CNST Center for Nanoscale Science & Technology

NIST National Institute of Standards and Technology

Current-induced magnetization dynamics

Mark Stiles – NIST

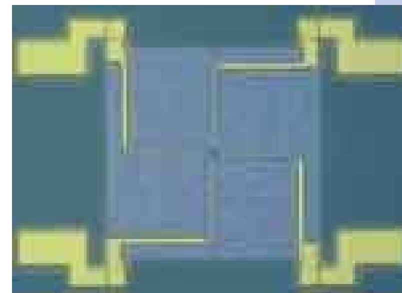
Tingyong Chen, Hongki Min, Keith Gilmore, Ion Garate, Christian Heiliger, Mark Hoefer, Yi Ji, Jiang Xiao, Jack Bass, C.-L. Chien, Michael J. Donahue, Allan H. MacDonald, Jacques Miltat, Daniel C. Ralph, Robert McMichael, Wayne M. Saslow, Thomas J. Silva, and Andrew Zangwill

Interaction between current and magnetization

Hard Magnets

Motors,
Generators

Soft magnets



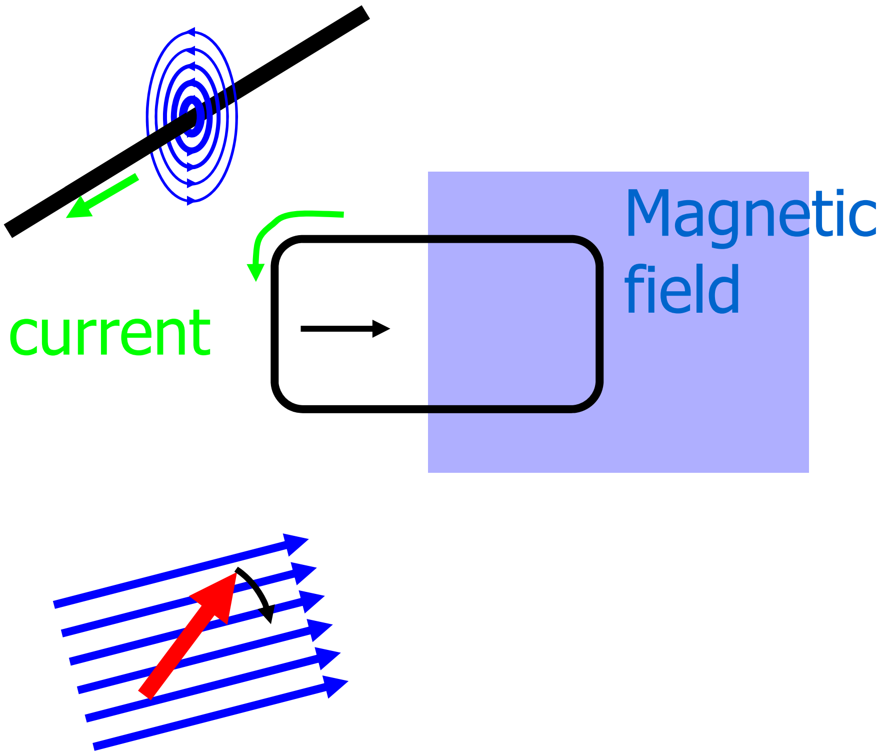
Sensors,
Transformers

Switchable but
Non-volatile

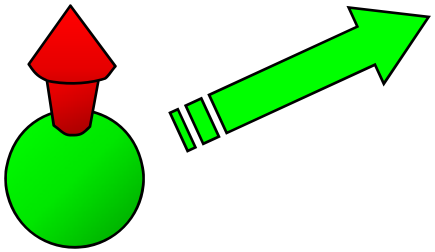
Memory

Interaction between current and magnetization mediated by

Magnetic fields

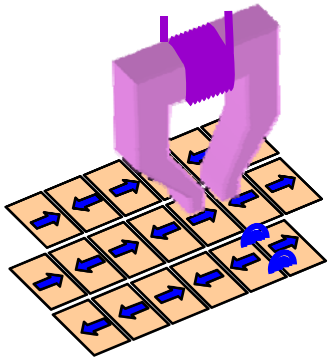


Spin currents

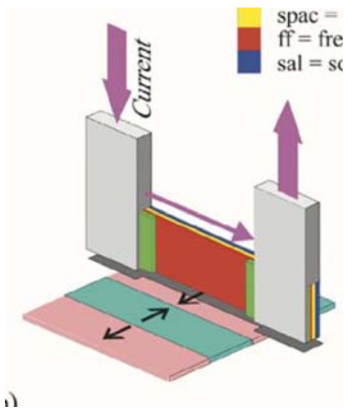


Spintronics: Exploiting the electron's other degree of freedom

Spintronics



Magnetic recording

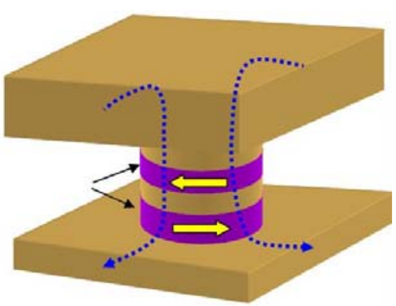


Giant Magnetoresistance (GMR)

- The Magnetic Configuration Affecting the Current Flow

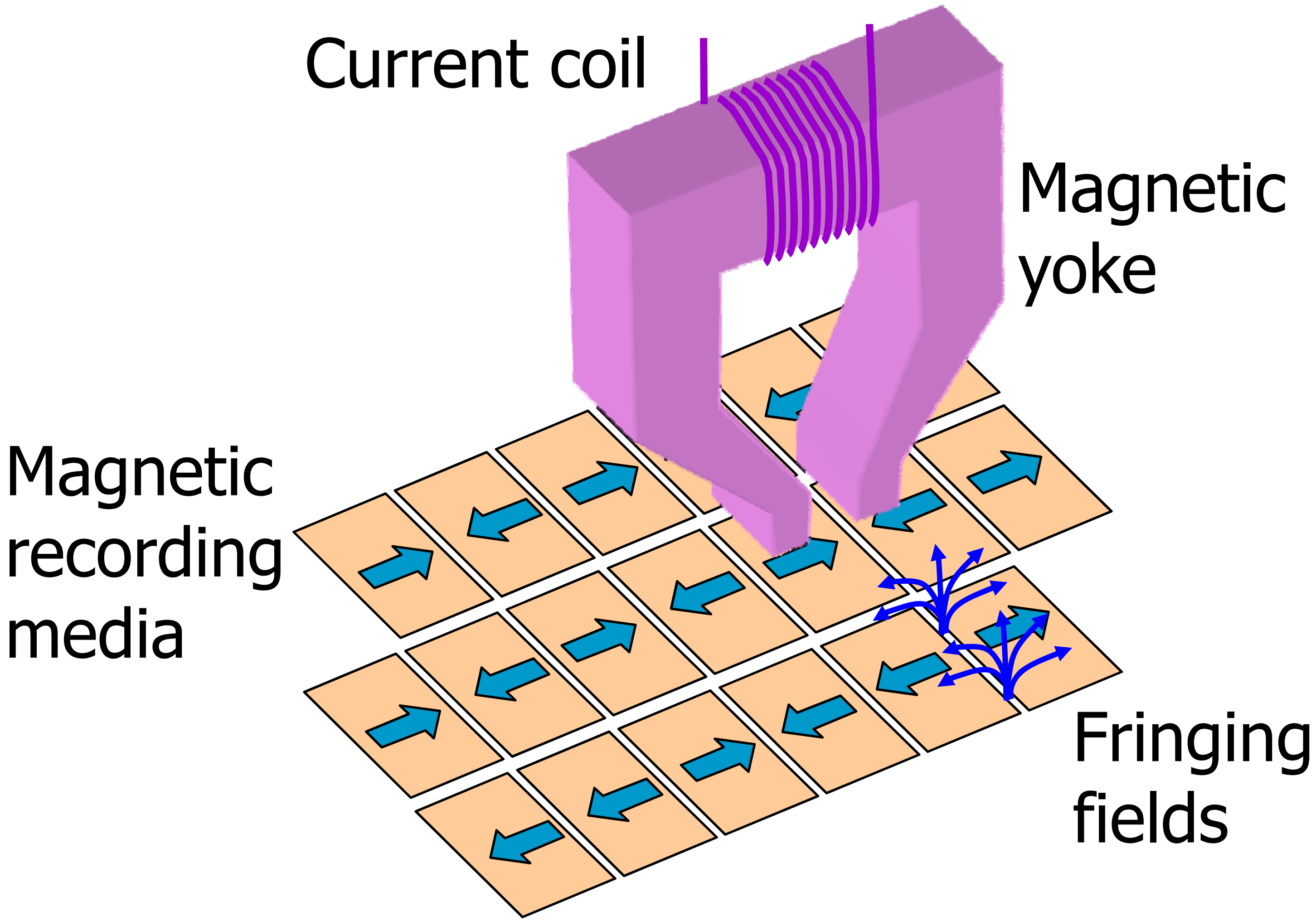
Magnetic Random Access Memory (MRAM)

Spin-transfer torques (STT)

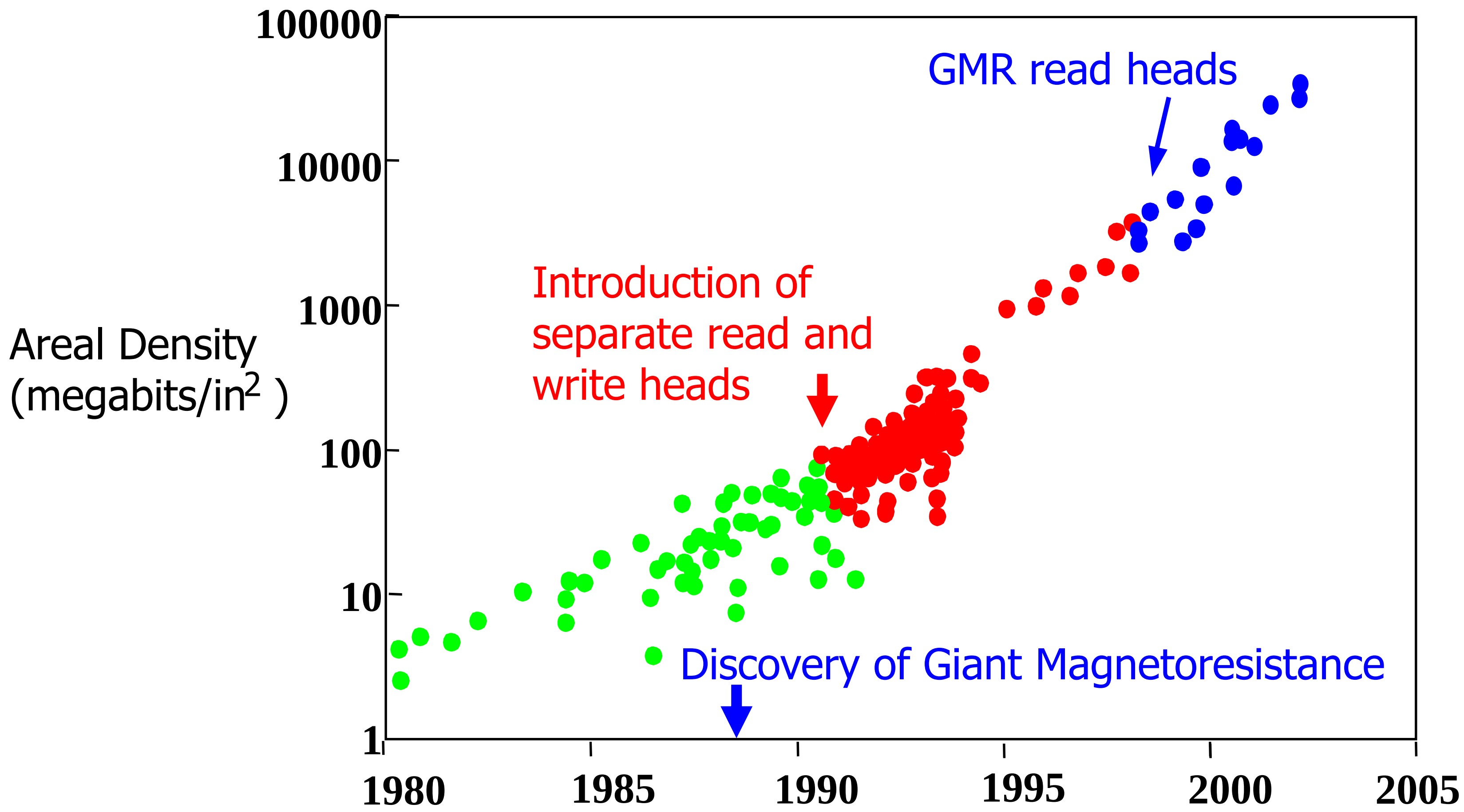


- the Current Flow Affecting the Magnetic Configuration

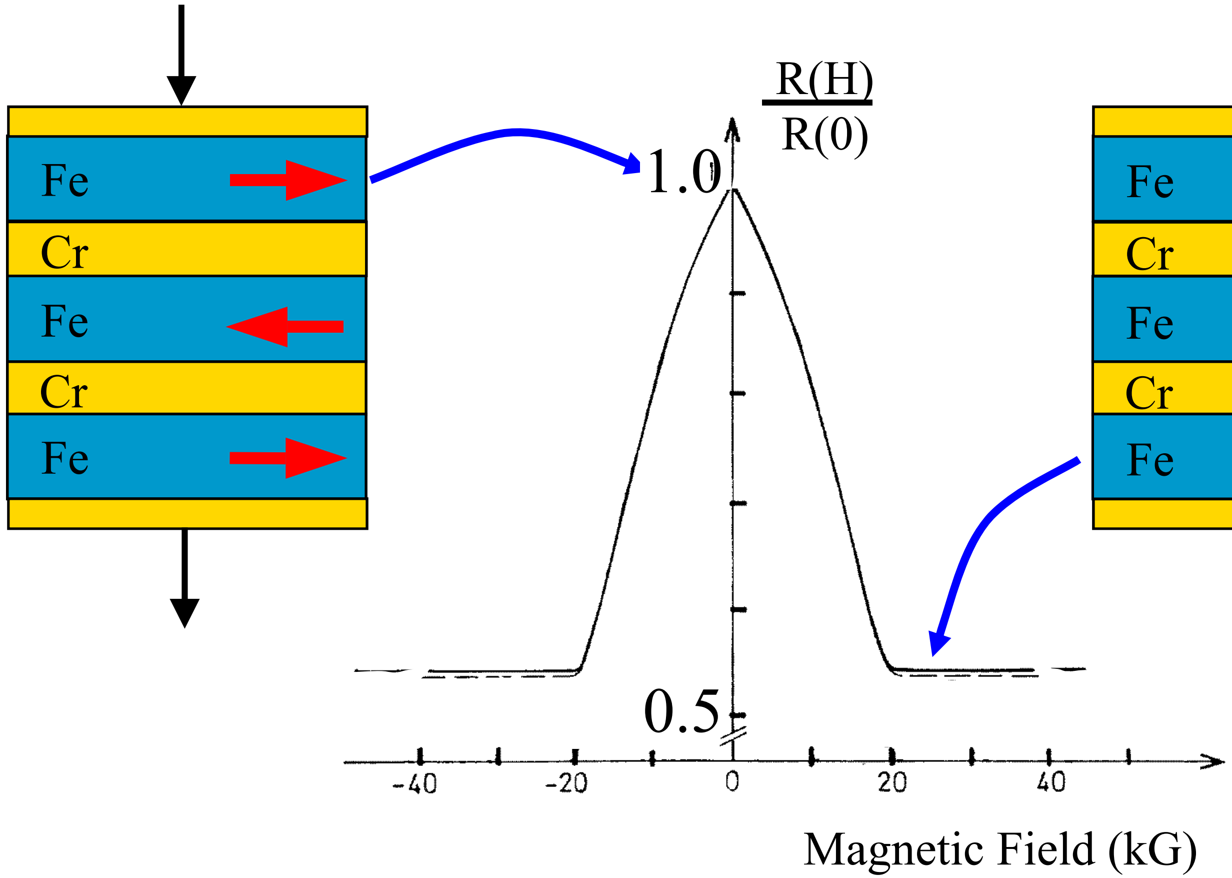
Magnetic recording



Hard Drive Recording Density



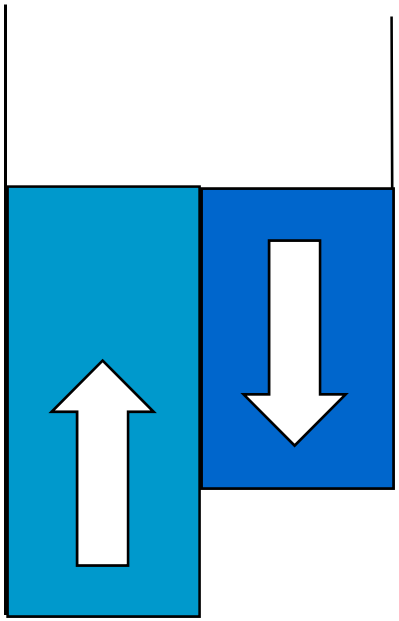
Giant Magnetoresistance (GMR)



Discovered in 1988 in FM/NM/FM multilayers

- 2007 Physics Nobel prize to Fert and Grünberg

One minute of (itinerant) ferromagnetism



- Exchange energy gain for parallel spins.
- Spins delocalized.
- Energy cost for being parallel (kinetic vs. potential).
- Net energy gain for Fe, Co, Ni, $\Rightarrow$ spin imbalance

$$\mathbf{j} = \mathbf{j}_{\uparrow} + \mathbf{j}_{\downarrow} = (\sigma_{\uparrow} + \sigma_{\downarrow})\mathbf{E}$$

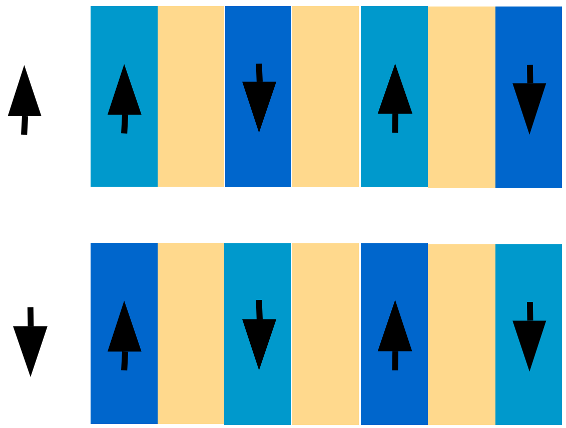
$$\sigma_{\uparrow} \neq \sigma_{\downarrow}$$

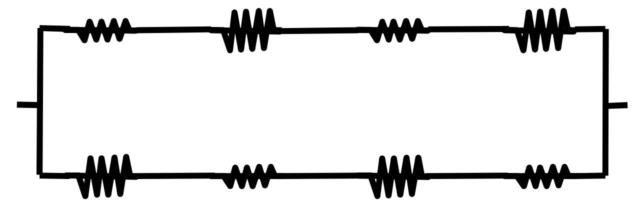
Two electric currents flow in parallel.

Electrical conductivity is spin-dependent.

Giant Magnetoresistance (GMR)

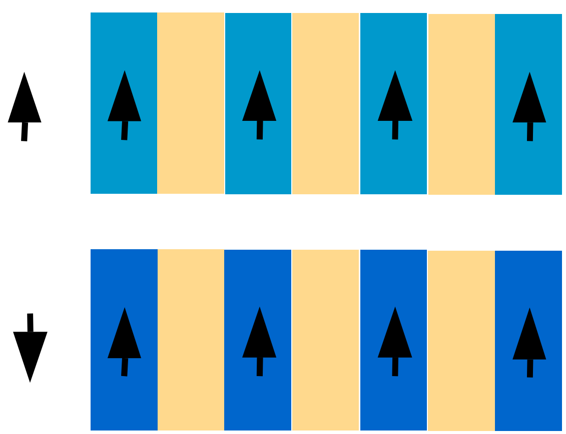
Antiparallel multilayer

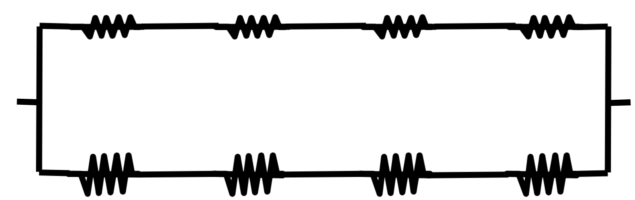




always a short circuit!

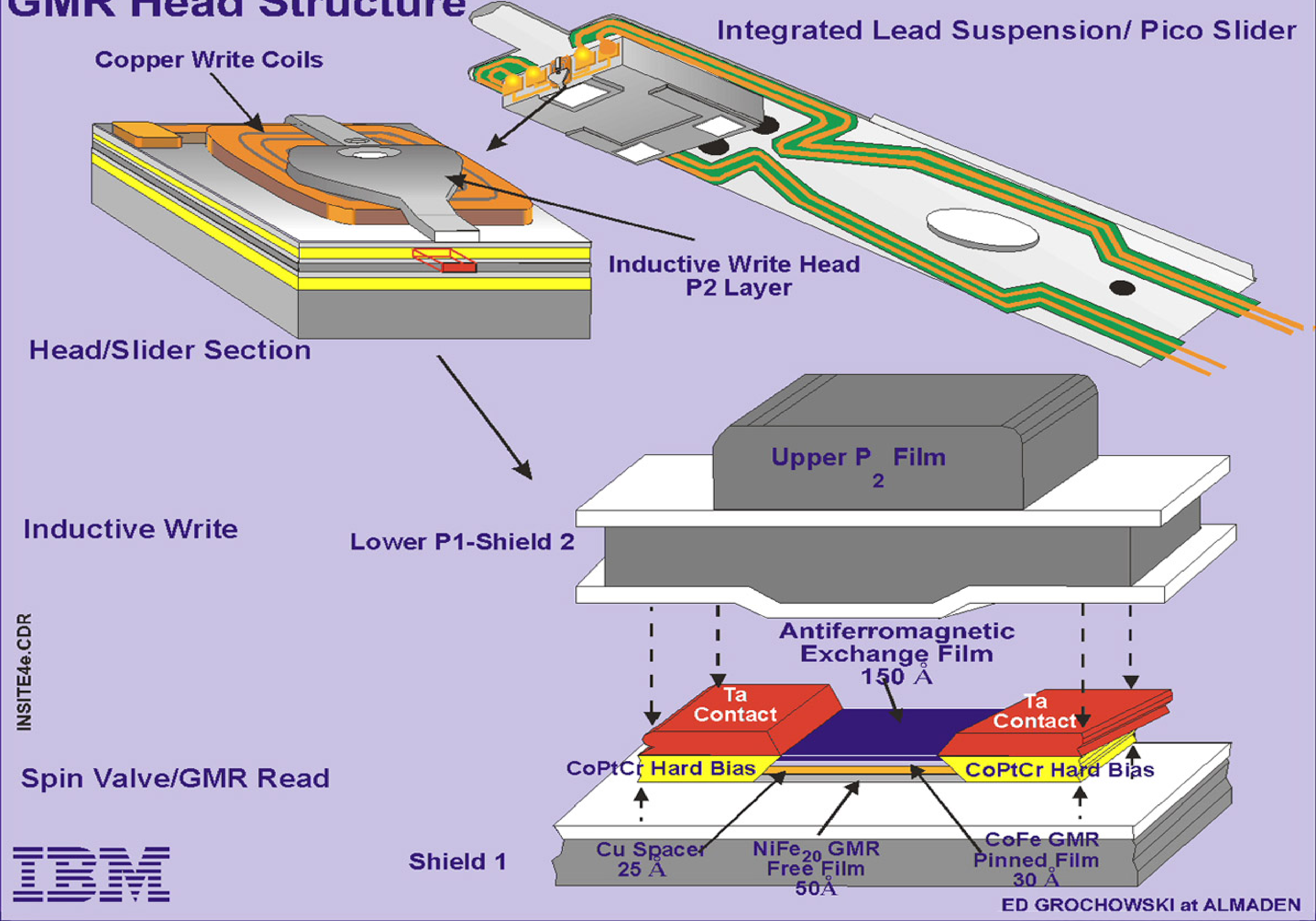
Parallel alignment



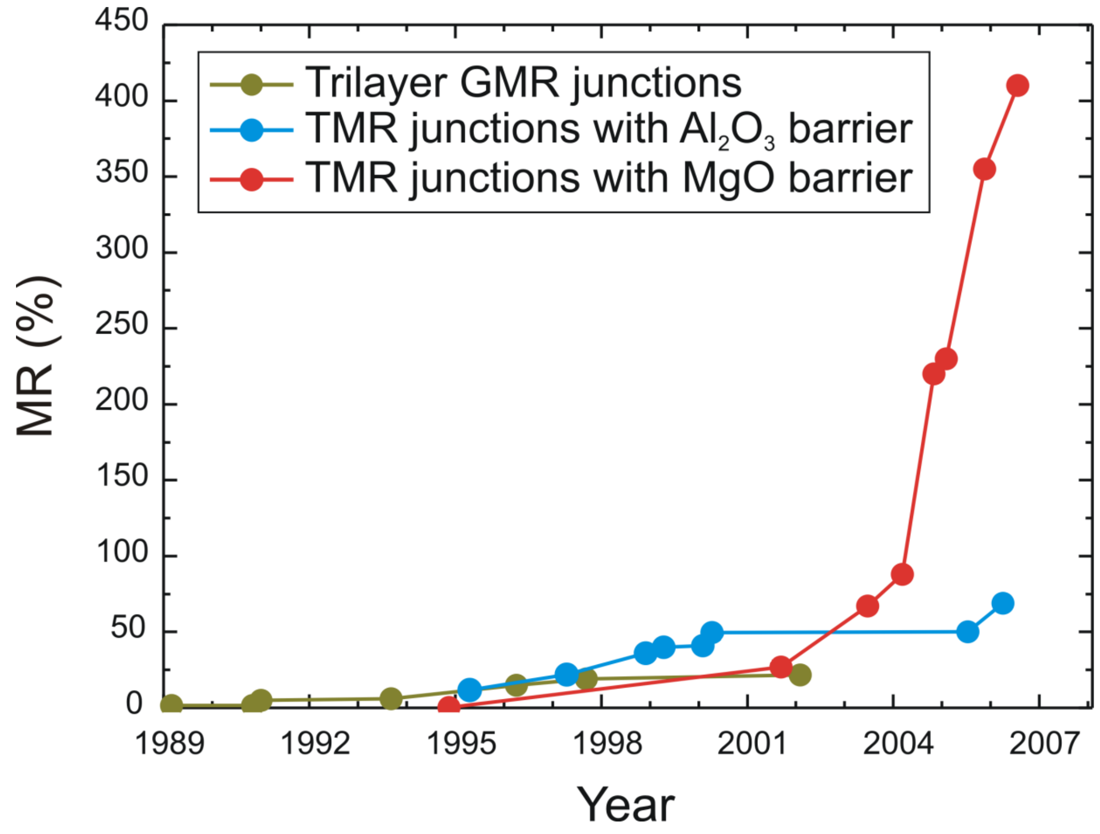


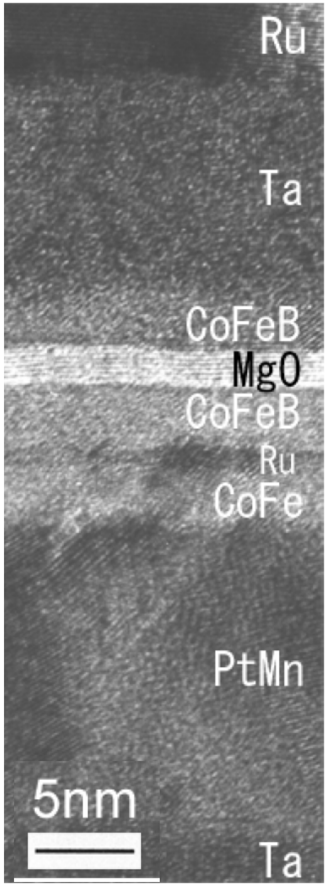
Both Current in Plane (CIP) and Current Perpendicular to the Plane (CPP)

GMR Head Structure



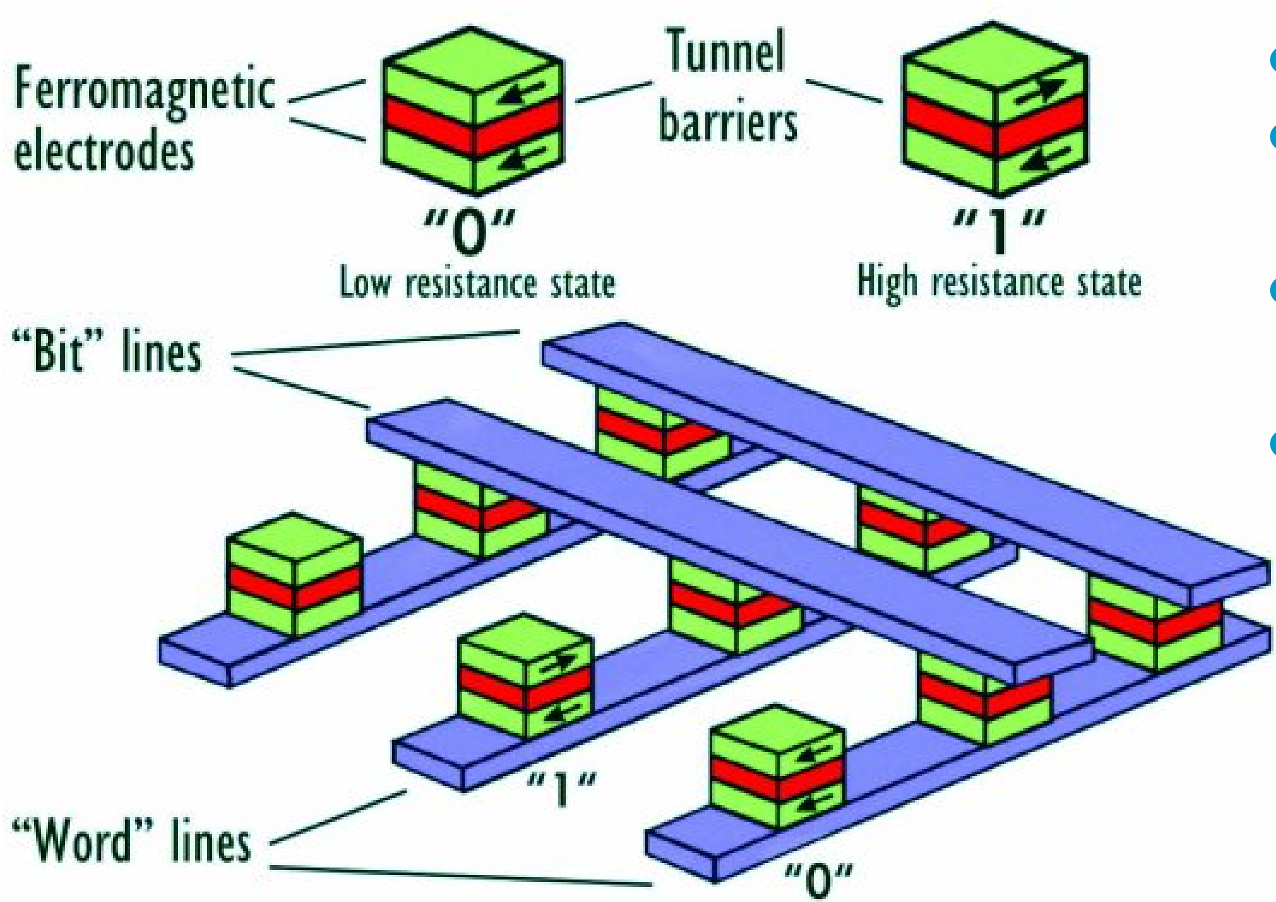
Tunneling Magnetoresistance (TMR)





Djayaprawira *et al.*
APL **86,** 092502 (2005)

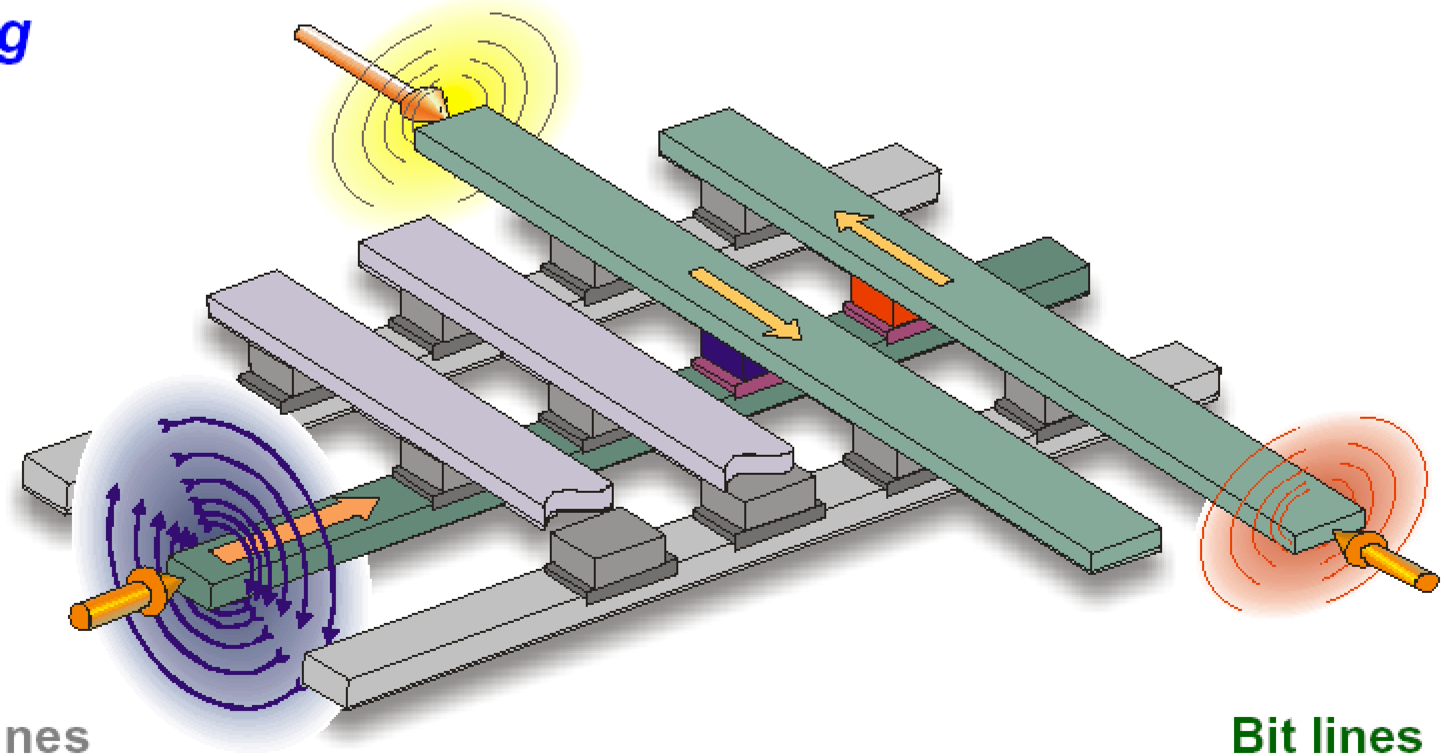
Magnetic Random Access Memory (MRAM)



- Non-volatile
- Potentially low power
- CMOS compatible
- Radiation hard

External Currents Used to Flip Bits

Writing

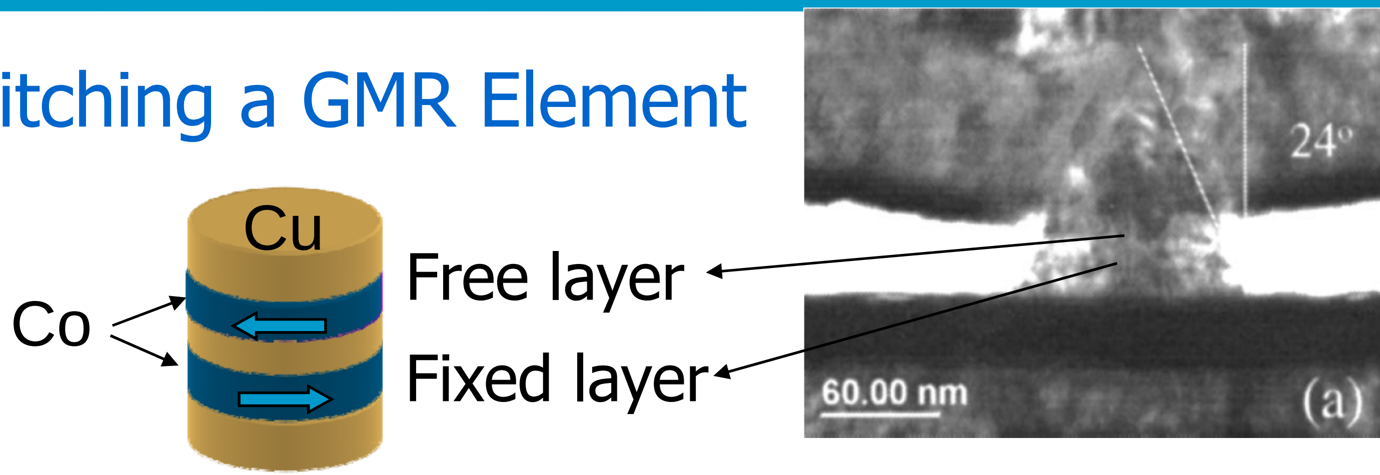


This writing scheme does not scale well.
Can Spin Currents Flip Bits?

GMR is the Magnetic Configuration Affecting the Current Flow.

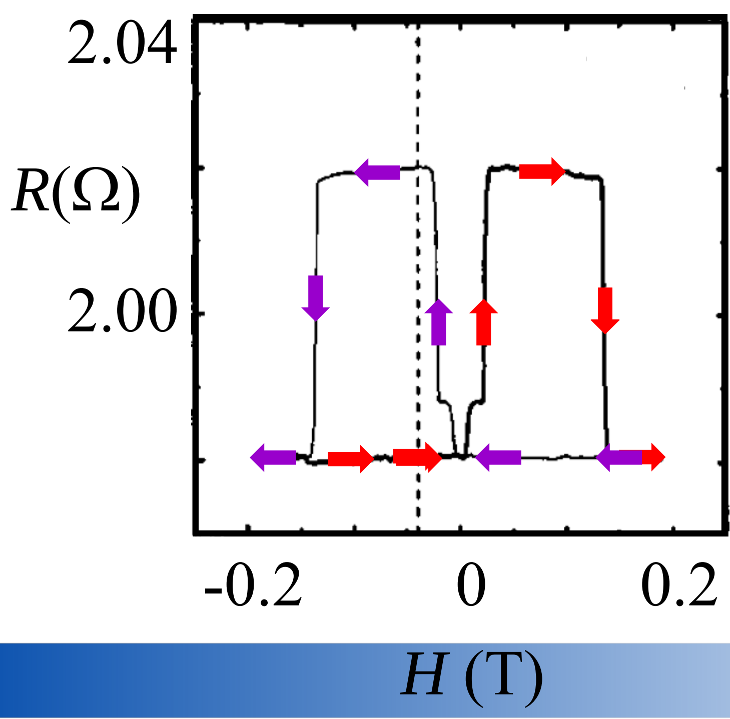
Spin Transfer Torque is the Current Flow Affecting the Magnetic Configuration.

Switching a GMR Element

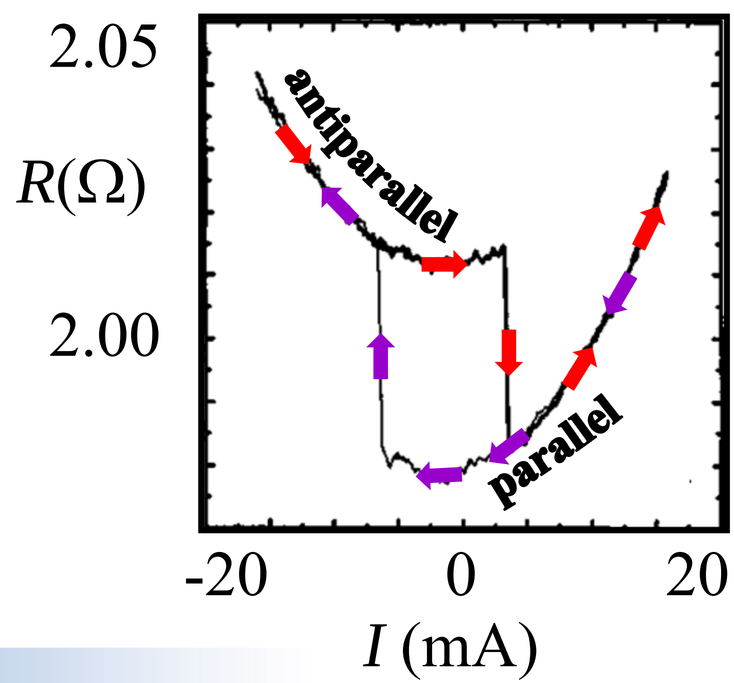


J. Z. Sun et al., JAP (2003)

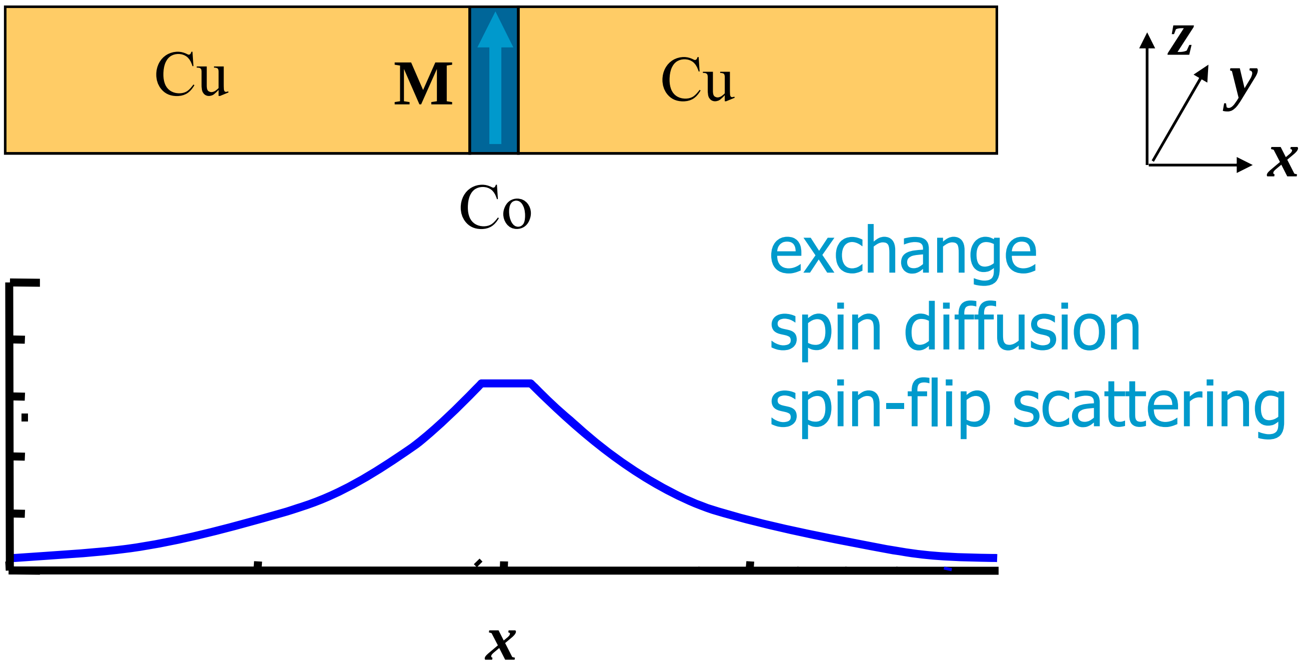
Giant Magnetoresistance



Current-Induced Switching



Nanopillar as a spin polarizer/analyzer.
Step 1: Polarize the Current



Spin current

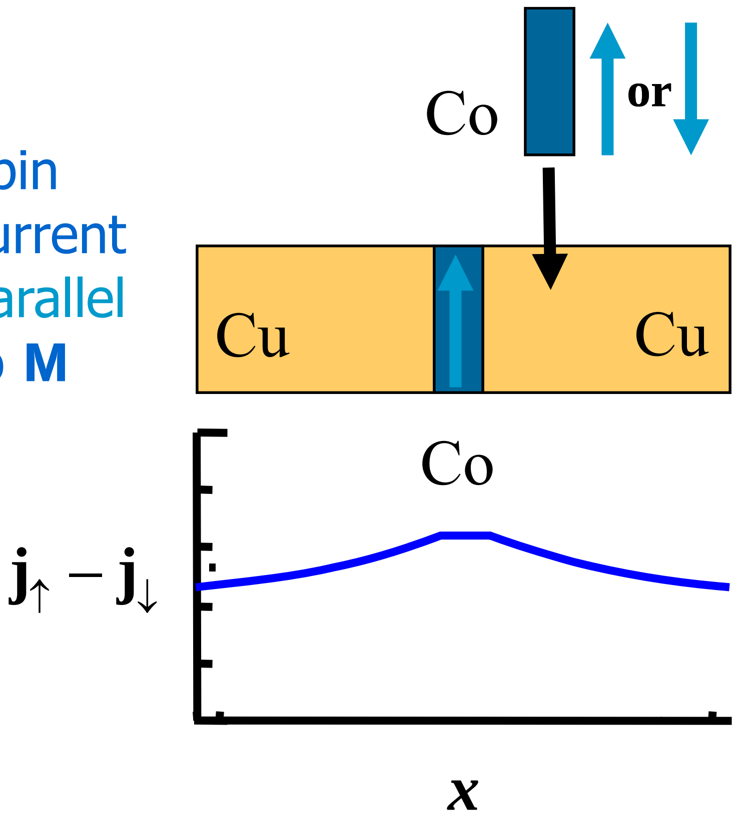
$\mathbf{j}_{\uparrow} - \mathbf{j}_{\downarrow}$

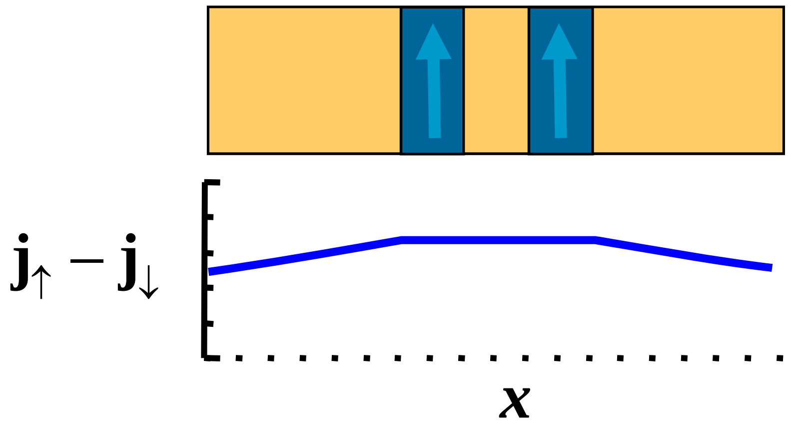
exchange
spin diffusion
spin-flip scattering

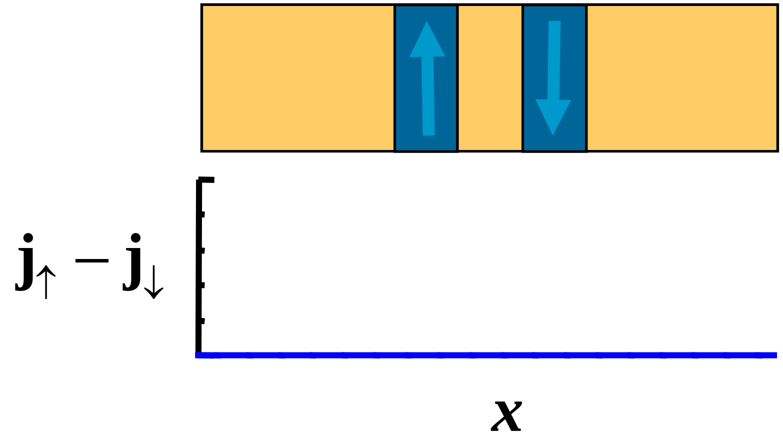
quantitative work: Boltzmann equation, drift-diffusion equation

Step 2: Analyze the Current

Spin current parallel to **M**

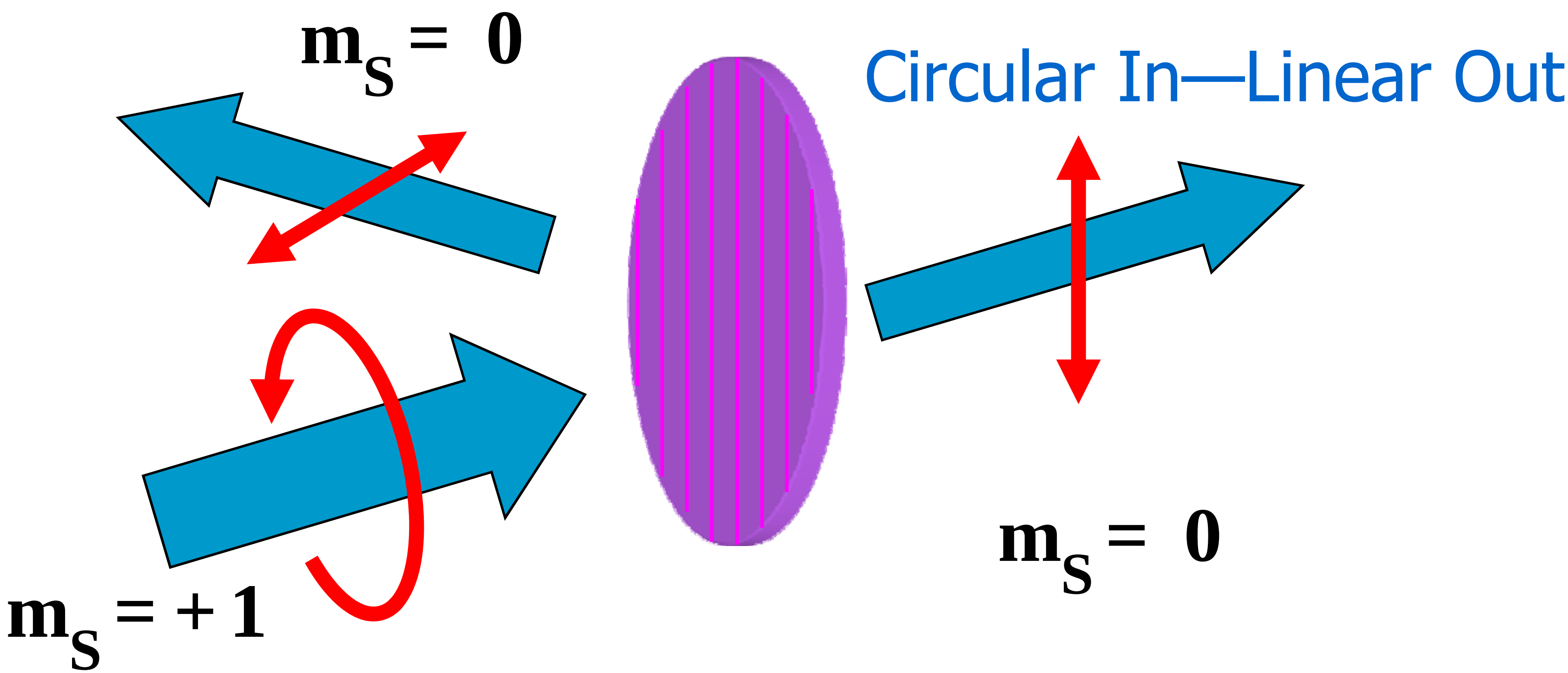






What happens if the polarizer and analyzer are not parallel?

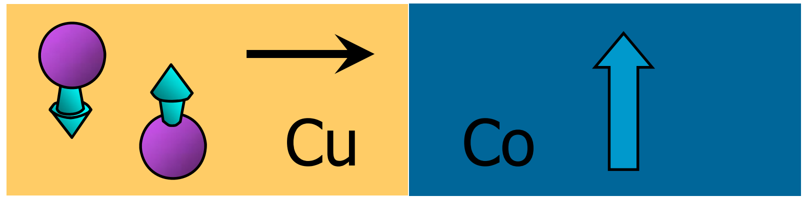
Angular Momentum and Analyzers: Optical Equivalent

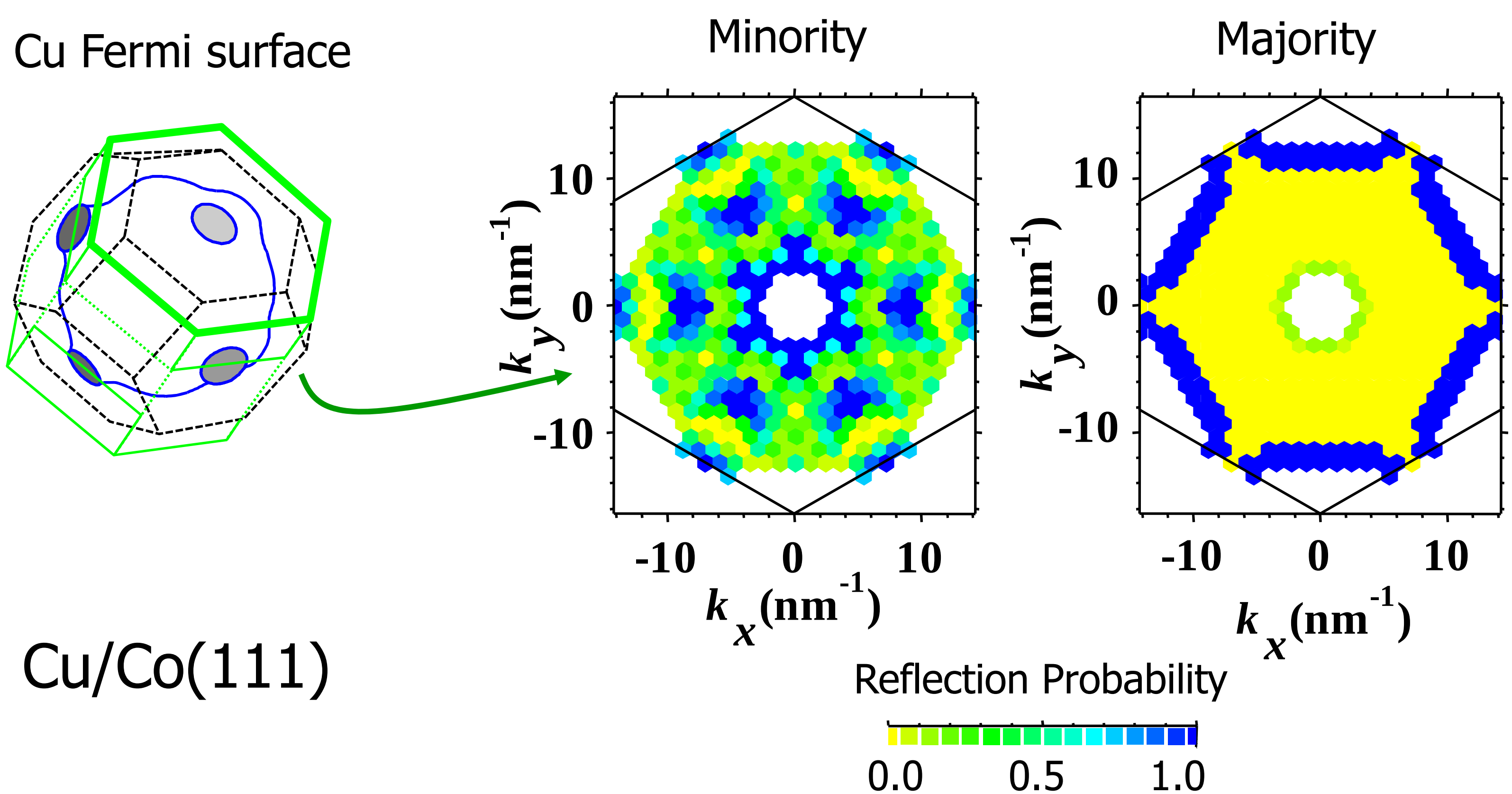


Optical Polarizer Feels a Torque

$$\tau \propto \Delta L$$

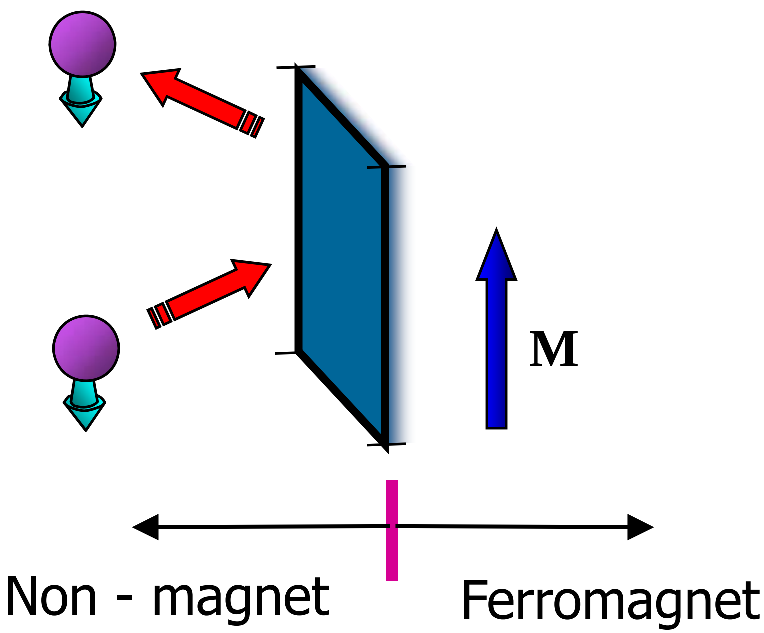
Spin-dependent reflection/transmission





Spin-dependent reflection/transmission

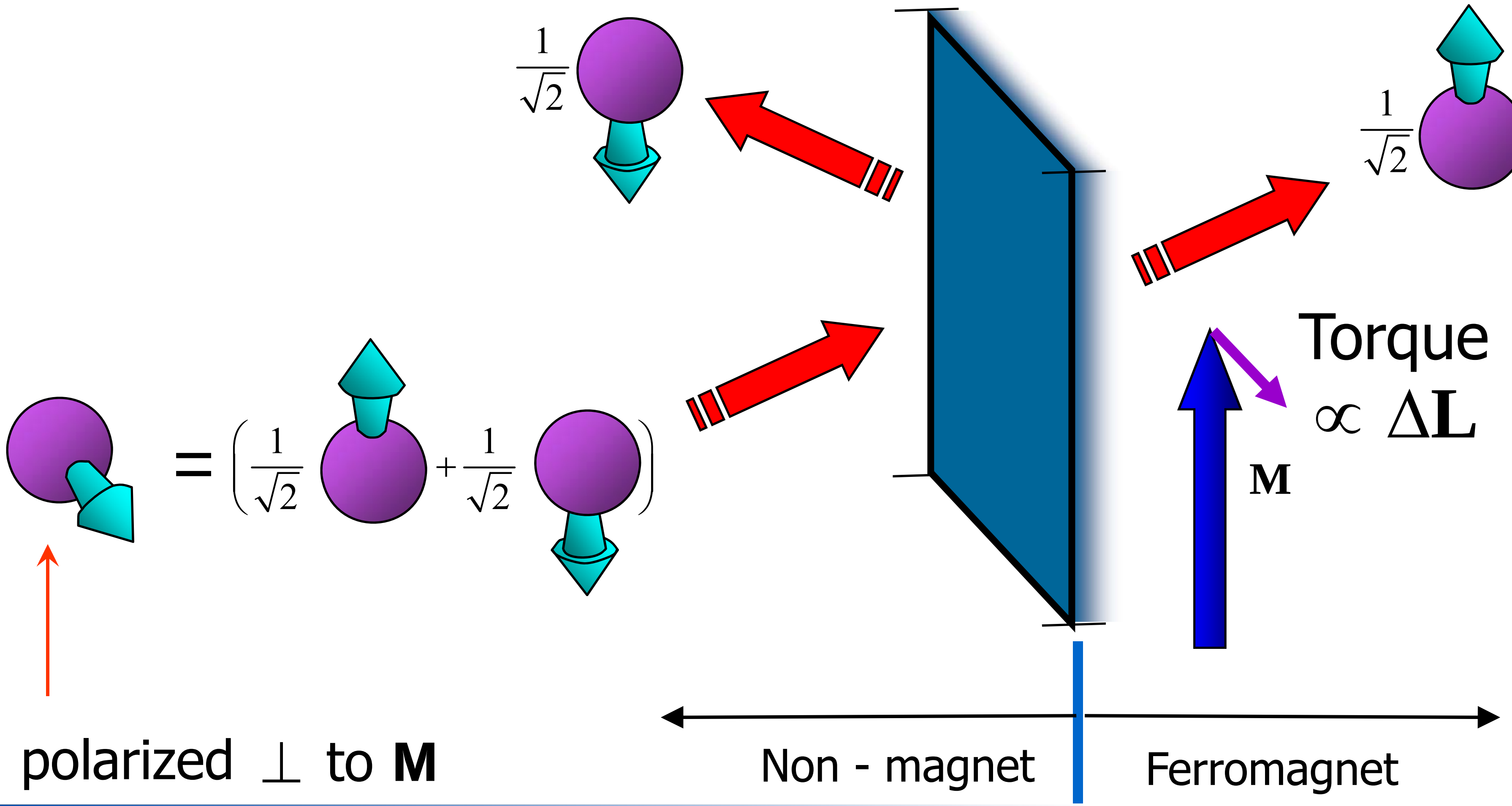
Simple Limit: $|R_{\downarrow}|^2 = 1$ and $|R_{\uparrow}|^2 = 0$



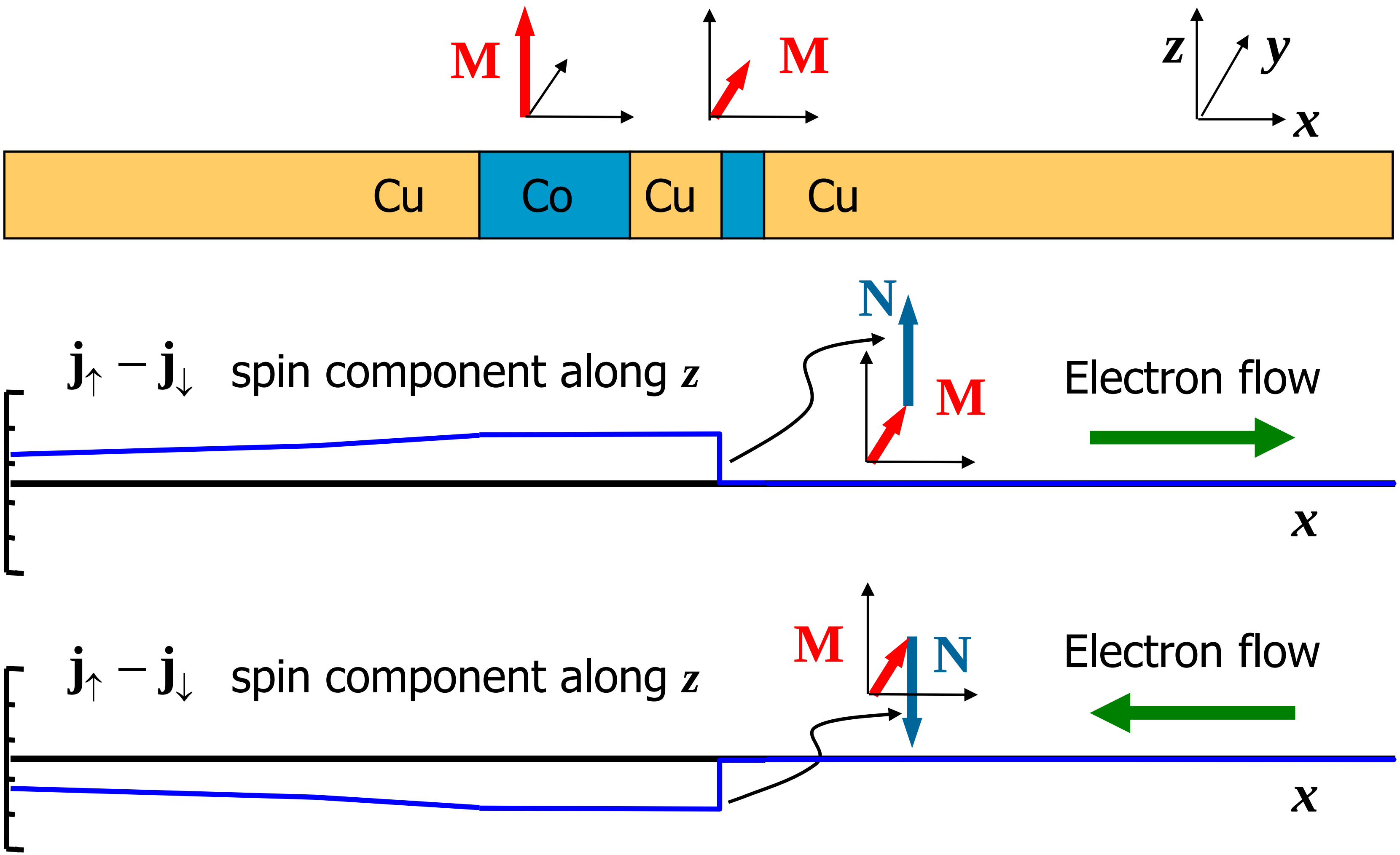
What if analyzer is rotated by 90° with respect to polarizer?

Absorption of Transverse Spin Current

Simple Limit: $|R_{\downarrow}|^2 = 1$ and $|R_{\uparrow}|^2 = 0$

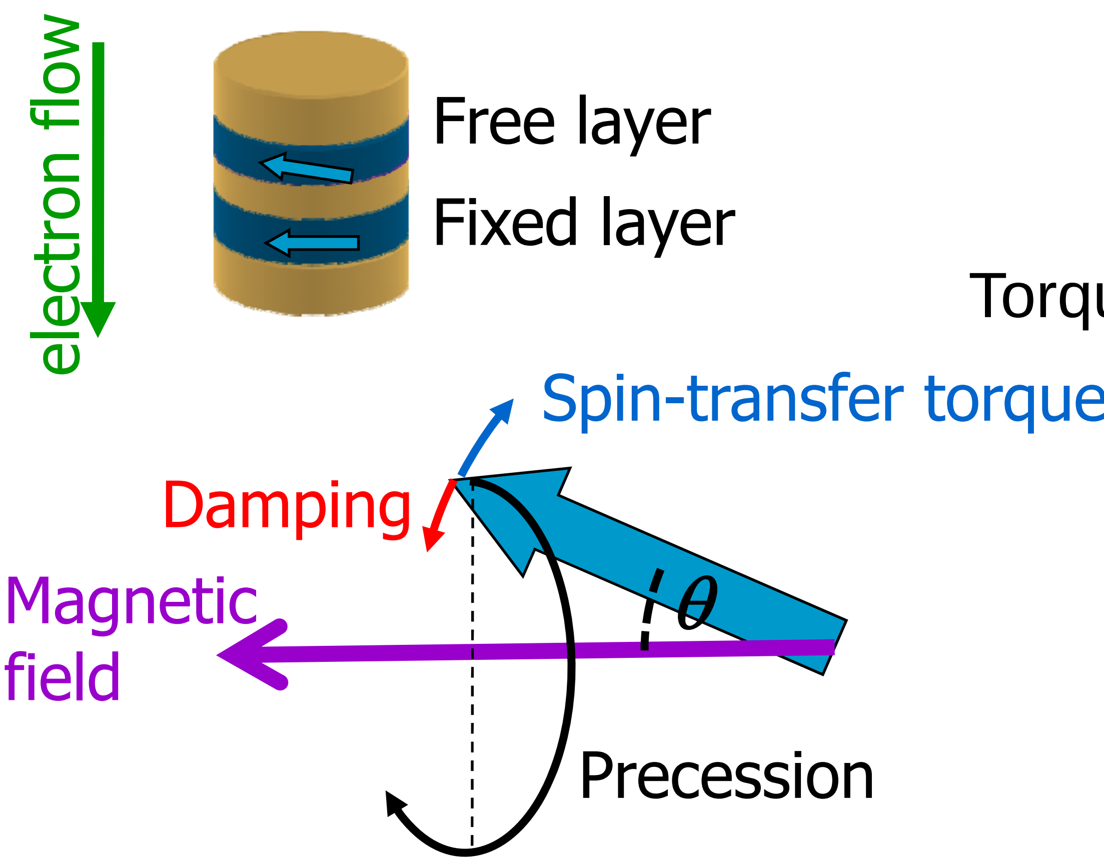


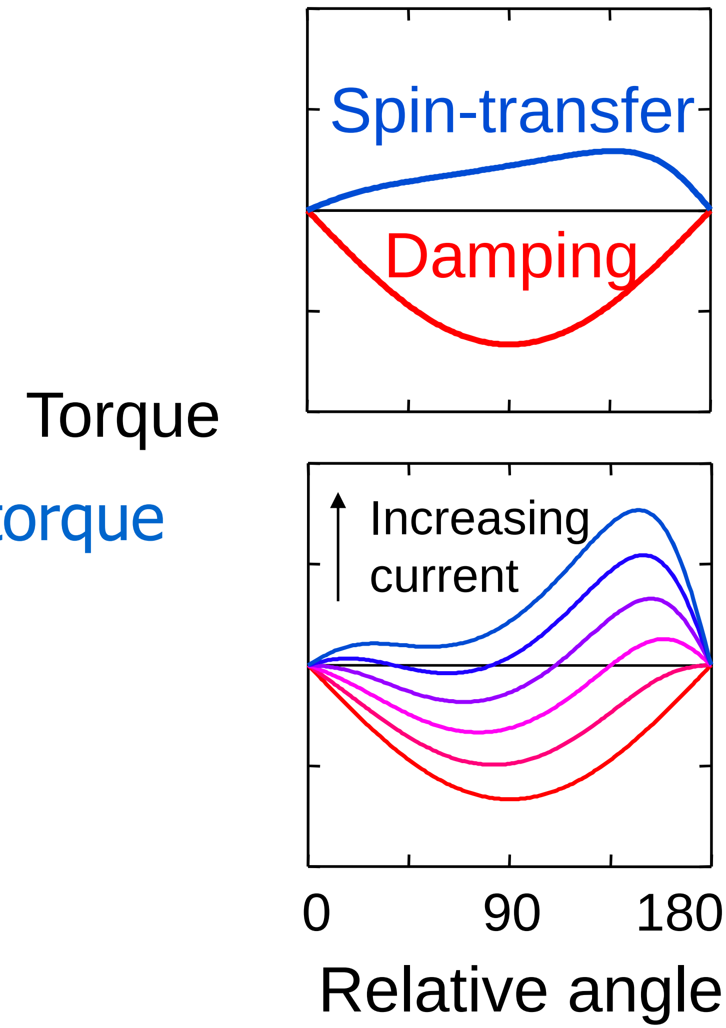
Transverse spin currents give torques



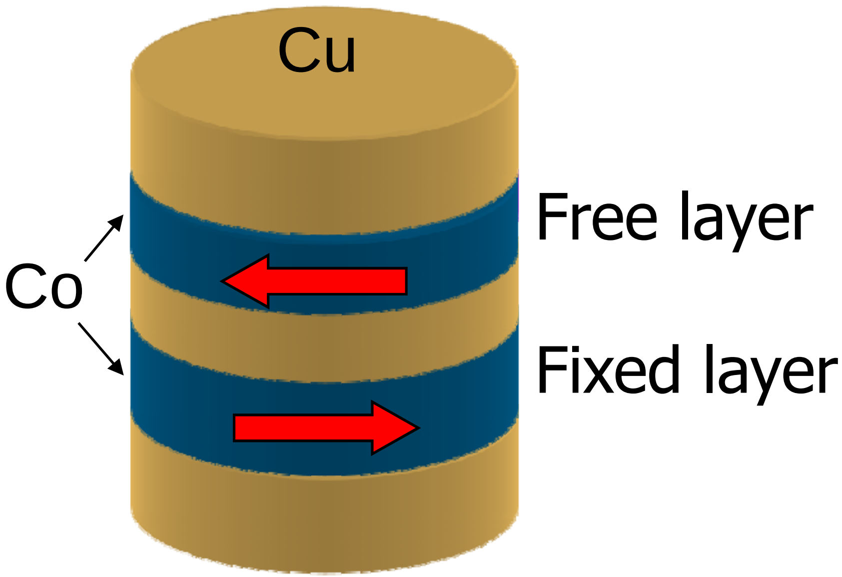
Switching by Amplification of Fluctuations

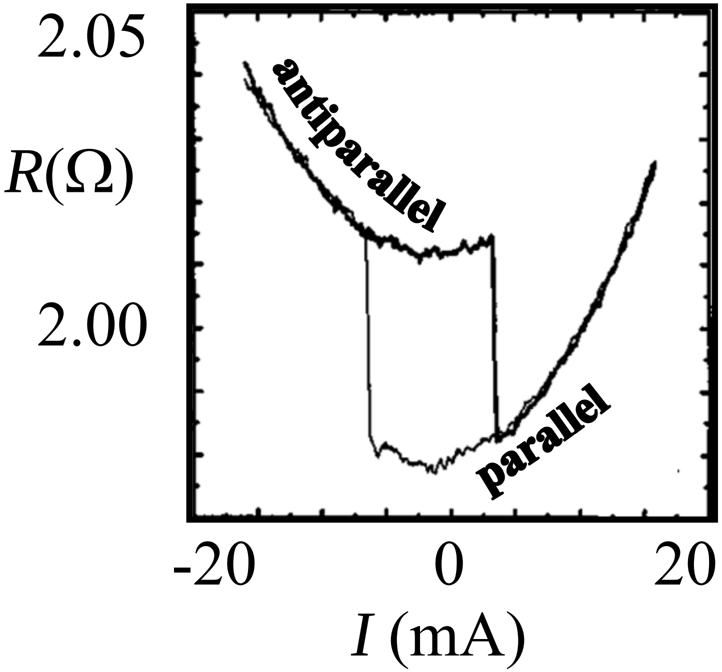
Simple model – no anisotropy





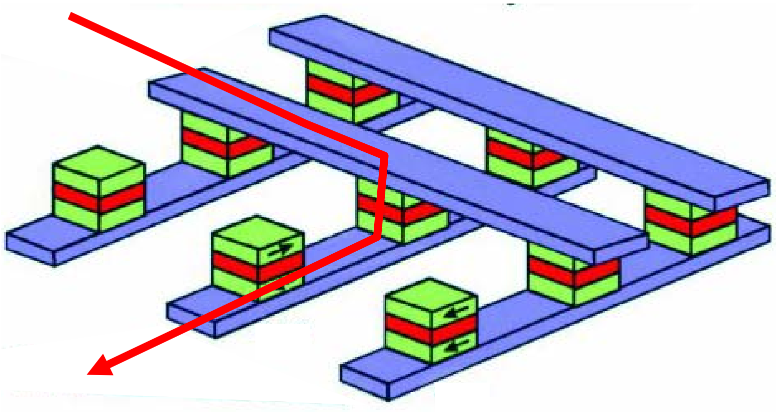
Asymmetric switching





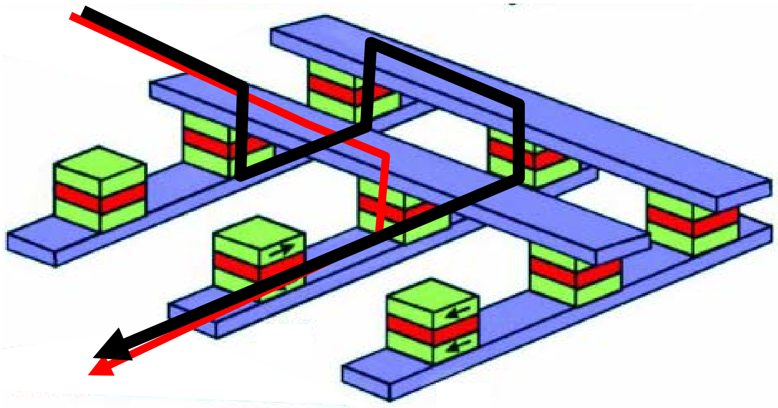
J. Z. Sun et al. JAP (2003)

Toggle MRAM is available, but does not scale well. What's needed to make STT-MRAM viable?



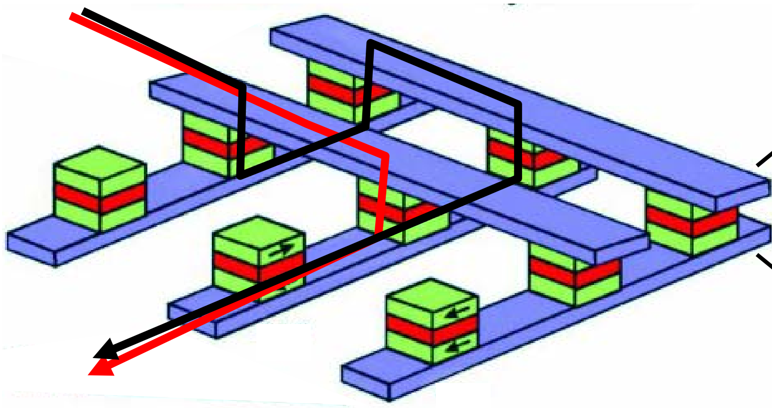
Desired path

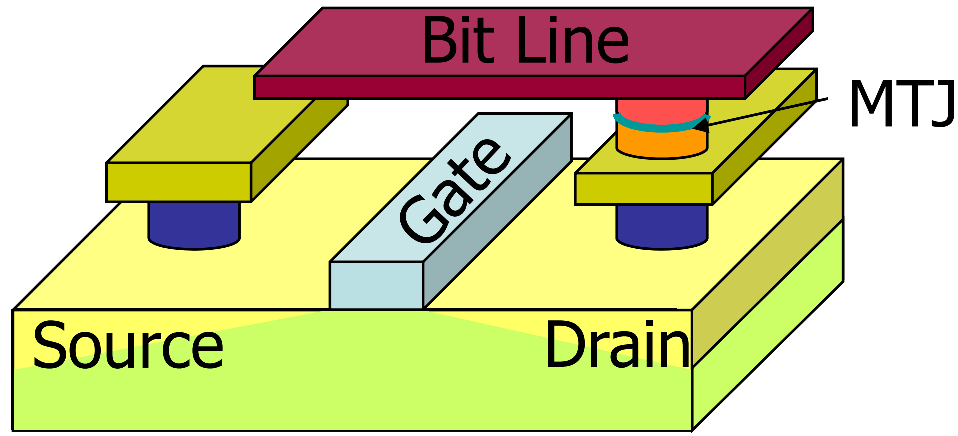
Toggle MRAM is available, but does not scale well. What's needed to make STT-MRAM viable?



Desired path →Need transistor
Alternate path

Toggle MRAM is available, but does not scale well. What's needed to make STT-MRAM viable?





Desired path

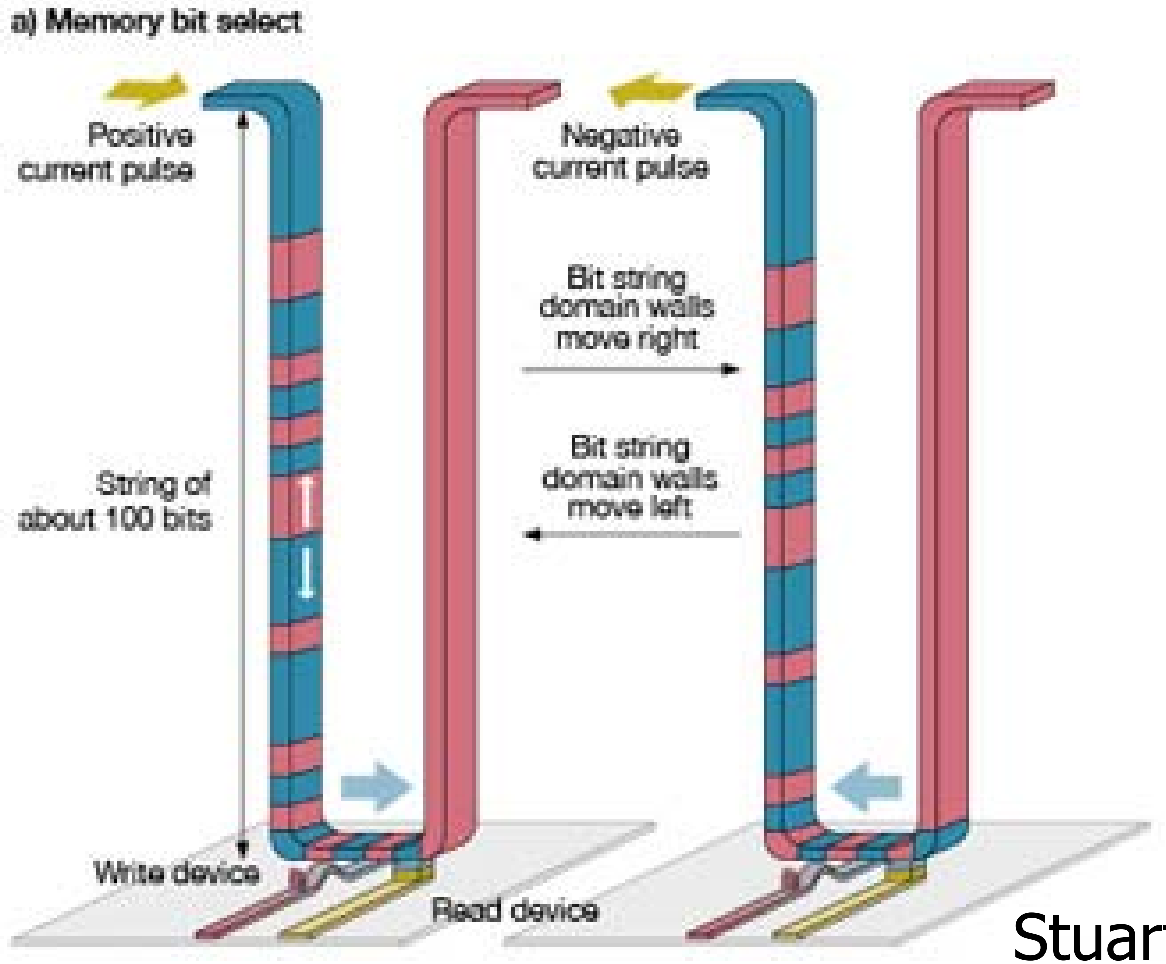
Alternate path

→Need transistor

- Thermally stable bit
- Large margin between read and write currents
- Low write current (single transistor)
- Manufacturable margins

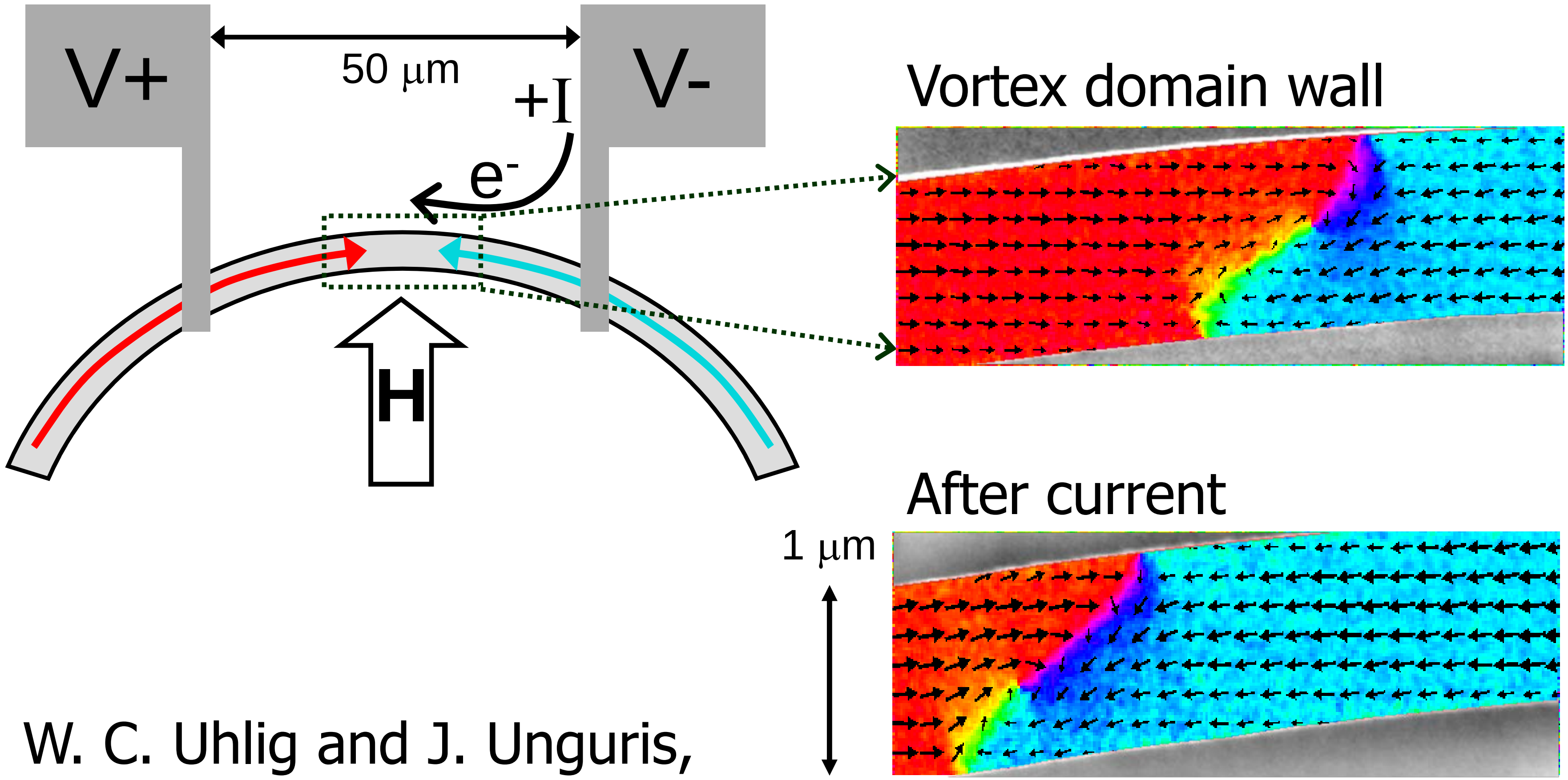
From Katine and Fullerton

A possible way to pack more information per circuit area: Magnetic Racetrack Memory



Stuart Parkin

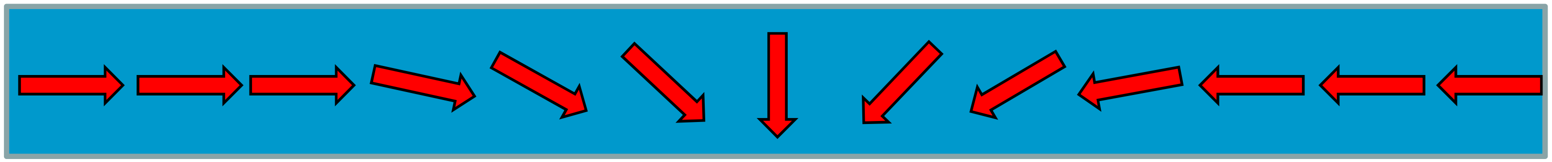
Spin transfer torques in nanowires



W. C. Uhlig and J. Unguris, CNST

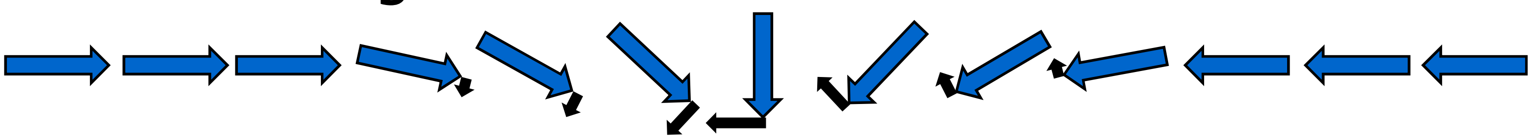
Spins adiabatically follow the magnetization

Domain wall

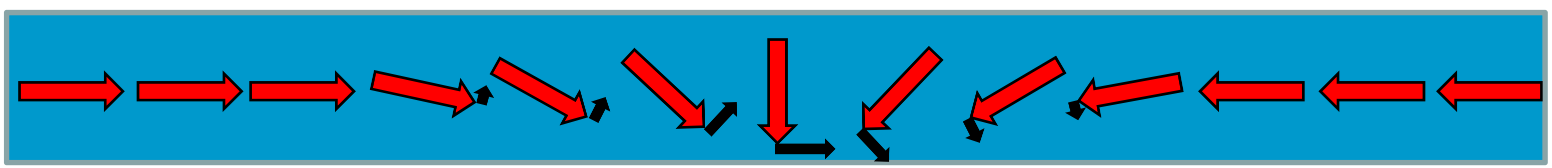


Electron flow 

Spins follow magnetization direction

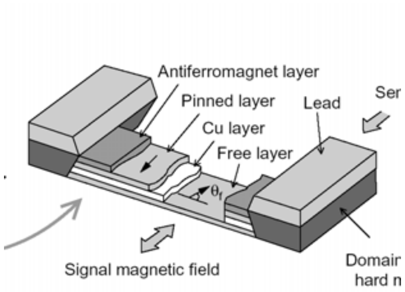


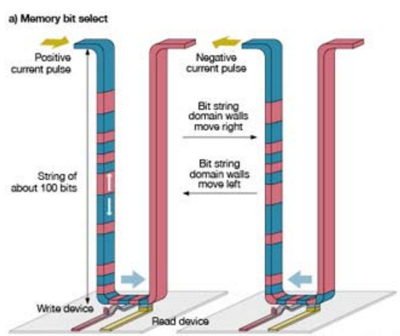
Reaction torque on magnetization



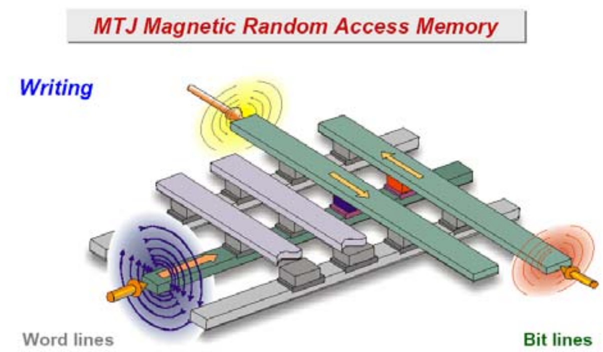
Domain wall translates 

Metal-Based Spintronic Applications

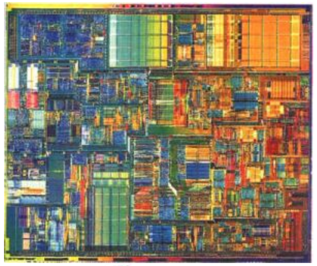




- Hard Disk Drive
- MRAM
- Racetrack memory
- Sensors
  - $1 B to $30 B market
  - Automotive, Process control, Medical, Military/Security
- Logical Processing



Wouldn't it be nice if …

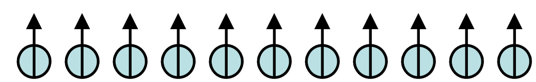


Processor

Hard-Disk

Information processing
→ CHARGE transport
in SEMICONDUCTORS

Non-volatile memories
→ SPIN alignment in
Ferromagnetic METALS



Integration:
Non-volatile memory
Reprogrammable logic
Semiconductor spintronics
Cheaper, faster, better???

Spintronics in Metallic Systems

- Why
  Non-volatile memory
  Magnetic field sensitivity
  Lower dissipation?
- GMR: using spins to influence current
  Hard Disk Drives
  Sensors
  MRAM
- Spin Torque: using current to influence spins

For more information http://cnst.nist.gov
For reviews, see J. Magn. Magn. Mater. v. 320 (2008)