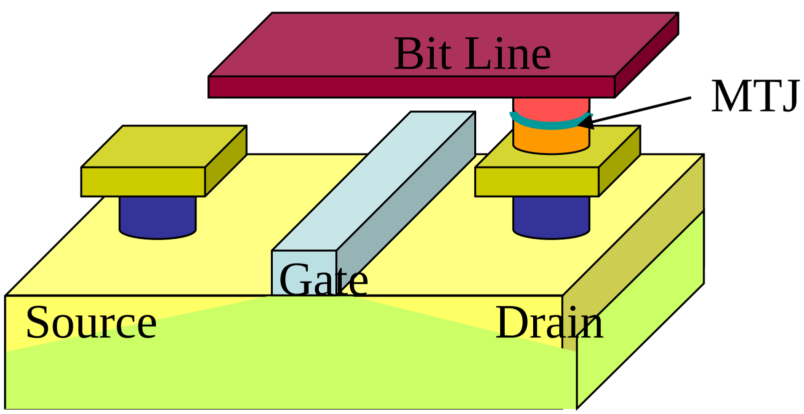
Magnetic Information technologies

Storage – Hard Disk Drive

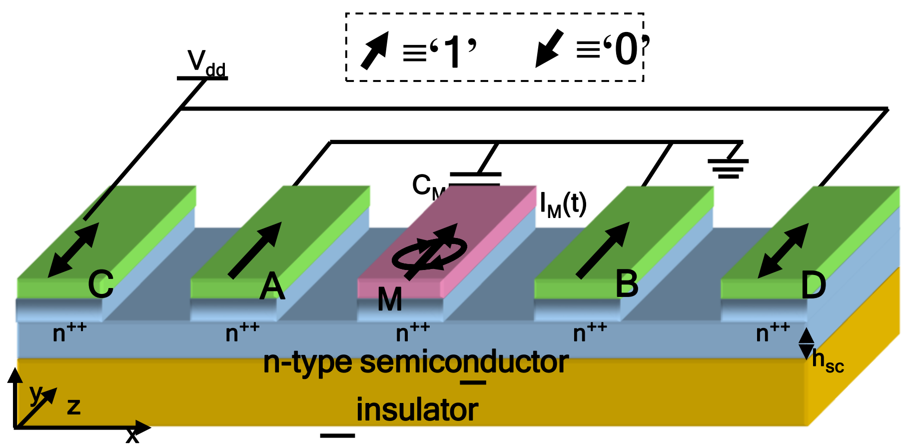




Memory – MRAM

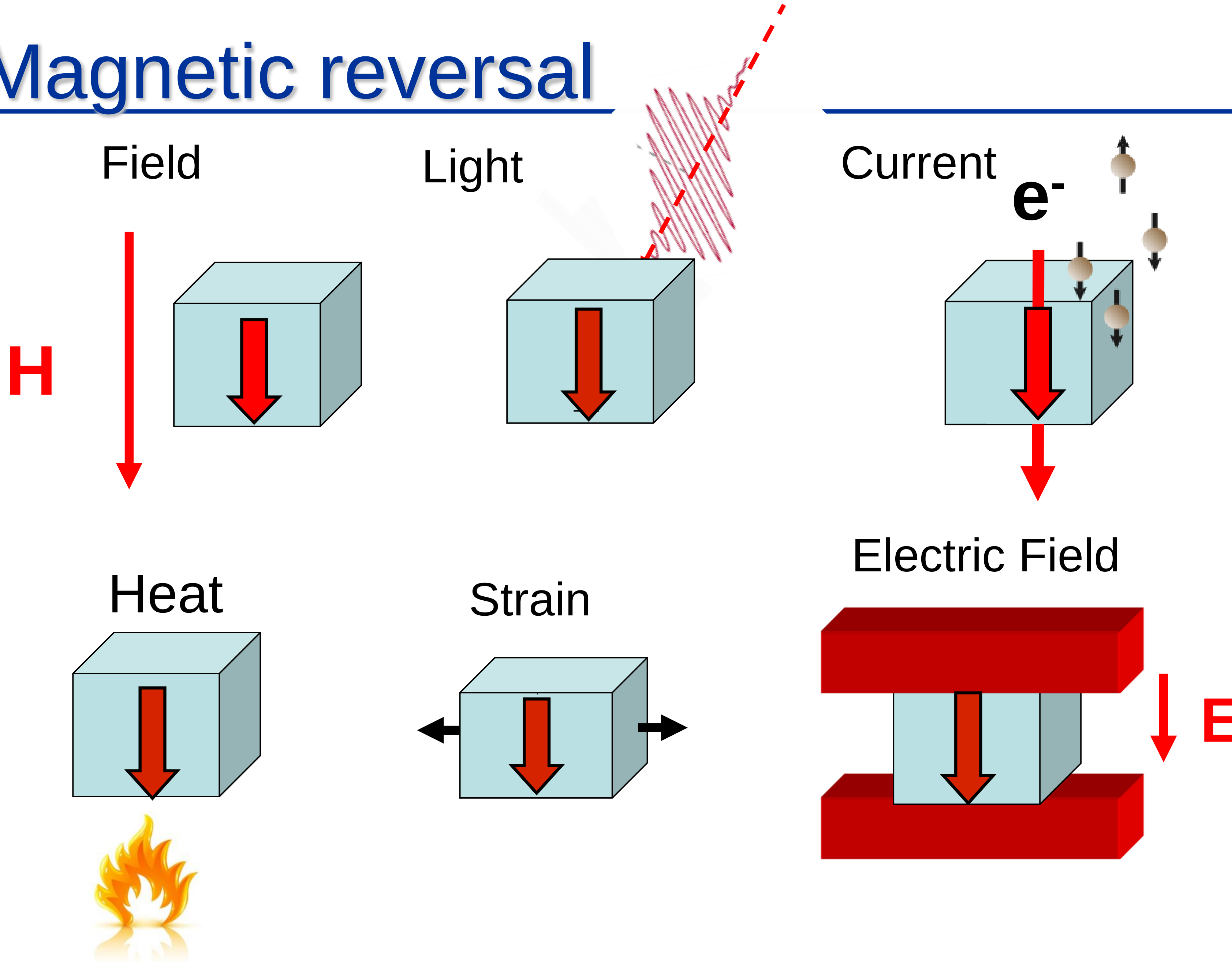


Processing

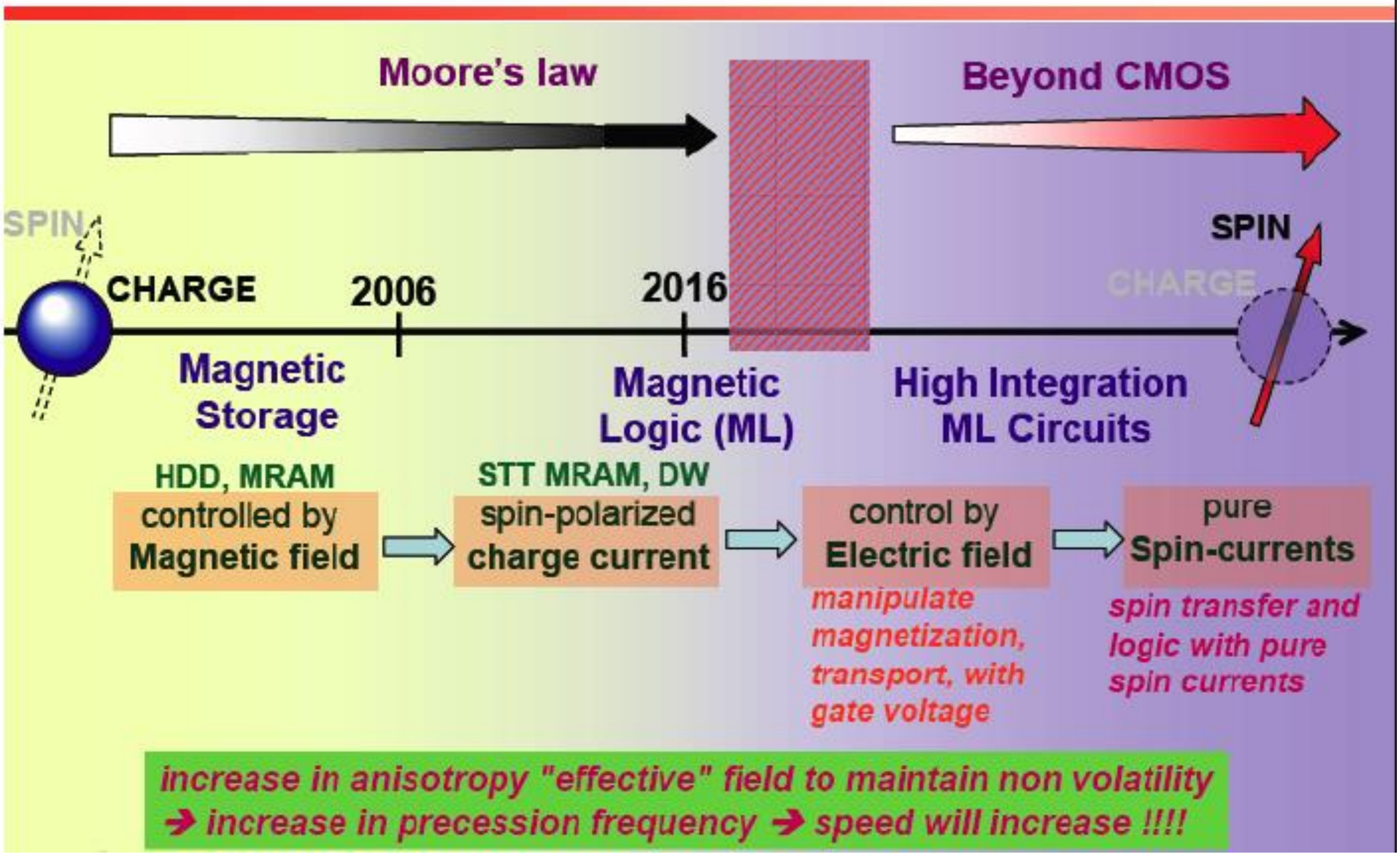


H. Dery, P. Dalal, L. Cywinski, L. J. Sham

Magnetic reversal



Claude Chappert's roadmap



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