Spintronics

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Workshop on Evolution & Control of Complexity: Key Experiments Using Sources of Hard X-Rays

October 11, 2010

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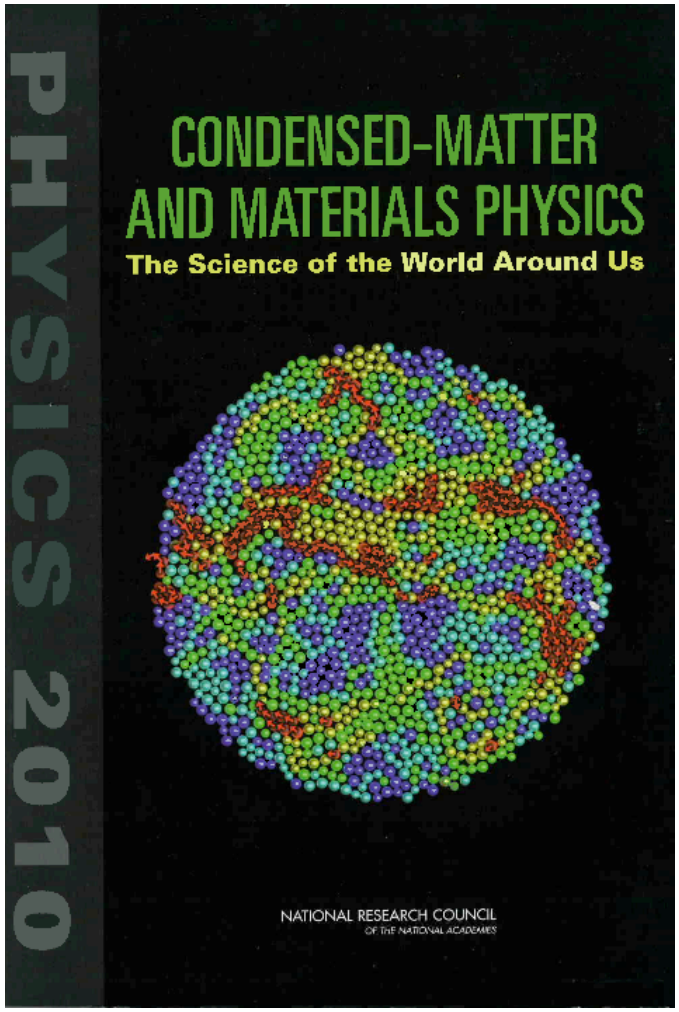
What is condensed matter and materials physics (CMMP)?

- CMMP embraces "the science of the world around us."

- It involves the *creation* of advanced materials,
- the *exploration* of their properties,
- and an *understanding* in terms of both the
- theoretical underpinnings of the phenomena of interest,
- and the structure-properties relationships exhibited.



Create
Explore
Understand

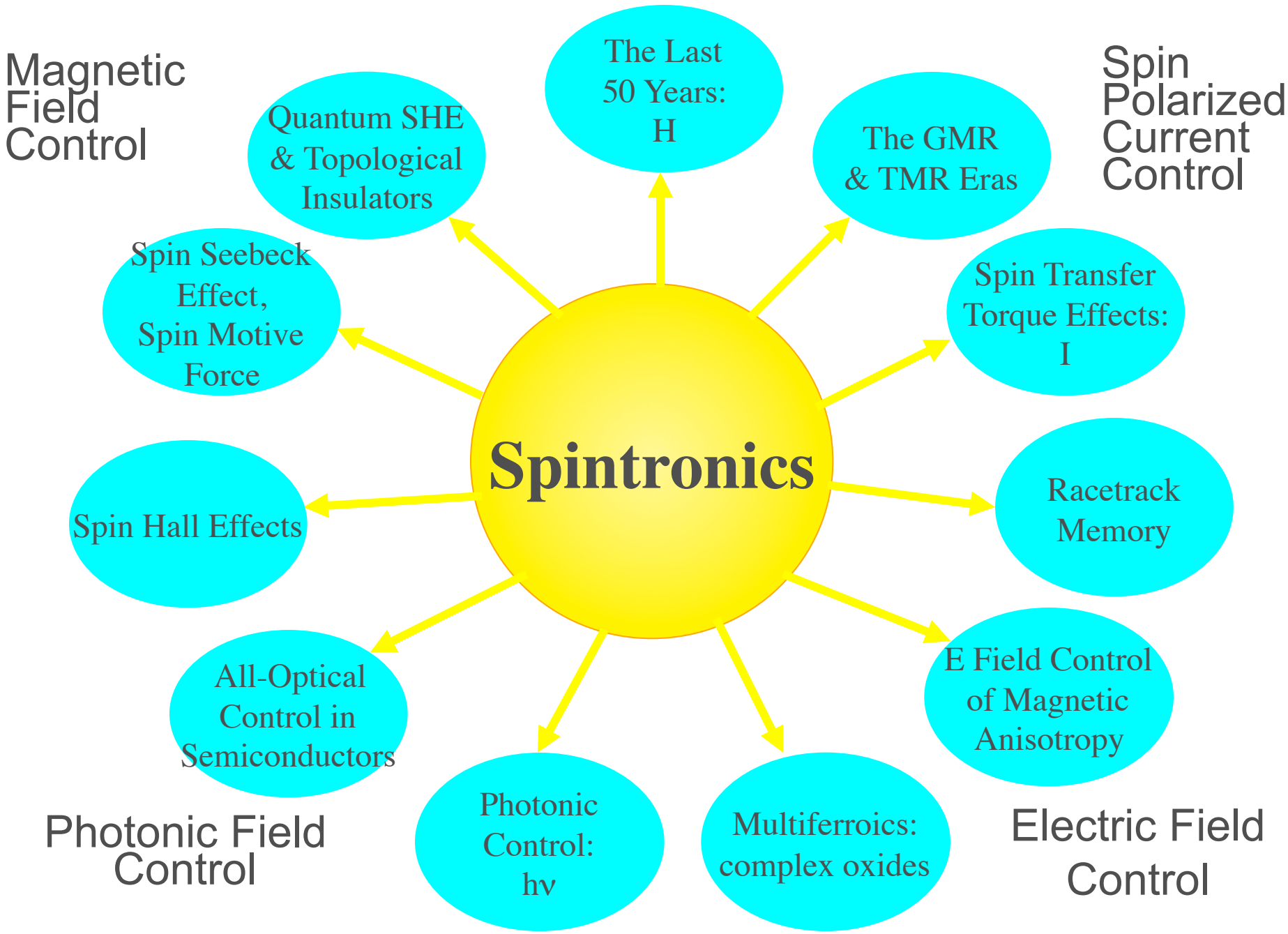
Six CMMP Science Challenges for the Next Decade

- How do complex phenomena emerge from simple ingredients?
- What is the physics of life?
- What happens far from equilibrium and why?
- What new discoveries await us in the nanoworld?
- How will the energy demands of future generations be met?
- How will the information technology revolution be extended?

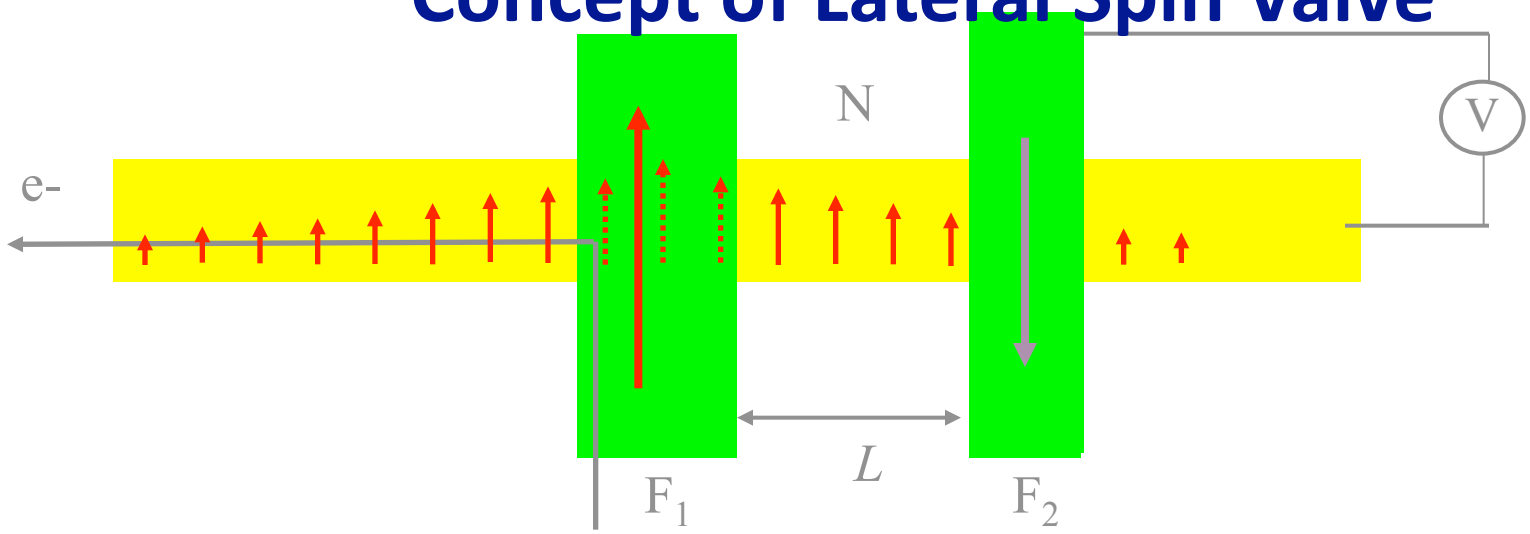
Age of physics -> Age of Biology

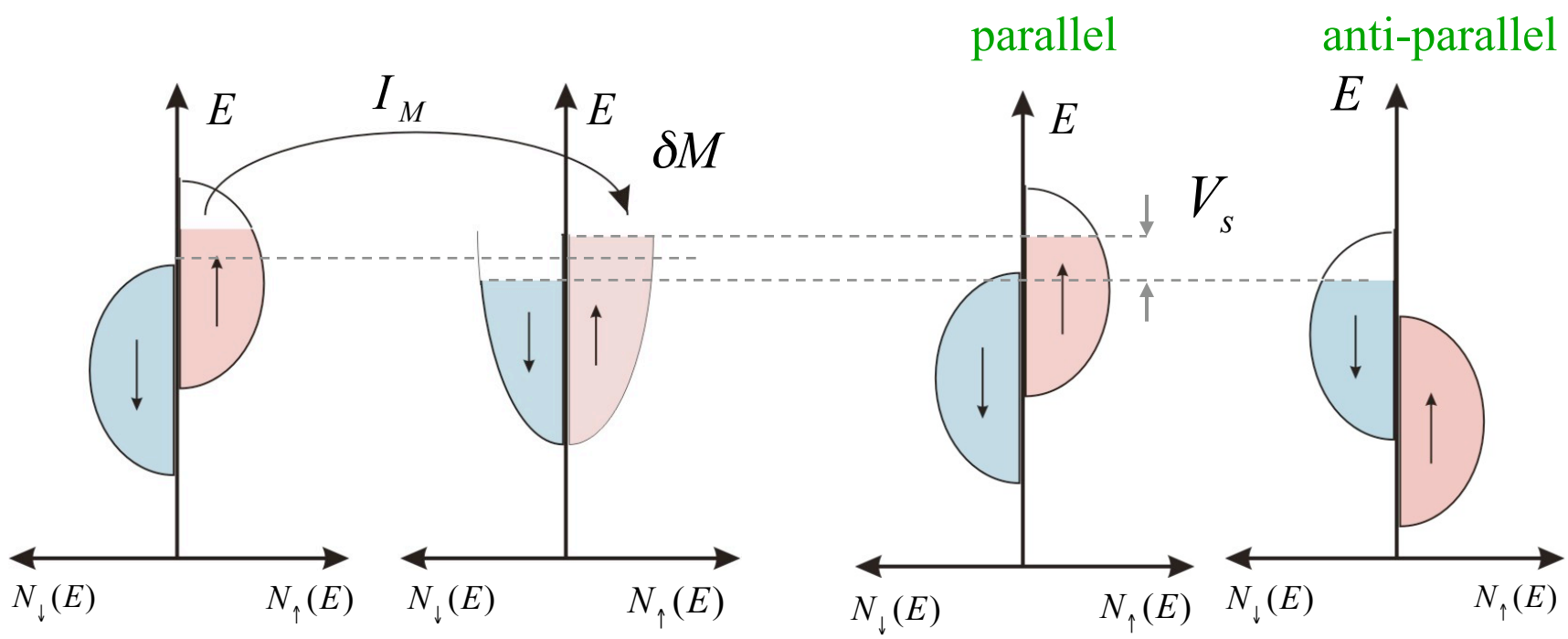
Age of Control or Age of Emergence

Age of Energy and Technology

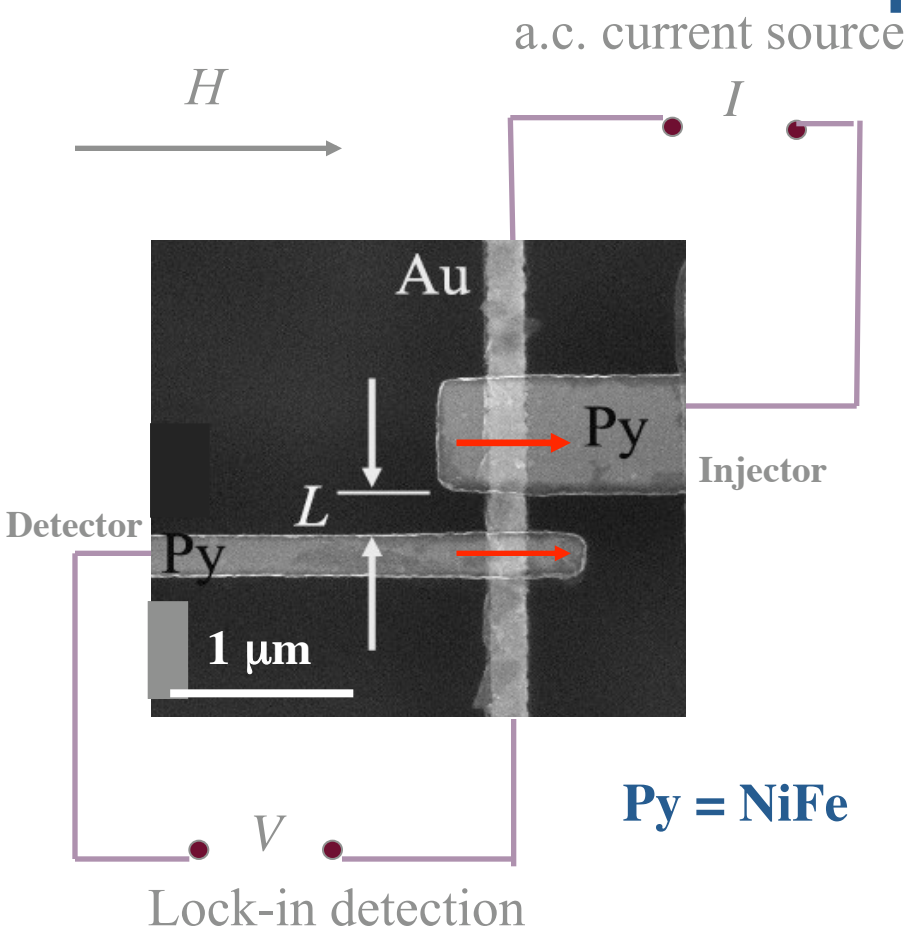

Spintronics
The Last 50 Years: H
The GMR & TMR Eras
Spin Polarized Current Control
Spin Transfer Torque Effects: I
Racetrack Memory
E Field Control of Magnetic Anisotropy
Electric Field Control
Multiferroics: complex oxides
Photonic Control: hν
Photonic Field Control
All-Optical Control in Semiconductors
Spin Hall Effects
Spin Seebeck Effect, Spin Motive Force
Quantum SHE & Topological Insulators
Magnetic Field Control

Concept of Lateral Spin Valve

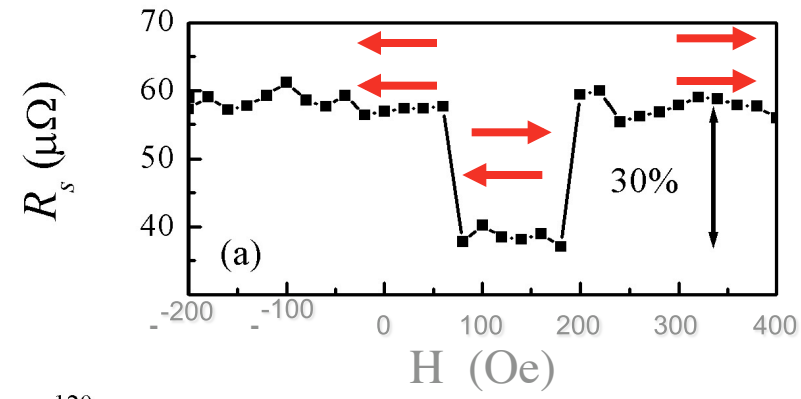


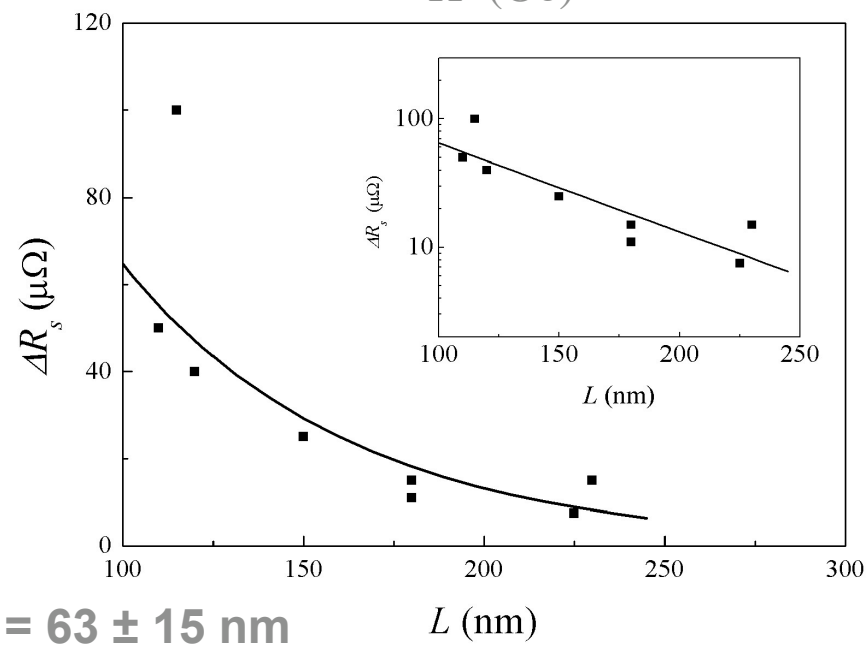


Spin Injection, Diffusion, and Detection in Lateral Spin-Valves



Py = NiFe





T = 10 K

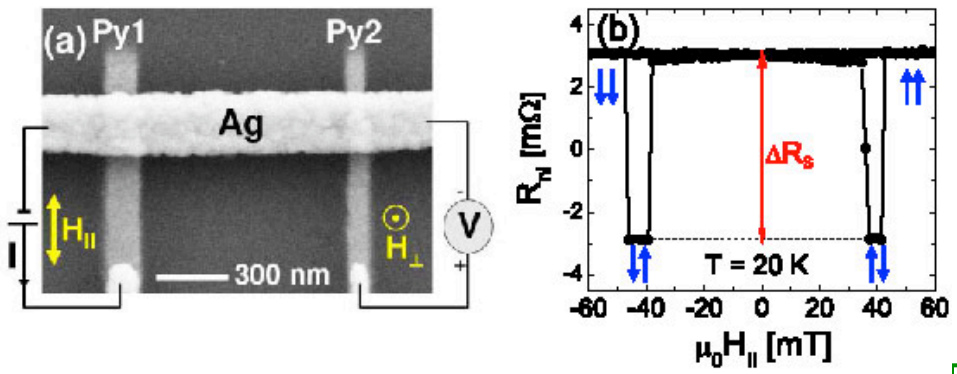
λ_s = 63 ± 15 nm

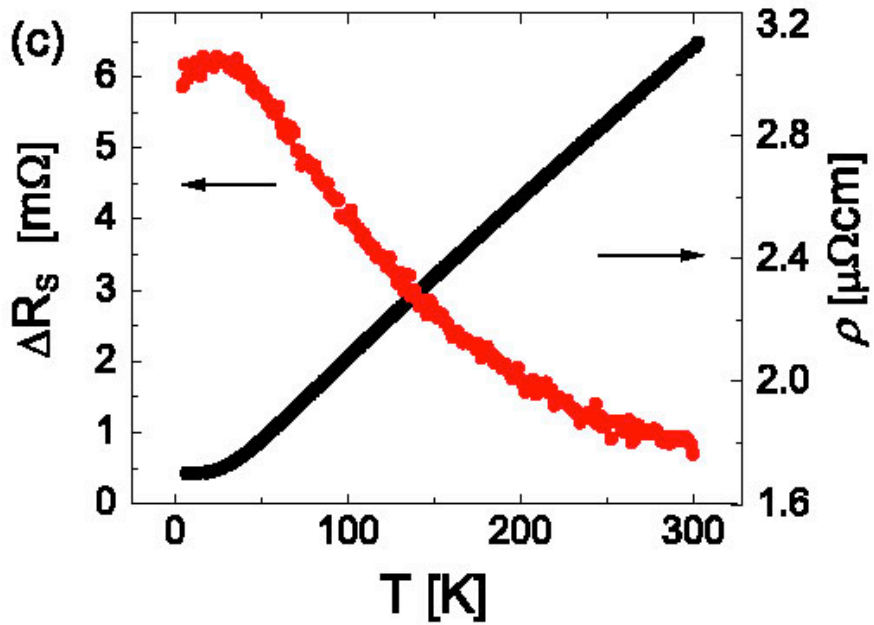
Yi Ji *et al.* APL **85**, 6218 (2004)

Spin-Orbit Effects

Surface Spin Flip Probability of Mesoscopic Ag Wires

G. Mihajlović*, J. E. Pearson, S. D. Bader, and A. Hoffmann





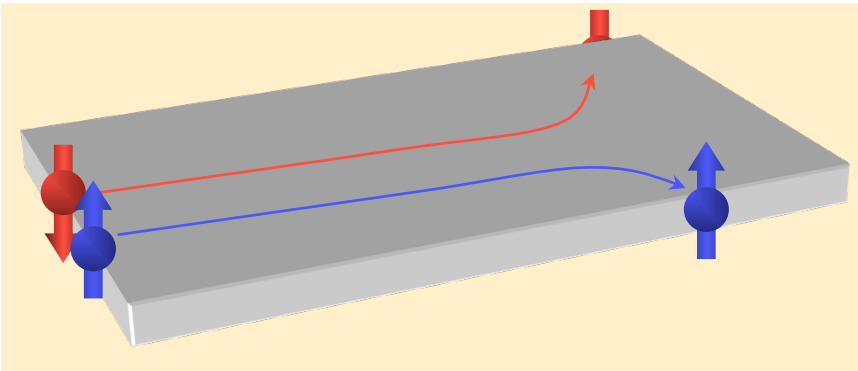
PRL **104**, 237202
11 June 2010 Issue

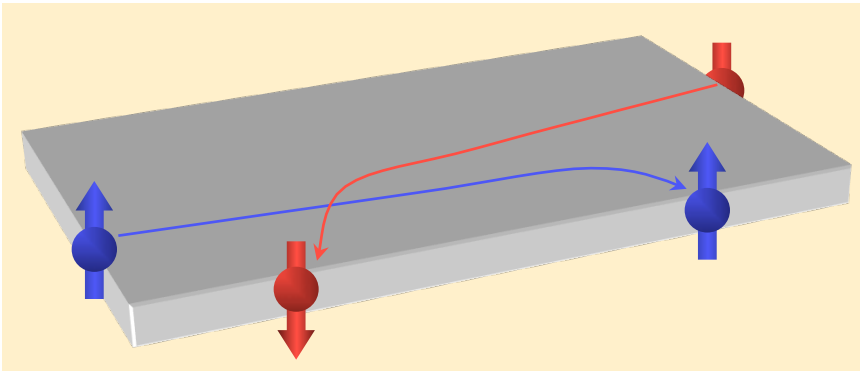
*Present Address:
Hitachi GS, San Jose, Ca

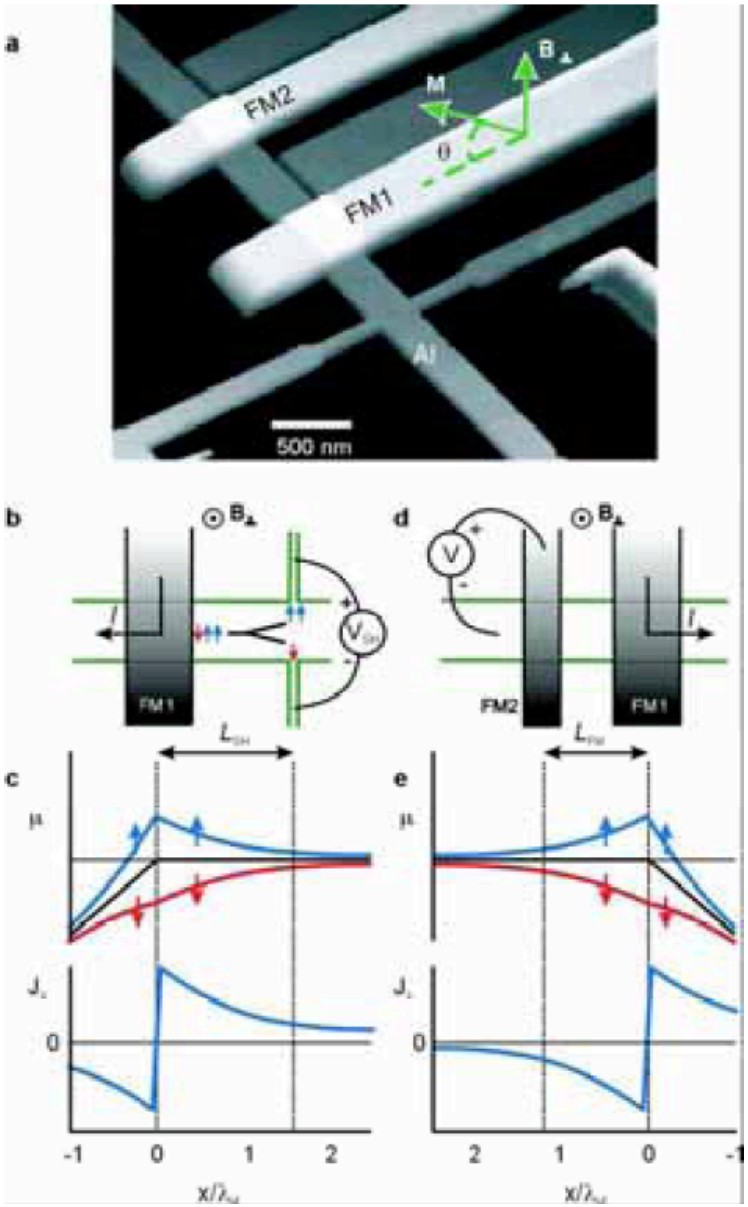
"…spin flip probability is highest for surface scattering."

Spin Hall *vs.* Inverse Spin Hall

Spin Hall	Inverse Spin Hall
Charge Current	**Spin Current**
⇓ Spin Dependent Scattering	⇓
Transverse	**Transverse**
Spin Imbalance	**Charge Imbalance**







Direct electronic measurement of the spin Hall effect

S. O. Valenzuela & M. Tinkham

Nature **442**, 176 (2006)

$$\gamma = \frac{\sigma_{SH}}{\sigma_c}$$

σ_{SH} ← spin Hall conductivity

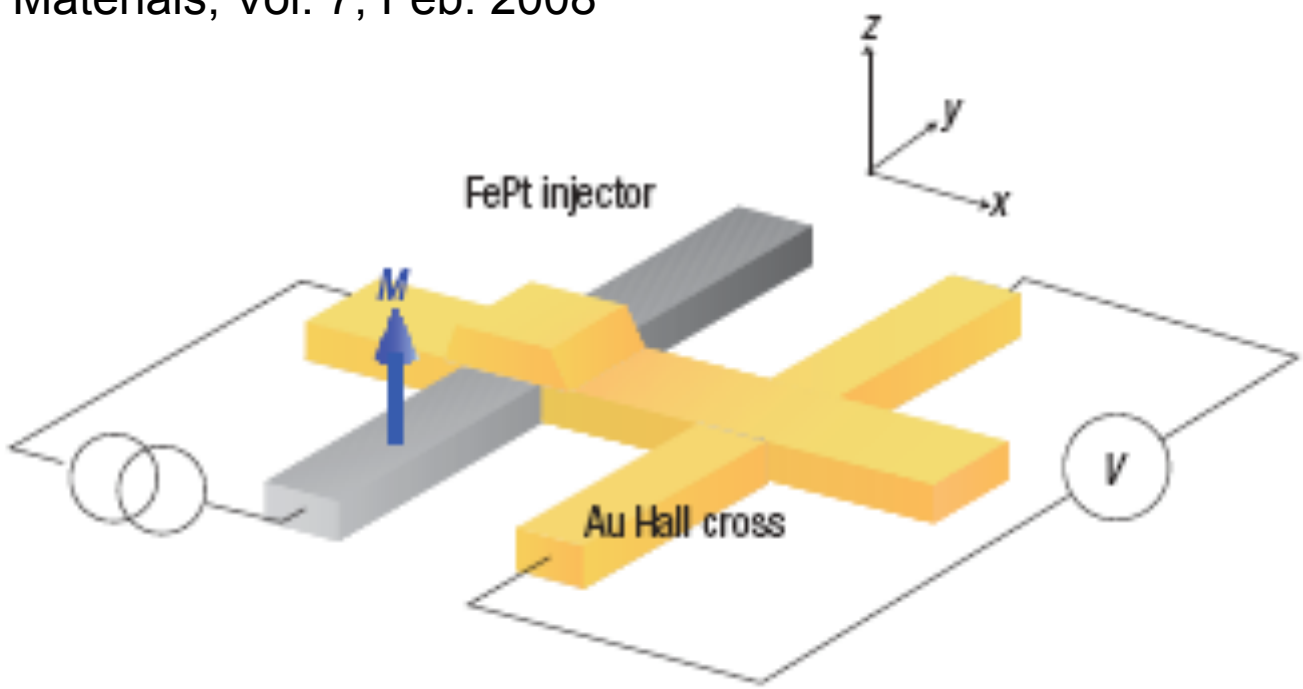
σ_c ← charge conductivity

S.D. Bader & S.S.P. Parkin , "Spintronics", *Annual Review of Condensed Matter Physics*, 1, 71 (2010)

Giant spin Hall effect in perpendicularly spin-polarized FePt/Au devices

TAKESHI SEKI[1]*, YU HASEGAWA[1], SEIJI MITANI[1], SABURO TAKAHASHI[1,2], HIROSHI IMAMURA[2,3], SADAMICHI MAEKAWA[1,2], JUNSAKU NITTA[4] AND KOKI TAKANASHI[1]

Nature Materials, Vol. 7, Feb. 2008



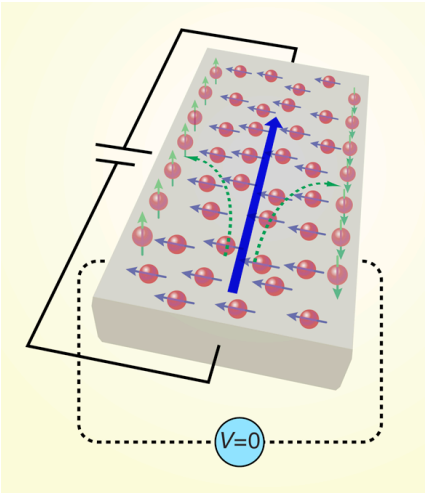
Negative Non-local Resistance in Mesoscopic Gold Hall Bars:
Absence of Giant Spin Hall Effect

Goran Mihajlović

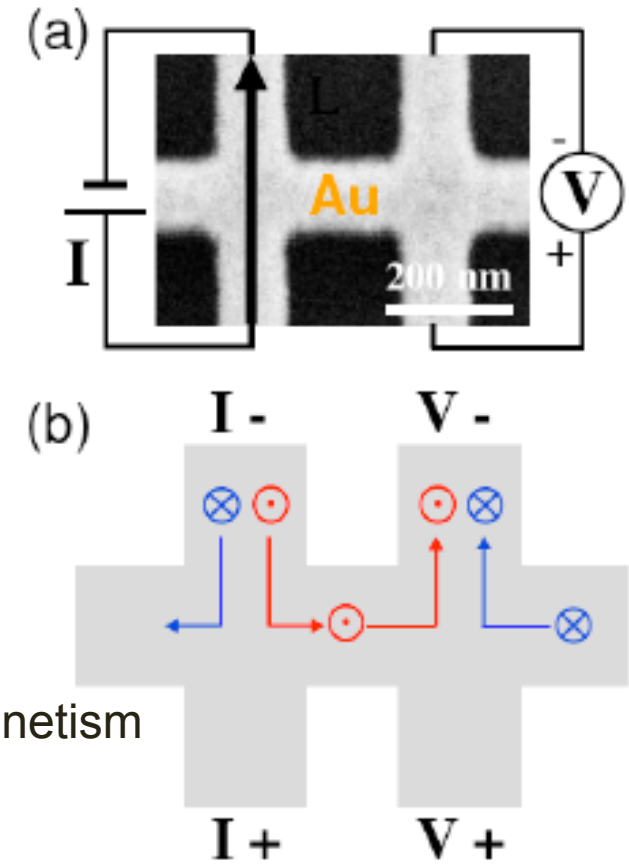
G. Mihajlović*, J. E. Pearson, Miguel Angel Garcia,**
S. D. Bader, and A. Hoffmann

**Dept of Mat'ls Physics, Univ Complutense, Madrid, Spain

Axel Hoffmann



Spintronics without Magnetism
Awschalom & Samarth
Physics **2, 50 (2009)**



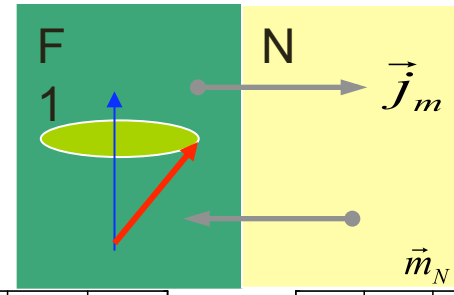
Spin-orbit Interaction:
High Z- Enhanced Spin Accumulation
Low Z- Enhanced Spin Diffusion Length

PRL **103**, 166601 (2009)

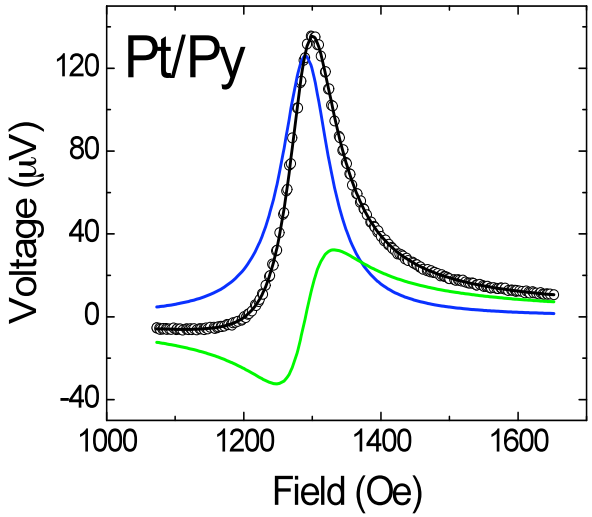
*Present Address:
Hitachi GS, San Jose, Ca

Quantifying Spin Hall Angle via Spin Pumping

γ_{Pd} = 0.0071, 0.0079 (9, 5 GHz)

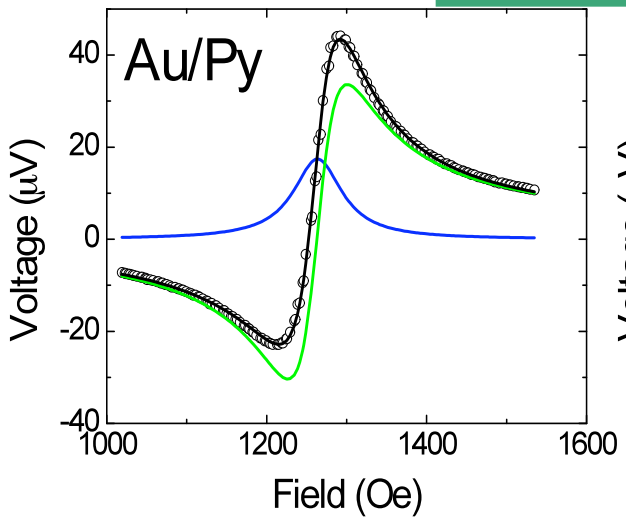


Pt



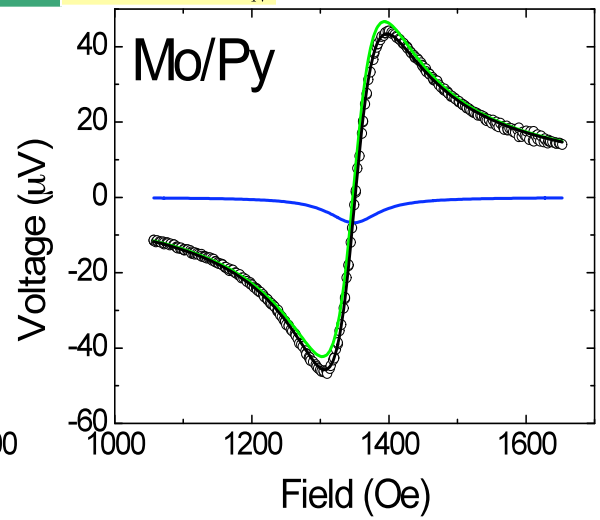
γ = 0.014 ±0.001

Au



γ = 0.0035 ±0.0003

Mo

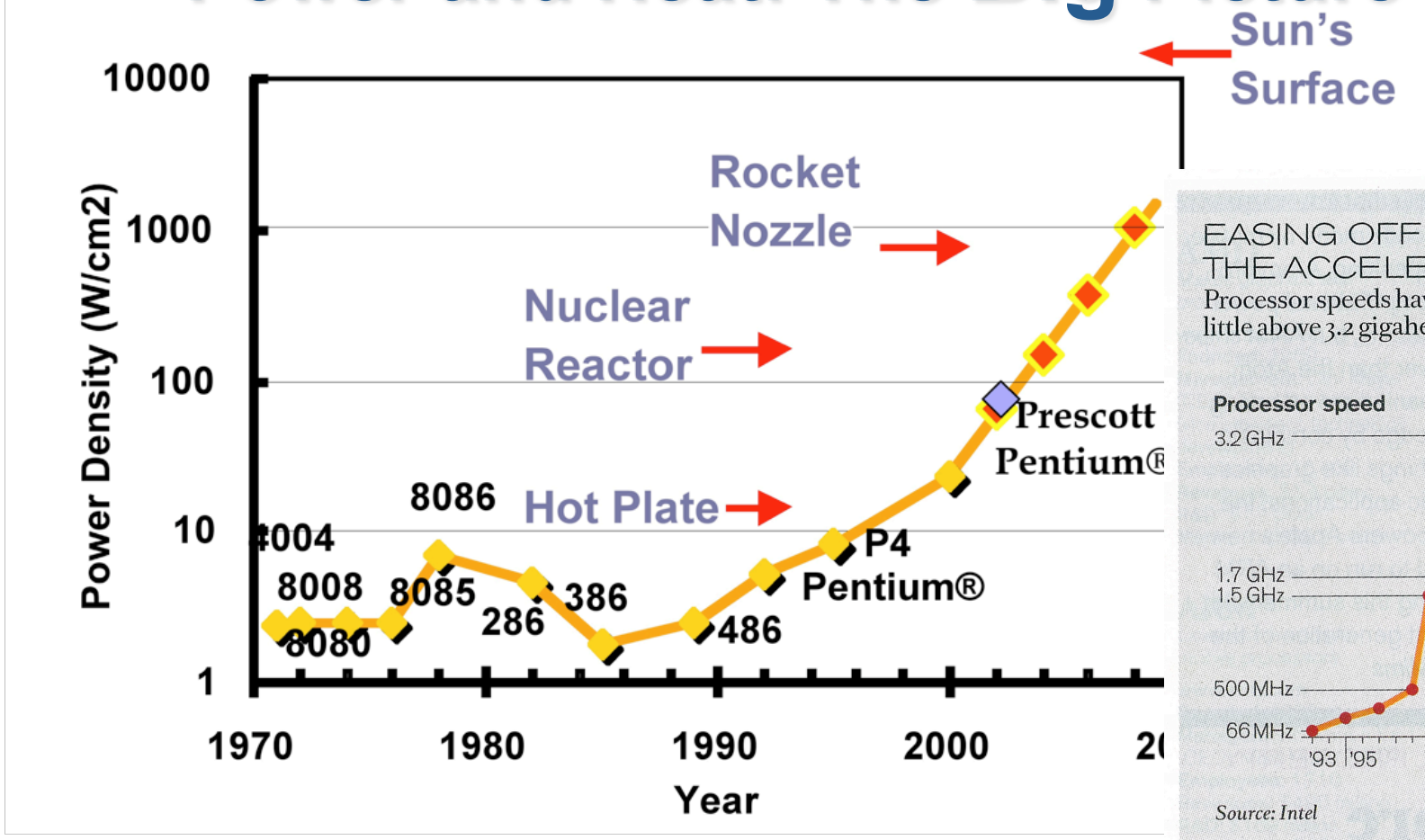


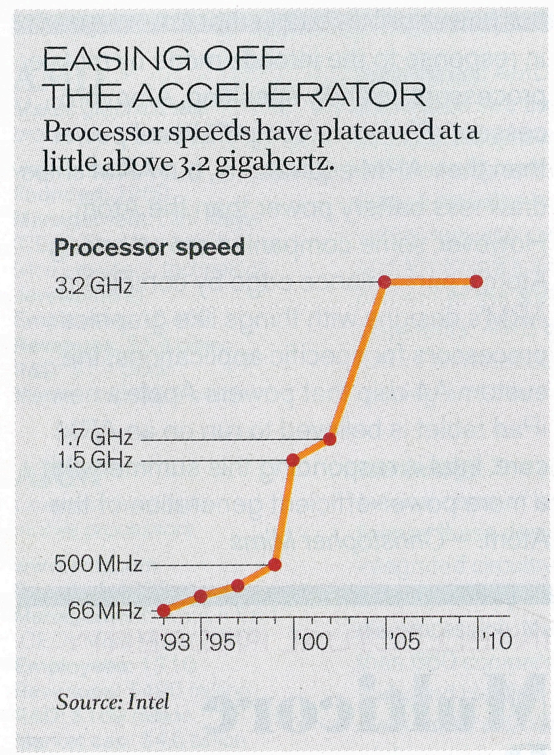
γ = -0.0005 ±0.0001

FMR – inject dc pure spin current into normal metal – in bilayer integrated into coplanar waveguides. Transverse dc voltage across bilayer contains AMR & ISHE components.

O. Mosendz J.E. Pearson, F.Y. Fradin, G.E.W. Bauer, S.D. Bader, and A. Hoffmann, *PRL* **104**, 046601 (2010) 4 GHz

Power and Heat: The Big Picture



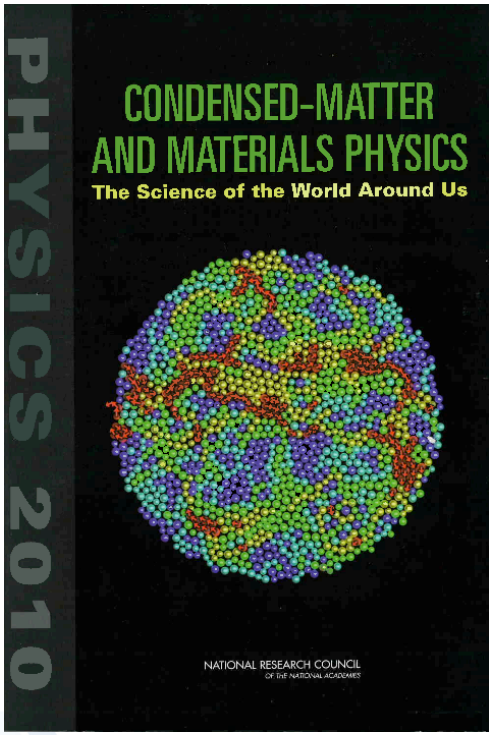


Power density of Intel processors since 1970.
Source: S. Borkar and V. De, Intel Corporation. See, for instance, www.rle.mit.edu/isg/documents/Chen_ICCAD08_slides.pdf

The Semiconductor Roadmap is reaching its limits

To satisfy the global demand from gadgets in 2030 will require building the equivalent of 540 coal-fired power plants, or 230 nuclear plants, according to the International Energy Agency.

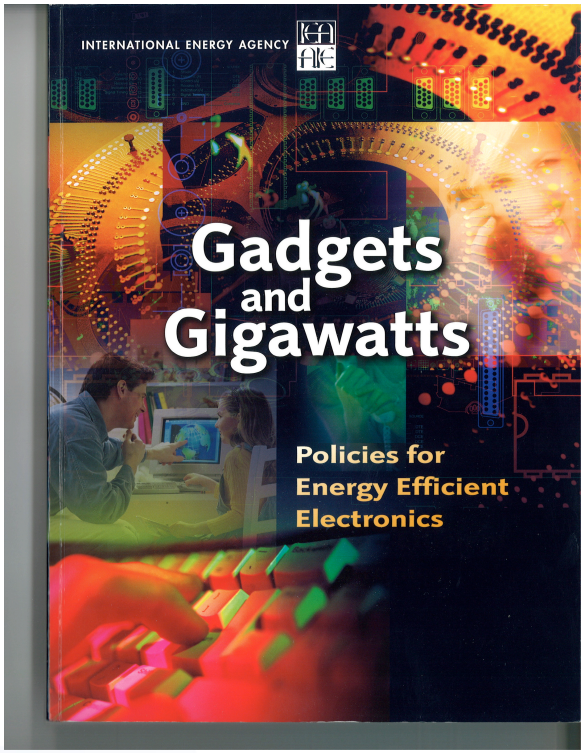
Message



Information Technology is an Energy Technology Challenge.

New devices are needed: Beyond Si

Basic Science can again play a central role

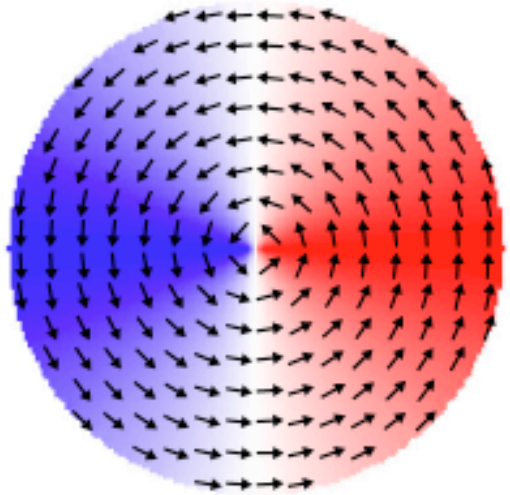


summary

Spin transistors are pre-1947 in their development compared to Si; they still lack gain. But they are rich in basic research opportunities.

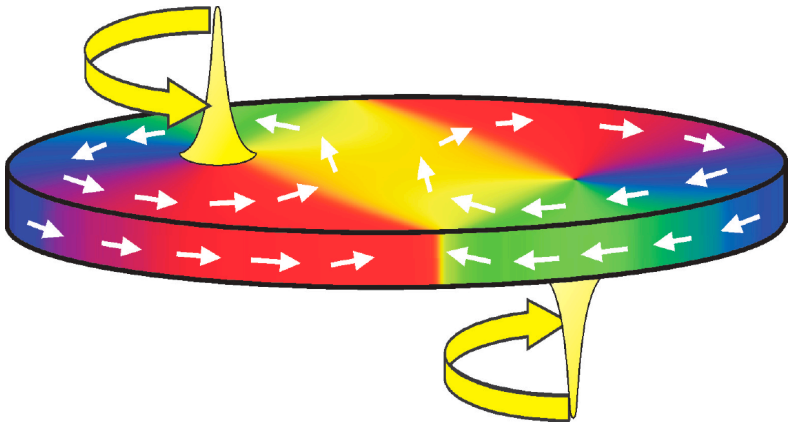
Exciting Developments in Spintronics

- Spin engineering concepts: *GMR, TMR, MTJ*
- Switching $\boldsymbol{M}$ via I_s, $\boldsymbol{E}$, $h\nu$
- Discovery & exploration of novel material systems.
- A complex zoology of novel transport & thermoelectric effects dependent on the interplay between I_s & I_c.
- Dissipationless spin-edge currents in a class of gapless semiconductors known as *Topological Insulator*.
- *Postscript*: Continuing the Information Technology Revolution *is* an Energy Technology Challenge.



Will Cross-Disciplinary Research be a Hallmark of the Future?

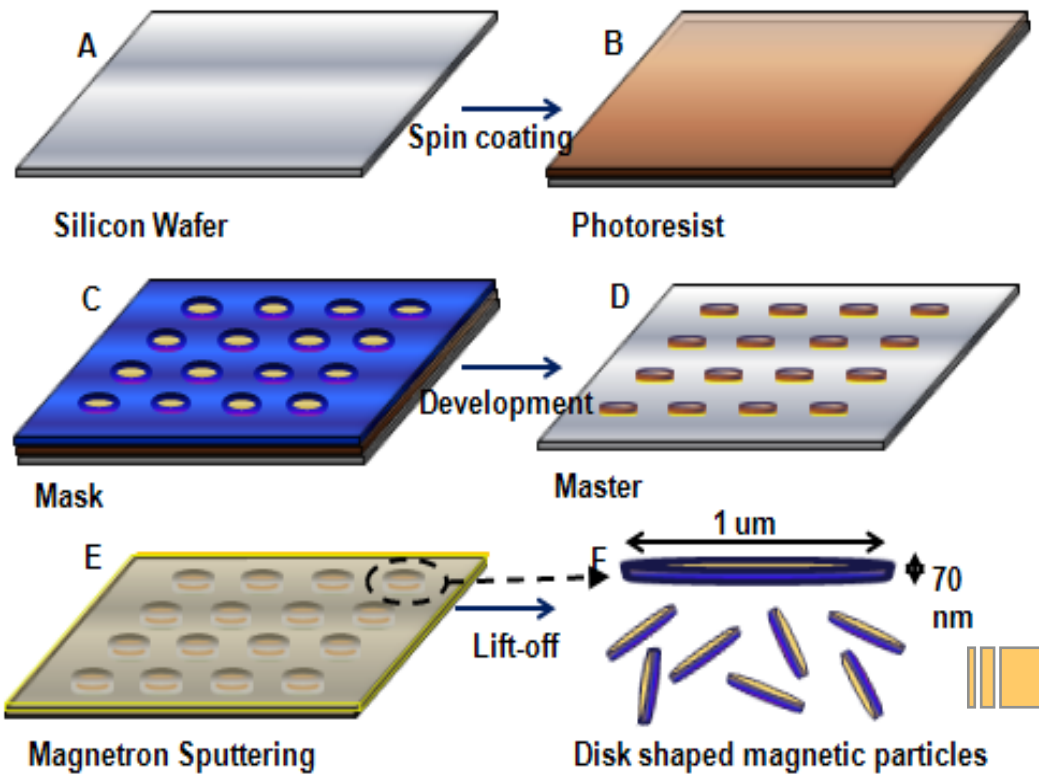
Vortex medical

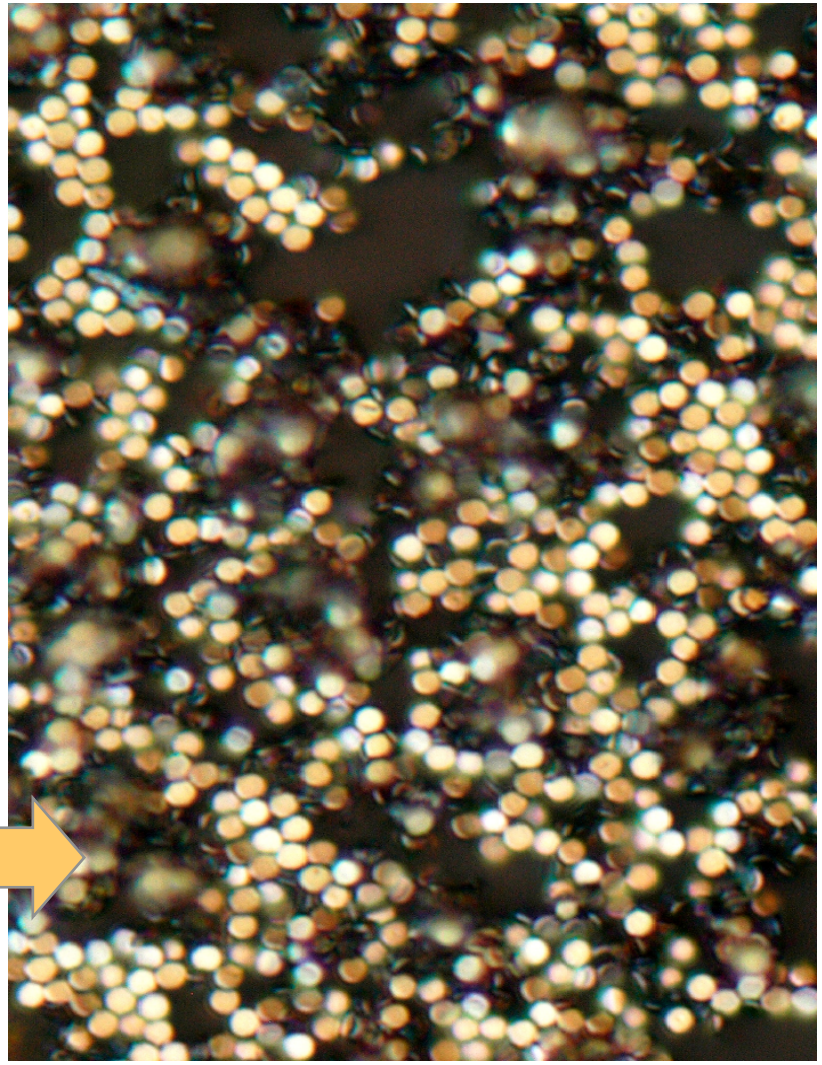


Colloquium:
Opportunities in Nanomagnetism
S. D. Bader, *Rev. Mod. Phys*. 78 (2006) 1-15.

Microdisk Fabrication♪

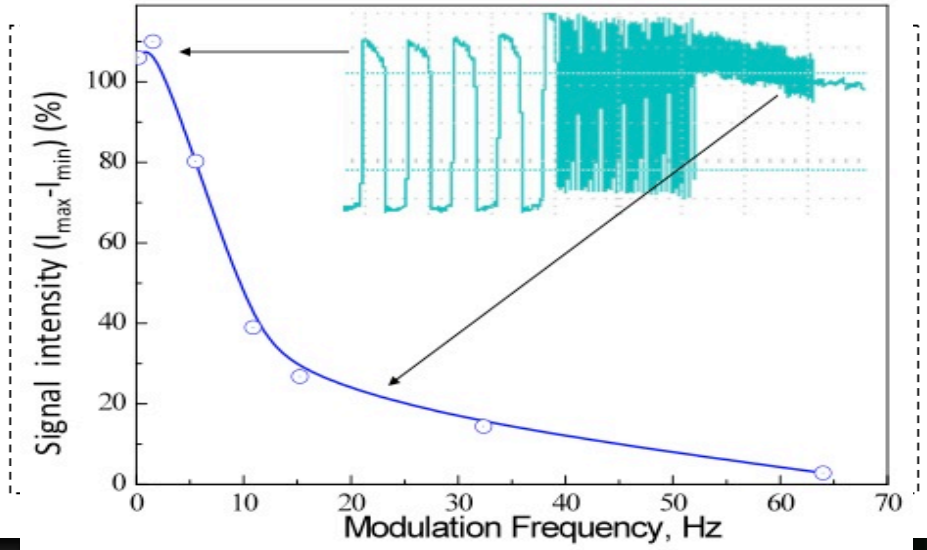
- Opt. lithography and magnetron sputtering



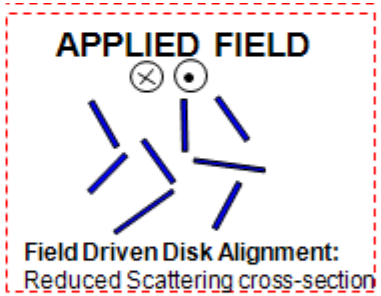


E. A. Rozhkova, V. Novosad, D.-H. Kim, T. Rajh & S. D. Bader, "Ferromagnetic microdisks as carriers for biomedical applications". *J. Appl. Phys*. 105, 07B306 (2009).

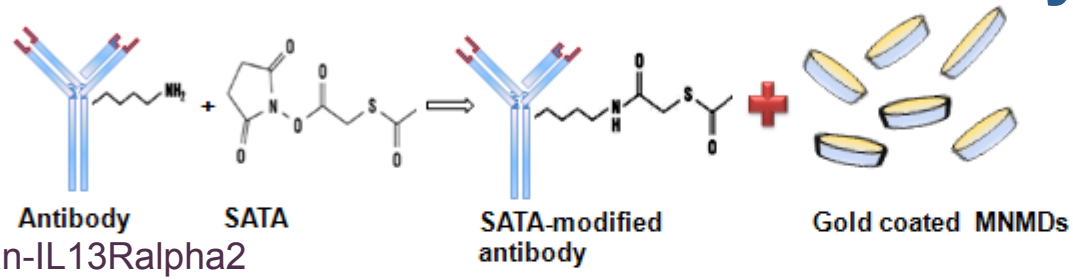
Magnetic Disks Rotation Experiment♪



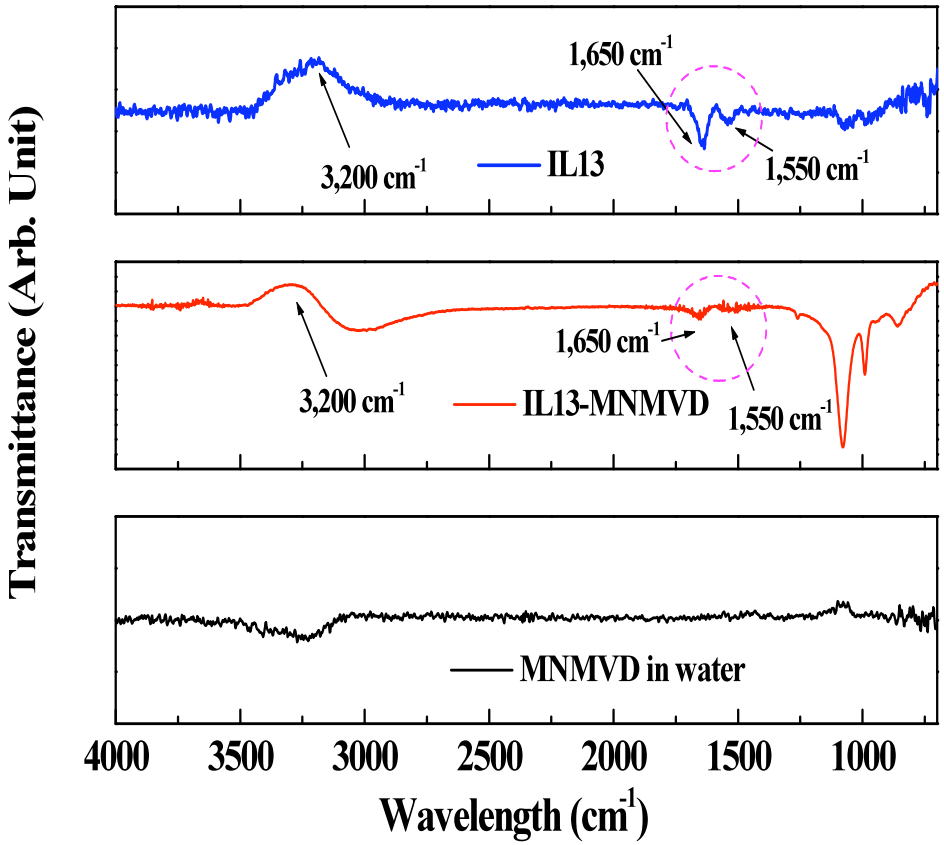
The light intensity passing though an aqueous disk suspension ~10^6 disks per 1 ml modulated by an external magnetic field.
The field strength was ~7 Oe; pulse duration is 1 s.

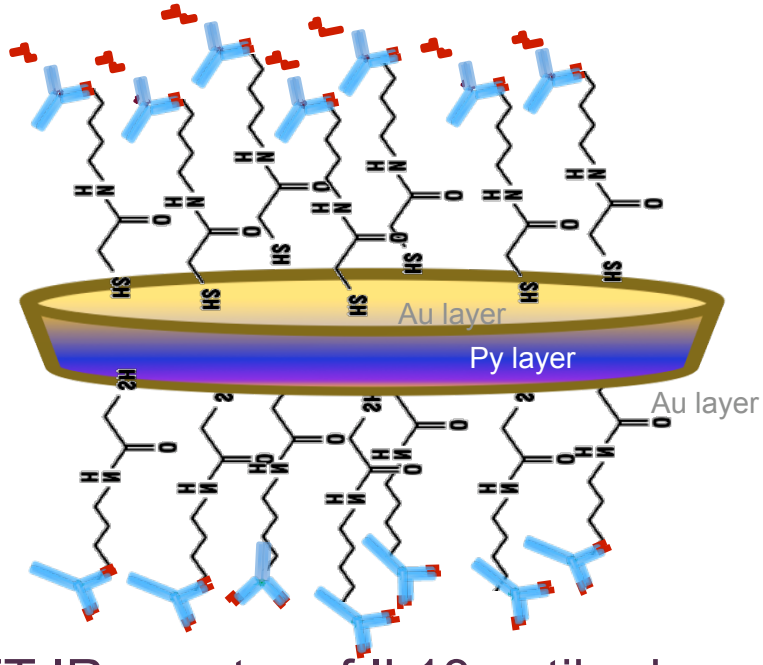


Biofunctionalization for TARGETED delivery♪



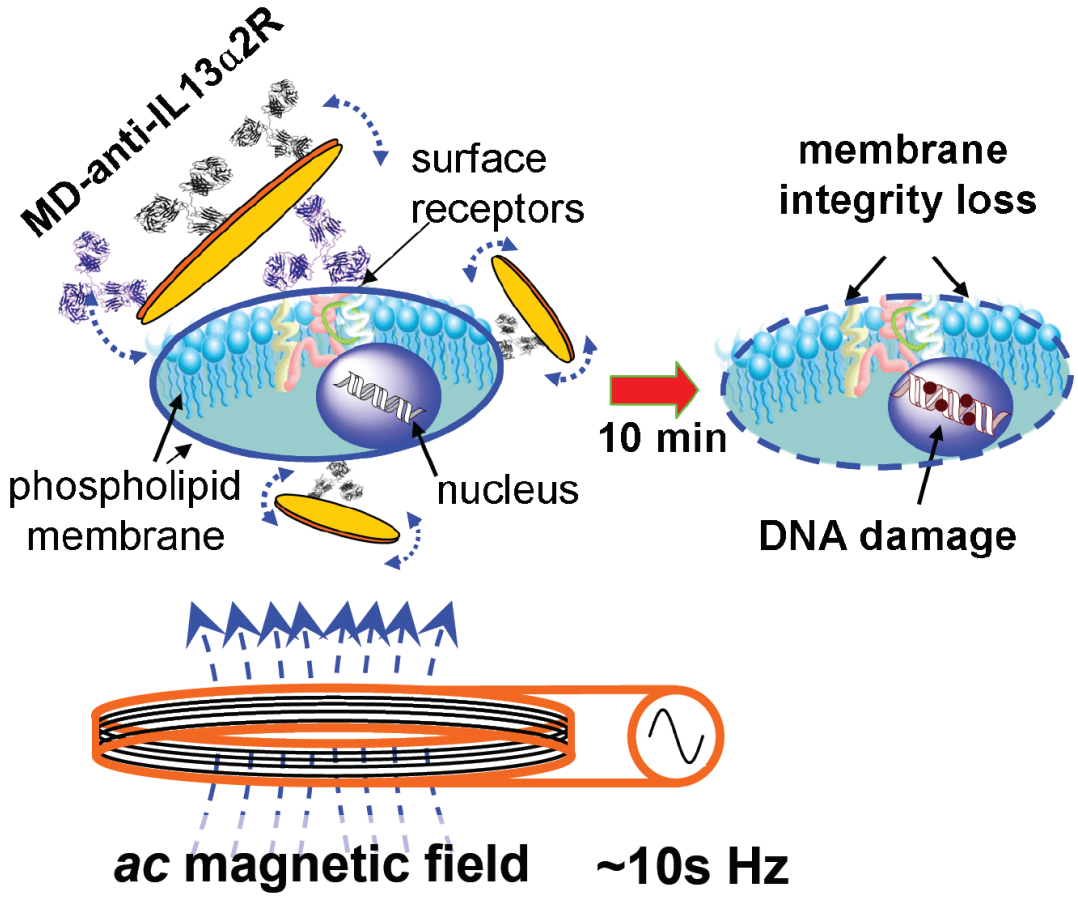
Monoclonal anti-human-IL13Ralpha2
N-Succinimidyl S-Acetylthioaceteate (SATA),





FT-IR spectra of IL13 antibody, IL13-functionalized and as-microfabricated magnetic disks.

Mechanism of Cancer Cell Destruction♪

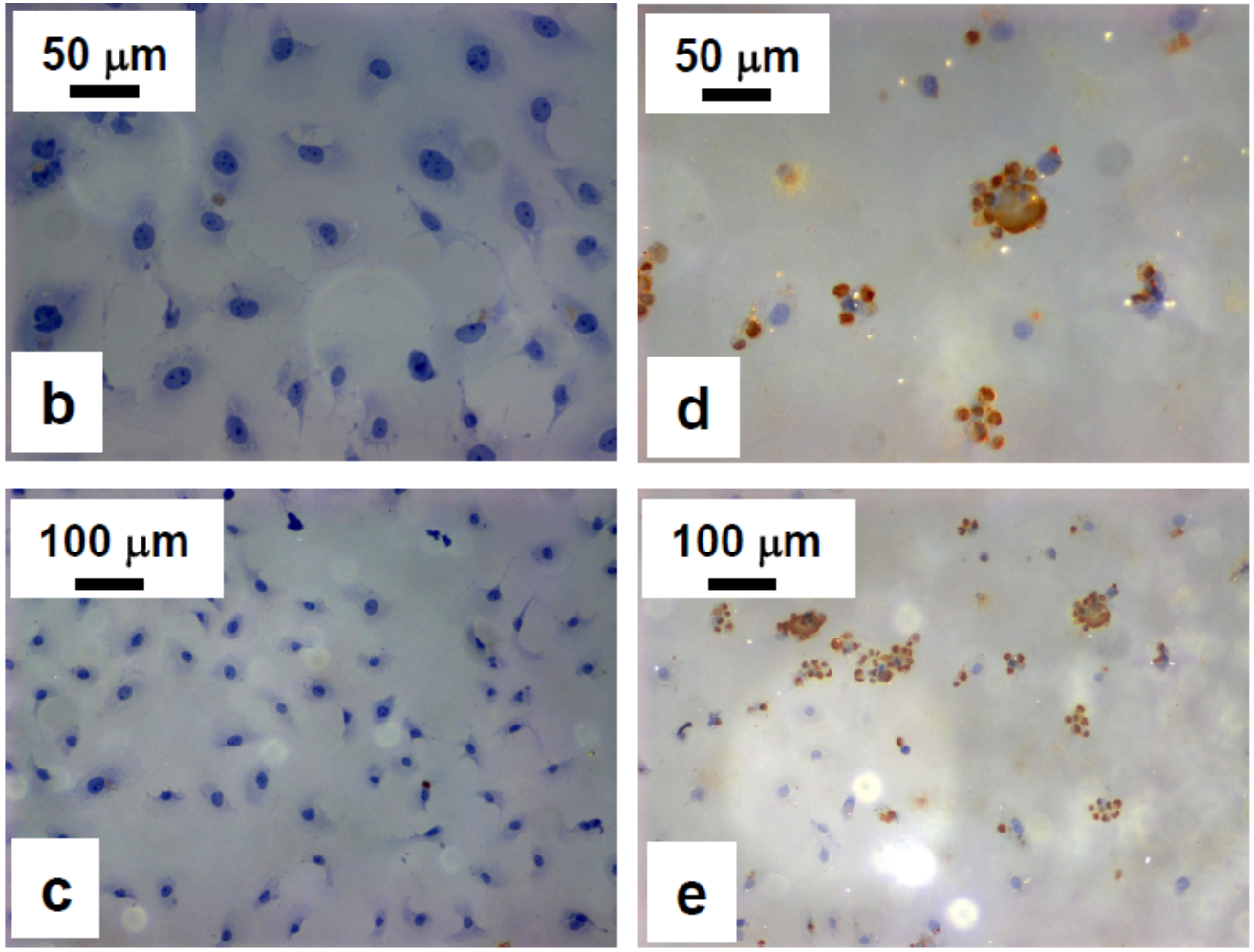


Direct Transfer of Magneto-Mechanical Energy to the Cell

Membrane Rupture – may lead to necrosis

Triggers Signal Pathways leading to apoptosis

Apoptosis Induced by Mechanical Force♪



(B,C) negative control and (D,E) IL13-MD functionalized N10 glioma cells subjected to 20 Hz / 90 Oe AC *magnetic field for 10 min and TUNEL* stained 4 h after the expt. (TUNEL assay = Terminal Deoxynucleotidyl Transferase dUTP nick end labeling)

Magneto-Mechanical Cancer Cell Destruction *vs.* Magnetic Hyperthermia ♪

Field Amplitude	Frequency Range	Mechanism
~100s Oe	~100s kHz	Heat exchange
~30 – 120 Oe	10-40 Hz	Direct energy transfer

In our experiments the external energy (~ $f \times H^2$) supplied to the cell cultures was ~100,000 times smaller than in hyperthermia use of magnetic nanoparticles.

D.-H. Kim, E.A. Rozhkova, I.V. Ulasov, S.D. Bader, T. Rajh, M.S. Lesniak & V. Novosad, "Biofunctionalized Magnetic Vortex Microdisks for Targeted Cancer Cell Destruction" *Nature Materials 9, 165-171 (2010)*.

Summary

~10 Hz magnetic fields destroy cancer cells by compromising the cellular membrane integrity, and sending a *magnetic vortex-mediated* cellular signal that triggers programmed cell death.