Magnetic Spin Devices: 7 Years From Lab To Product

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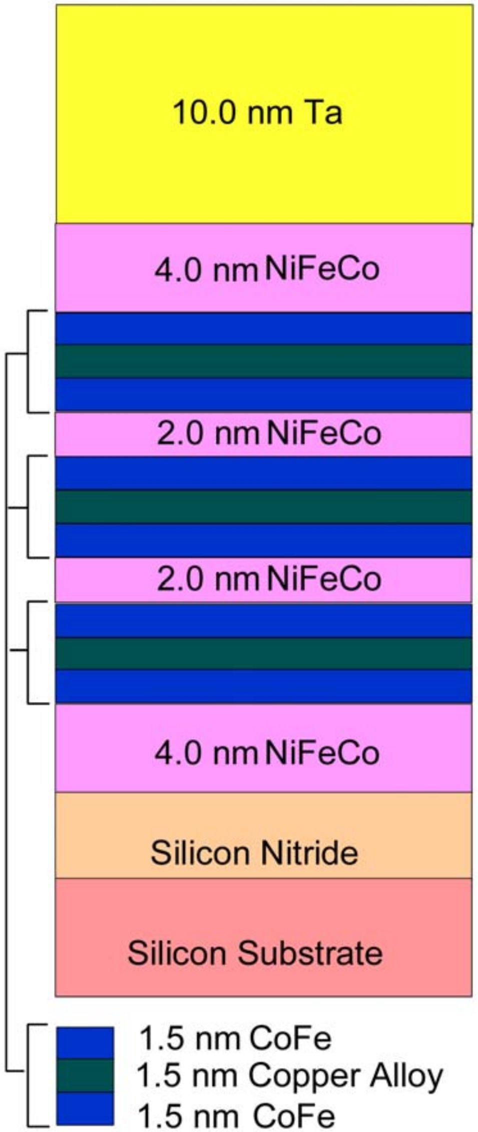
Outline of Presentation

- “Early Discoveries” - 1988 to 1995
- Resulting Products – Potential Products
- “New Discoveries” - 1996-2004
- Future Products

Giant Magnetoresistance (1988)

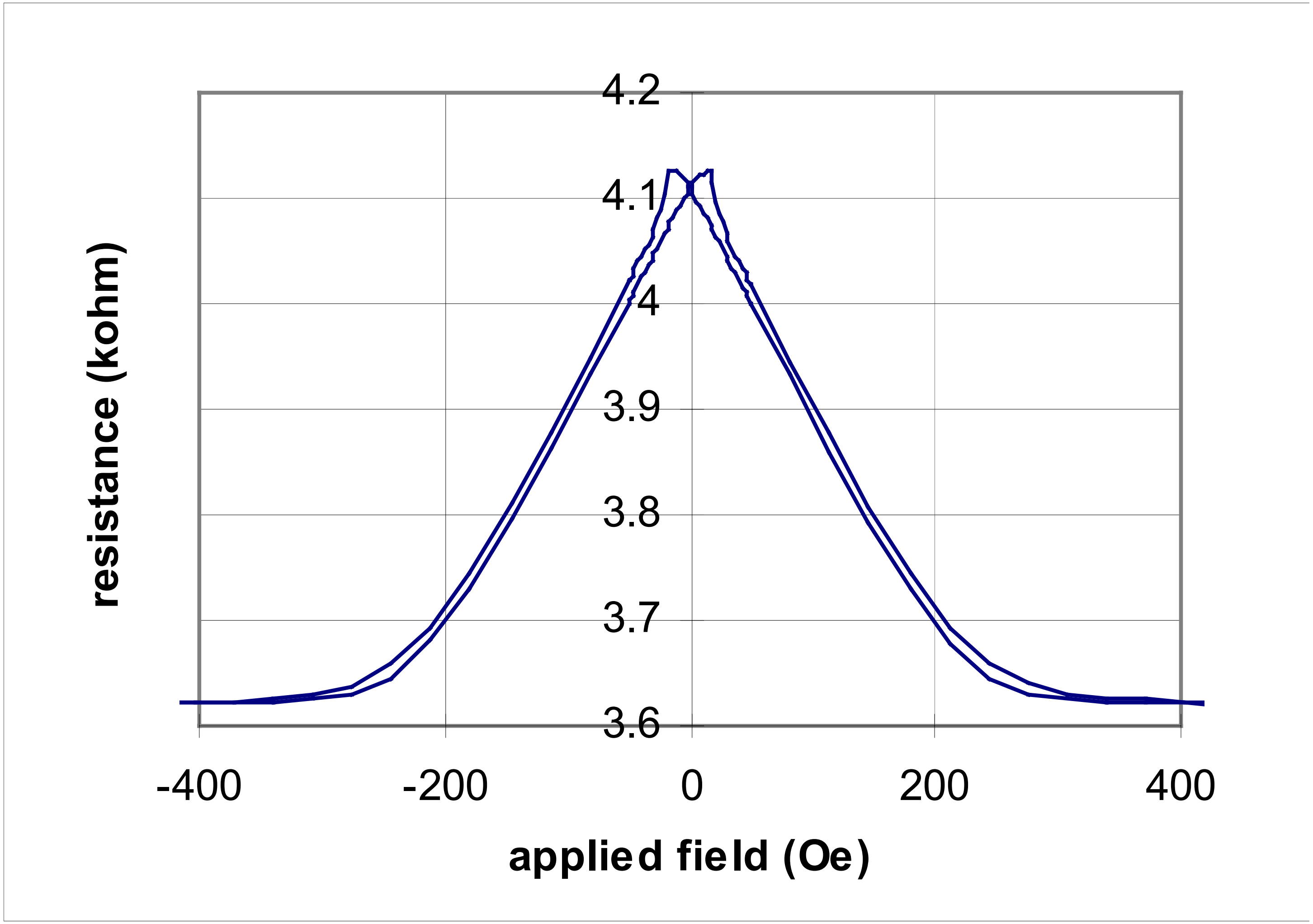
- **Simultaneous Discovery**
  - Fert (France)
  - Grunberg (Germany)
  - Multi-Layer Devices
  - Ferromagnetic Materials
- **Previous Magnetoresistance Materials**
  - Anisotropic Magnetoresistance
  - ~ 2% Magnetoresistance R.T. Thin Films
  - Current Direction
- **Much Higher Magnetoresistance Observed**

NVE GMR Multilayer Cross-Section



- Magnetic Layers AF Coupled
- Antiparallel - High Resistance
- Magnetic Field Overcomes Coupling
- Parallel - Low Resistance

Typical Characteristic

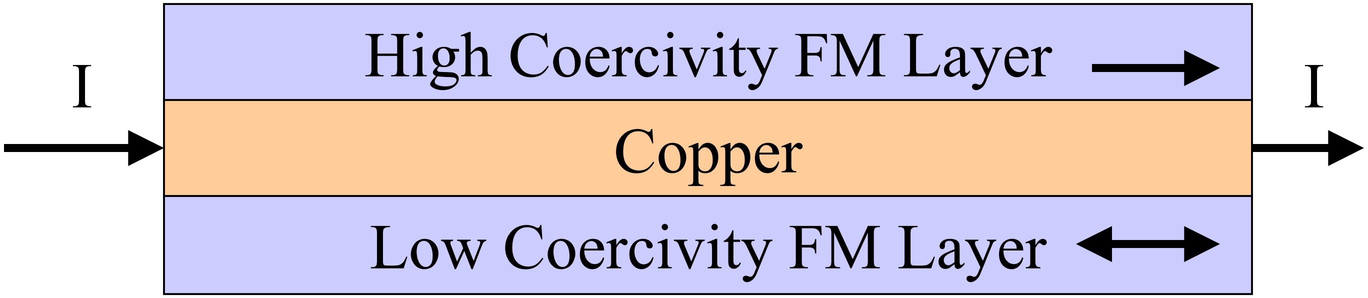


New Outlook For Magnetoresistance

- **Conduction Electrons In FM's - Polarized**
  - Same Direction - "Spin Up"
  - Opposite Direction to M - "Spin Down"
- **"Spin Up" Electrons - A Longer MFP**
- **"Spin Down" Electrons - Shorter MFP**

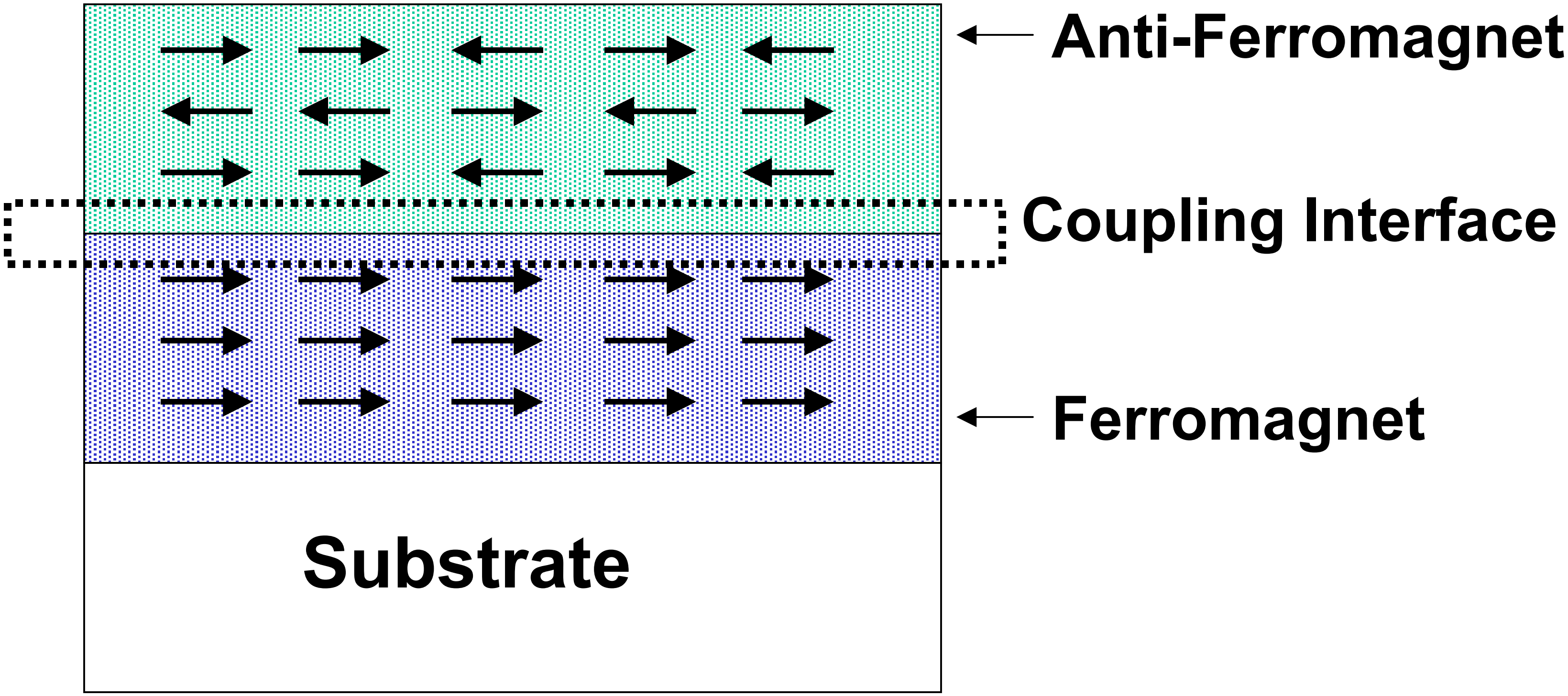
Conduction Between Ferromagnetic Bodies Depends On How They Are Magnetized.

Spin Valve (1990)



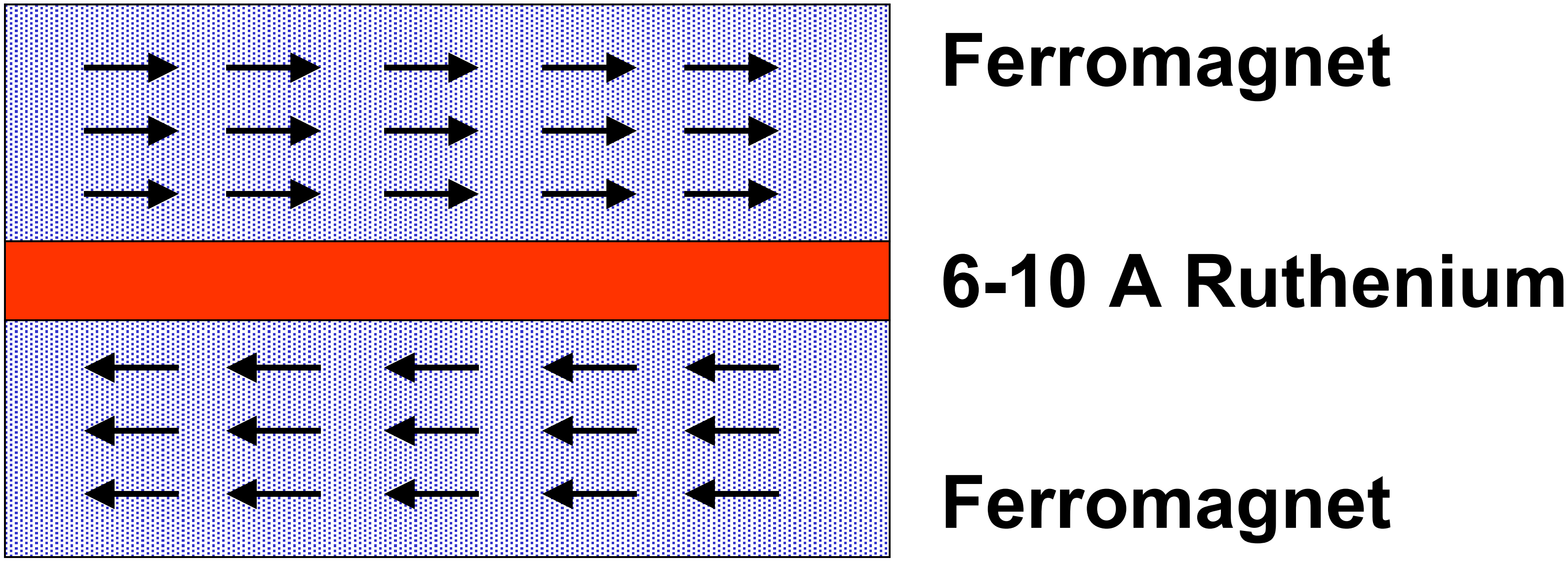
- Antiparallel M’s - Higher Resistance
- Parallel M’s - Lower Resistance
- Magnetoresistance ~ 6% Initially
- Easy to Switch “Soft” Layer

Pinning With An Anti-Ferromagnet



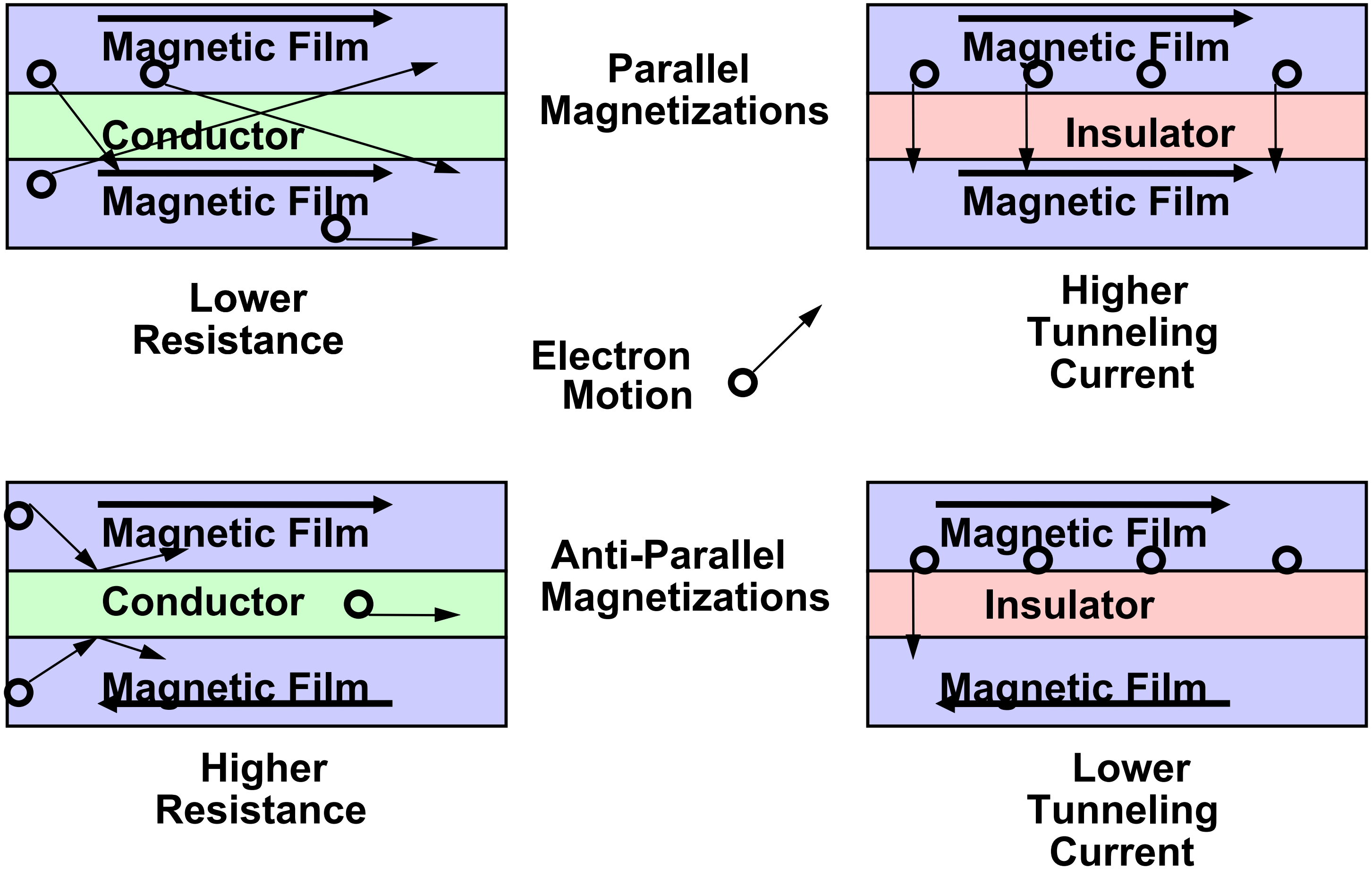
- Cool To Below Neel Temperature In A Field
- Ferromagnet Can Be “Pinned” To High Fields

Synthetic Antiferromagnet (SAF)



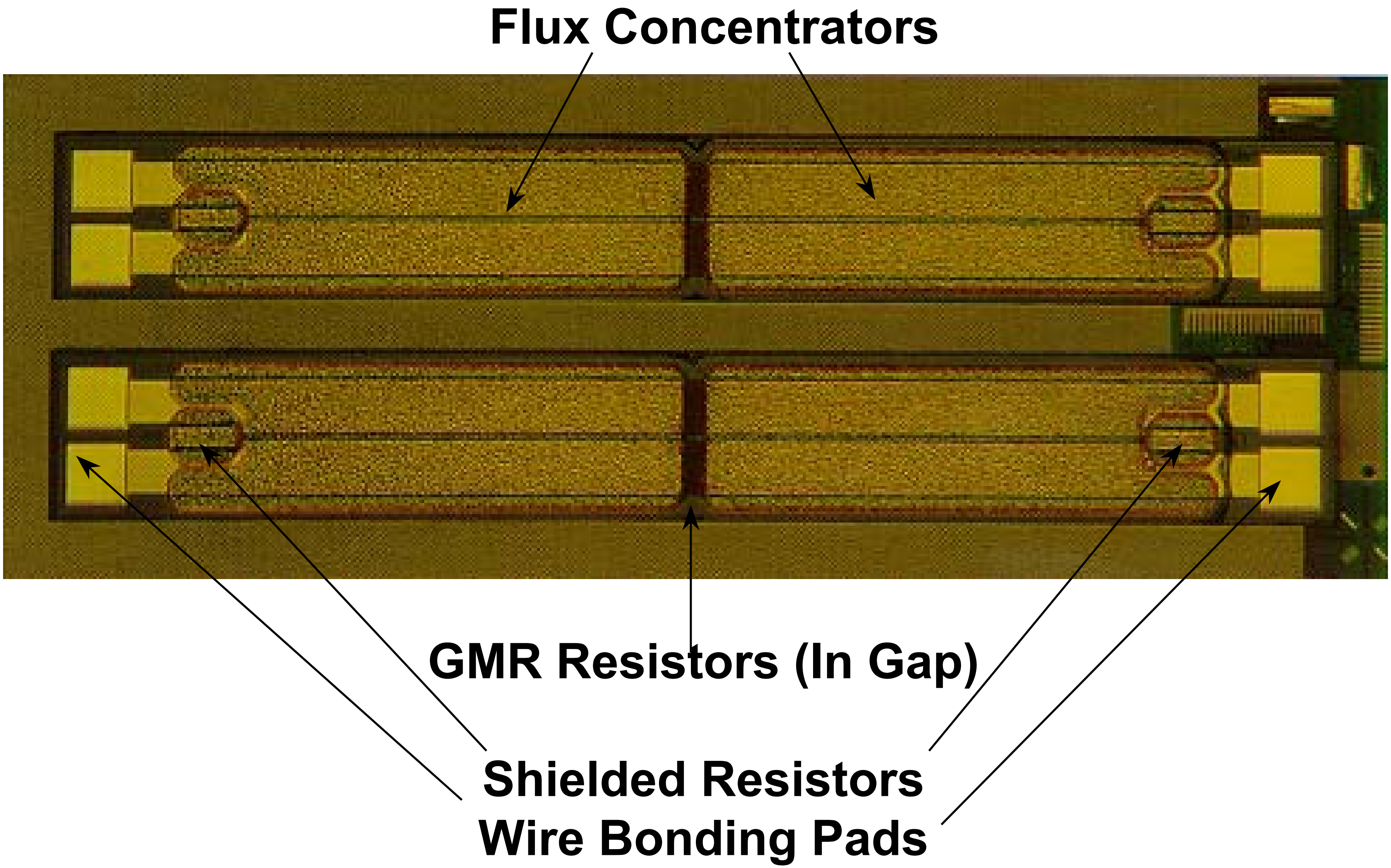
- Thin Inner Layer of Certain Materials (Ru)
- Very High Antiparallel Coupling (~2500 Oe)
- Pin One FM Layer - Really Pinned M’s

Tunneling Magnetoresistance (1995)

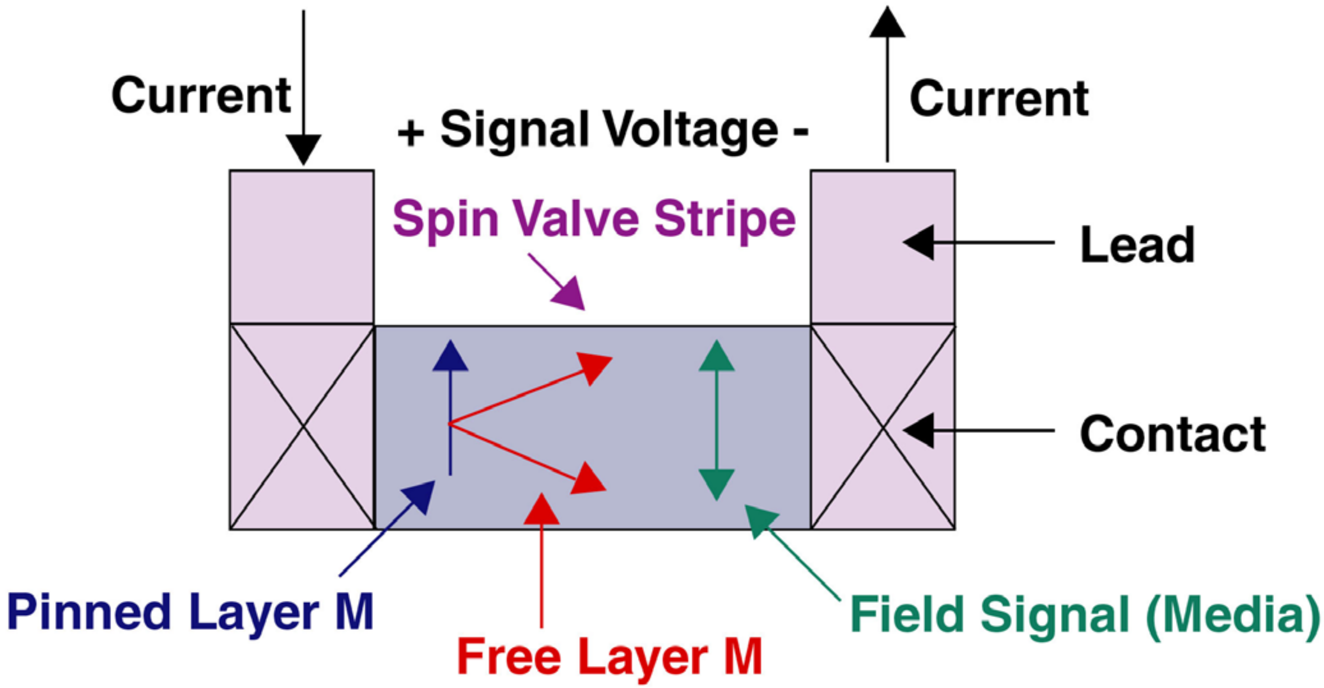


- Practical Devices - Moodera, Miyizaki
- Much Higher Magneto-Resistance

GMR Bridge Sensor (Two Shown) - 1995

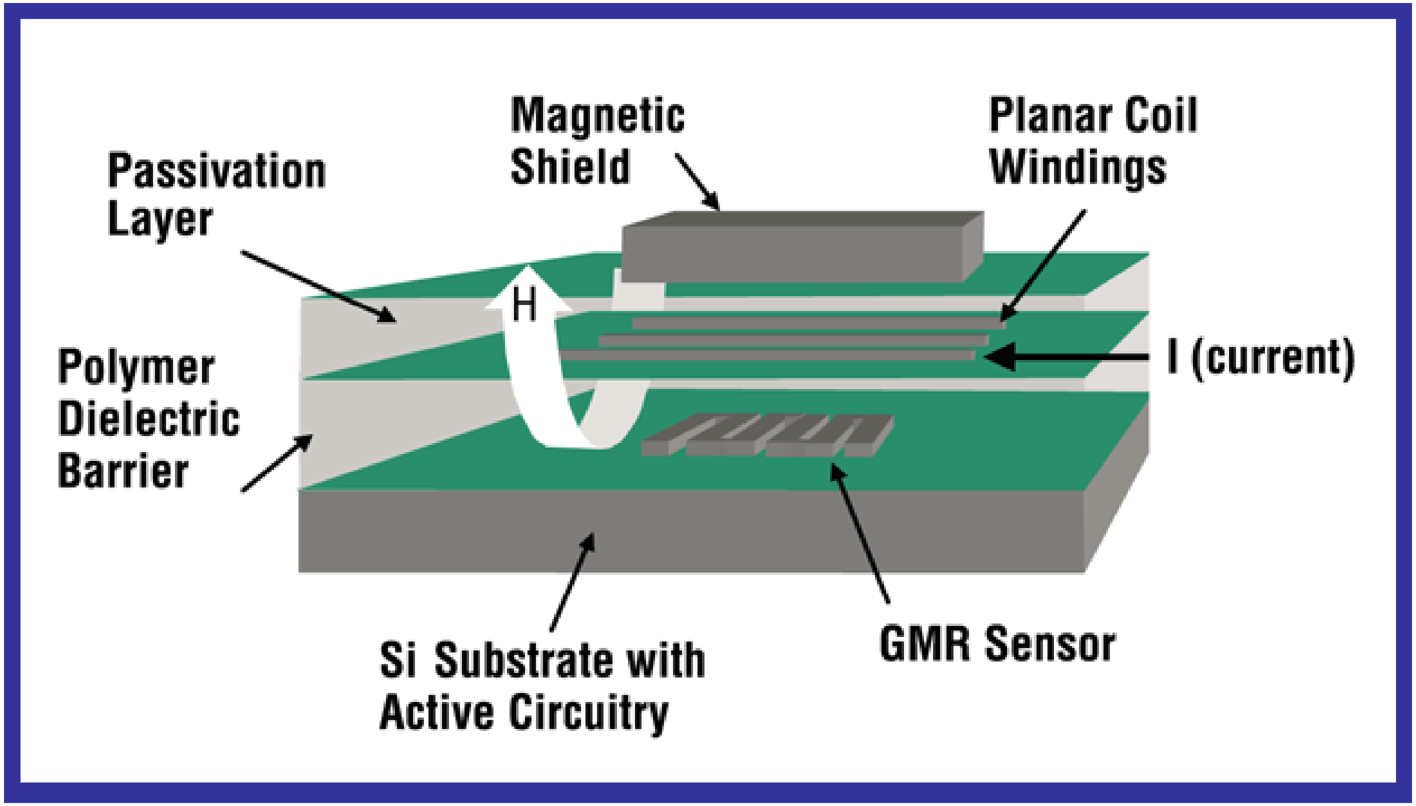


GMR Read Heads (1996)



- **Most Commercial Heads - Tsang et al (IBM,1994)**
  - Spin Valves - Pinned and Soft Layer
  - Pinned Layer Magnetization Across Stripe
  - Senses Vertical Fields
- **New Additions - Pinned SAF and NOL**

GMR Isolators (1998)

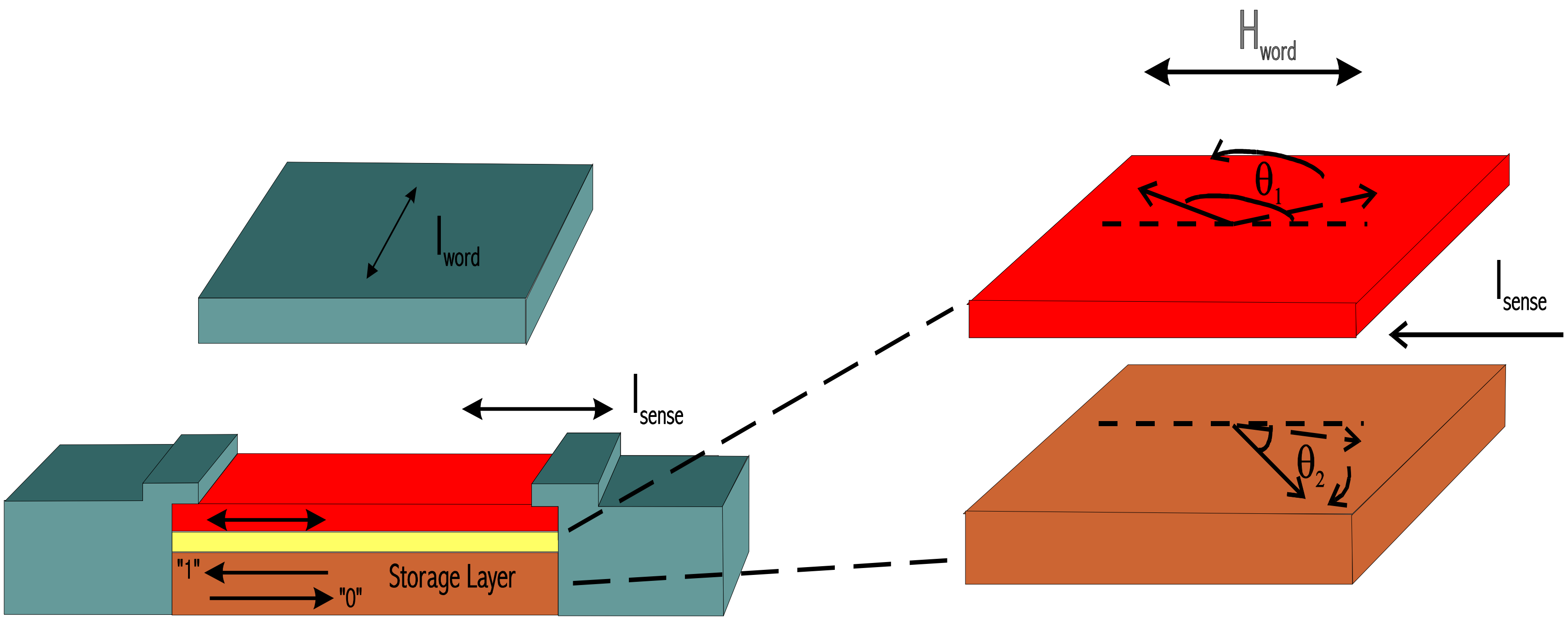


- Spin Valve Sensor
- Used For Ground Isolation

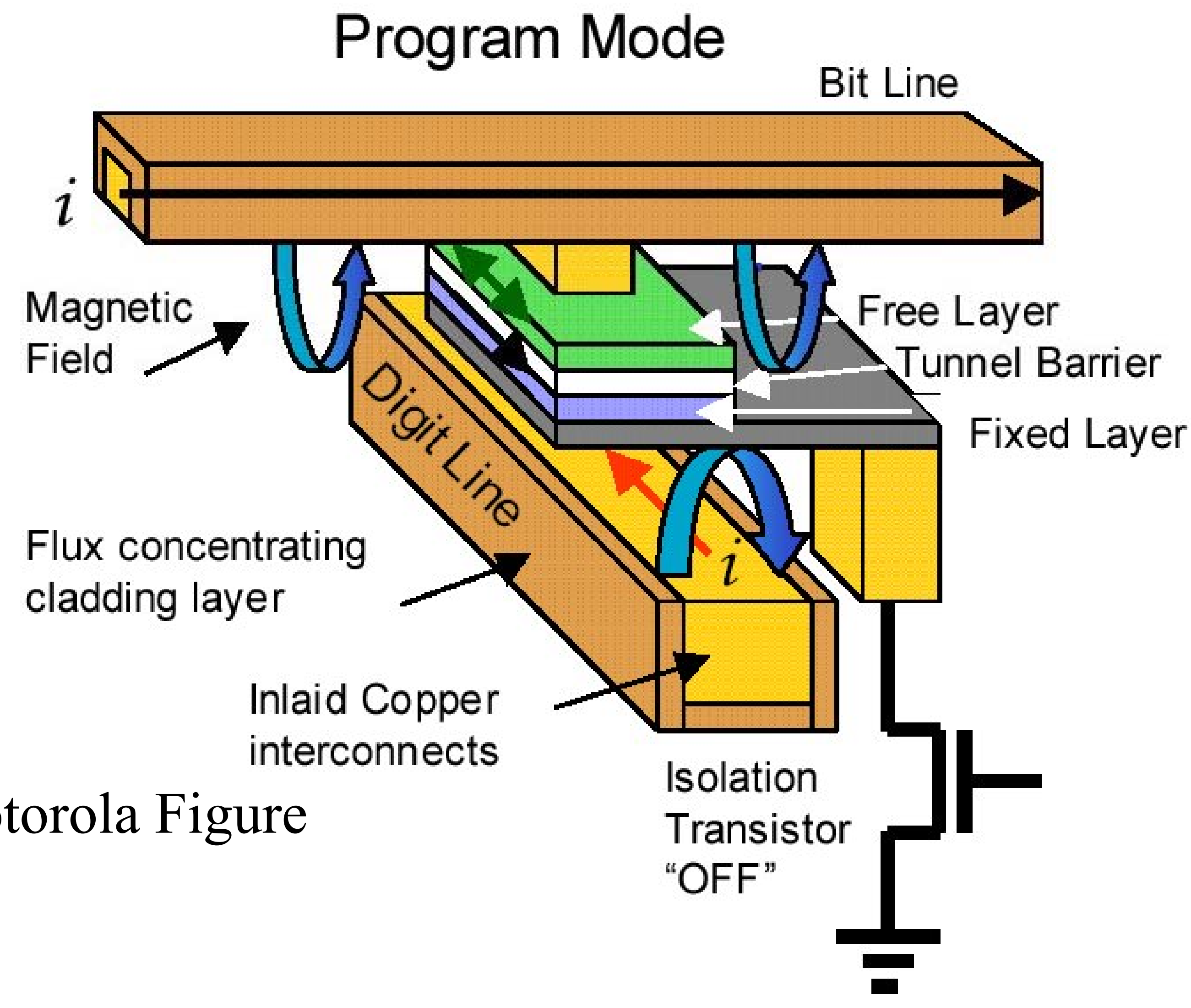
MRAM Concept

- **Magnetic Hysteresis For Data Storage**
  - Material Properties - Anisotropy, Coercivity
  - Shape
- **Magnetoresistance of Storage Element - Readout**
- **Magnetic Elements on Integrated Circuit**
- **Advantages**
  - Doesn't Wear Out With Writing (Unlike Flash)
  - Nonvolatile (Unlike SRAM or DRAM)
  - Writes Fast (Unlike Flash)

GMR MRAM Pseudo-Spin Valve



TMR MRAM



Motorola Figure

MRAM Products (2004?)

- **Many Developers - Two Near Products**
- **Motorola (Freescale)**
  - Samples 2003
  - Limited Production Y/E 2004 or 2005
  - 4 Mbit Capacity
- **Cypress Semiconductor**
  - Samples - Early 2005
  - 256K bit Capacity

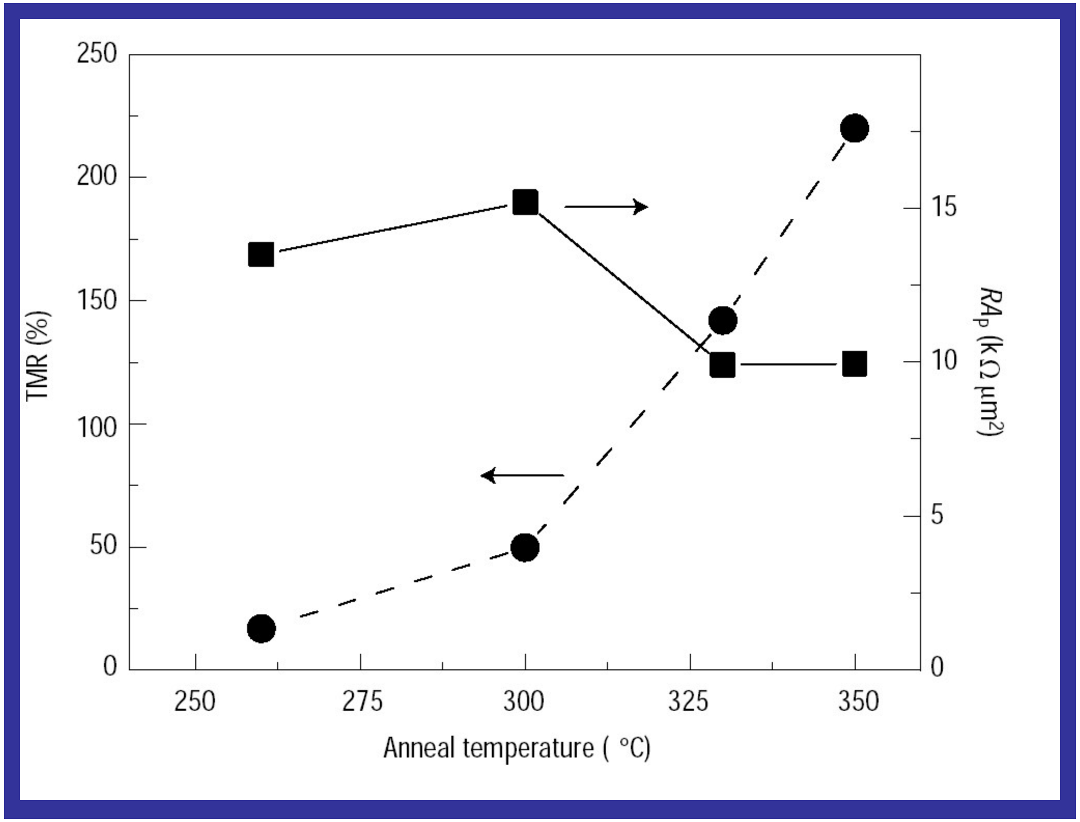
MRAM Scaling Challenge

- **Road Map Projections**

Year	2003	2005	2007	2010
Lithography (μm)	0.1	0.08	0.07	0.05
Cell Size (μm^2)	0.06	0.04	0.03	0.01
Capacity (bits)	1G	2G	4G	8G

- **Stability Requires Es/kT >~50:1**
- **Small Volume** $\rightarrow$ **High Energy Density**
- **Write Currents Get Big** (Conventional Designs)
  - Transistors Are Big (~2 X 5mA)
  - Heating in Narrow Conductors

Still Higher TMR

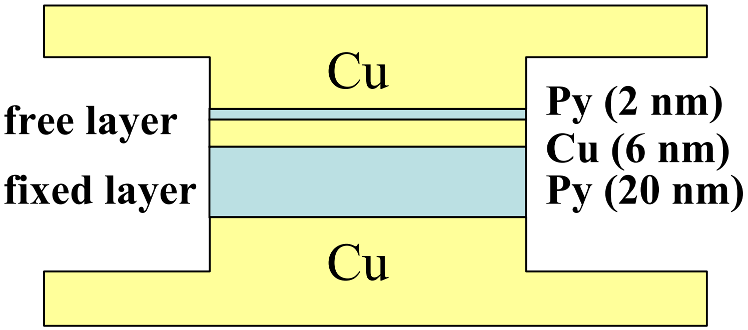


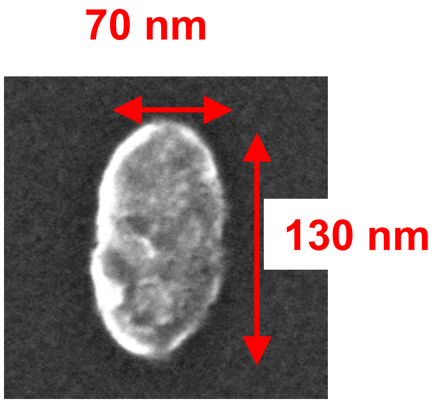
Parkin et. al.,

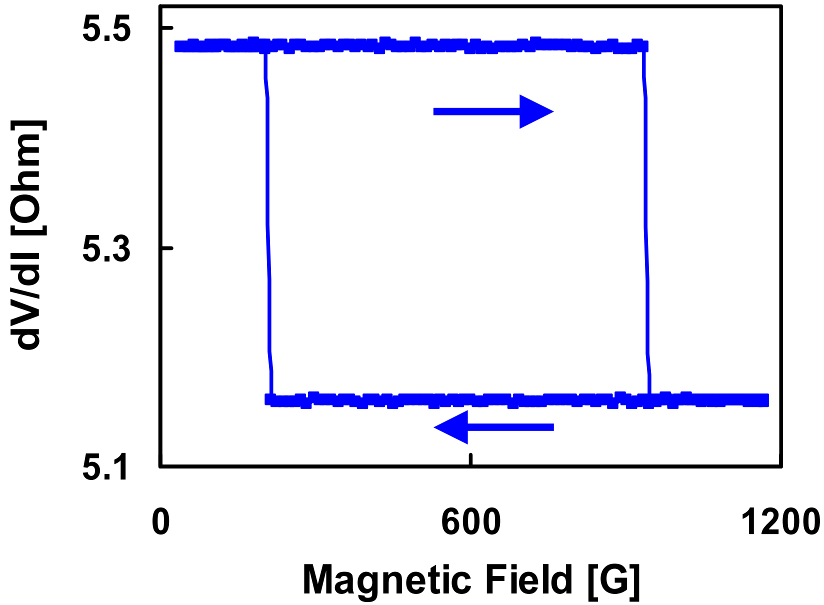
Nature (2004)

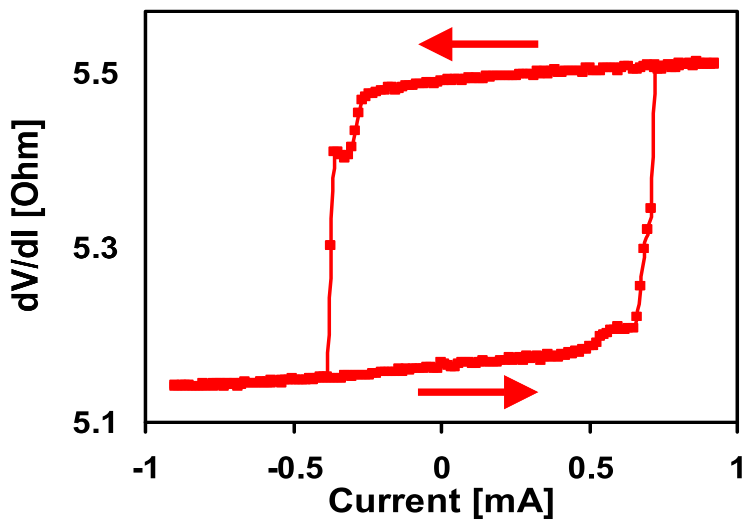
- **Over 200%**
- **Challenges Understanding of TMR**
  - $2P_1P_2/1 - P_1P_2$
  - Believed P_1, P_2 Understood
  - Obviously Overconfident
- **Large On-Off Ratios Possible!!**

Spin Momentum Transfer (SMT)







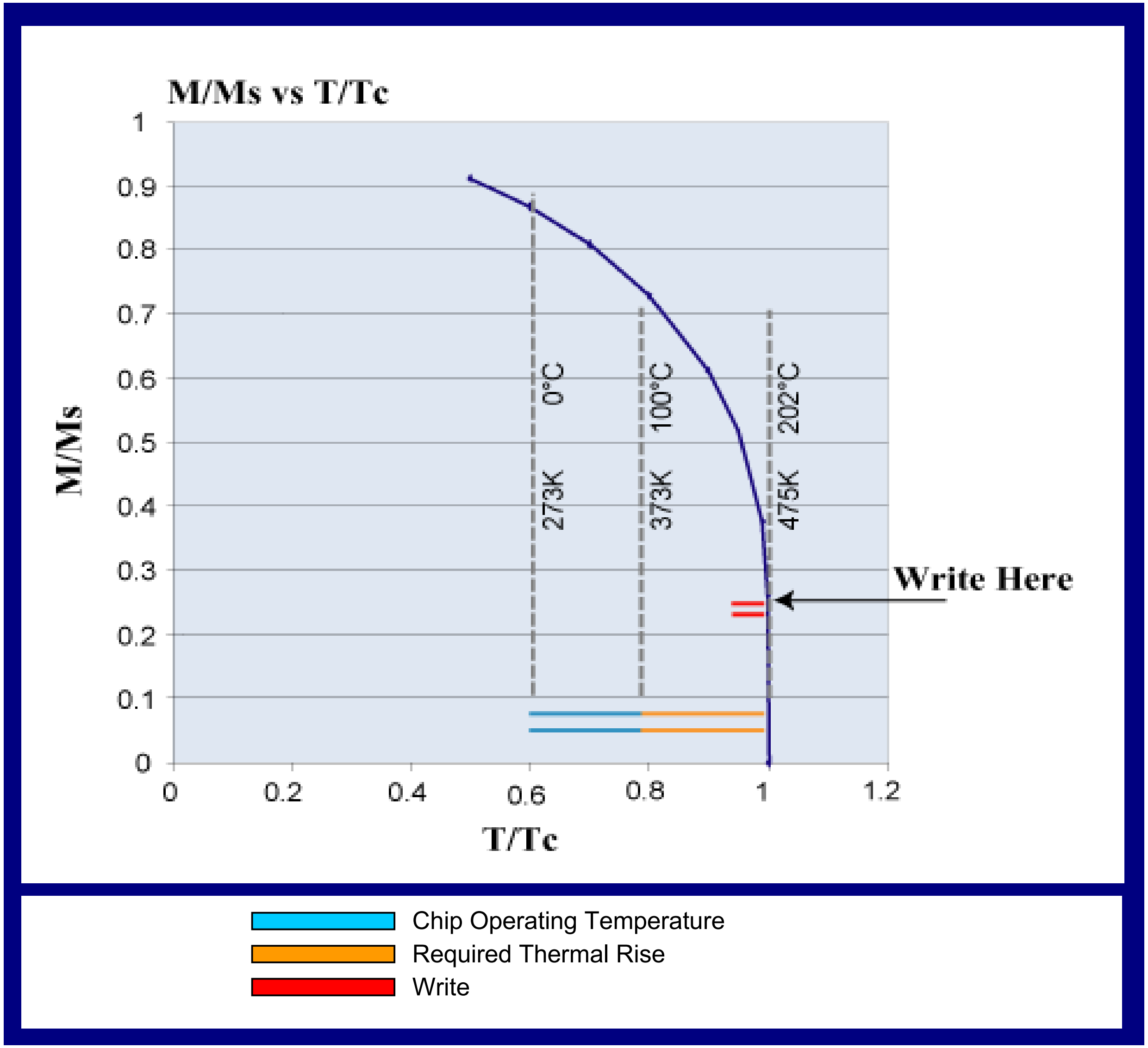


Bob Buhrman, Dan Ralph, et.al. Cornell

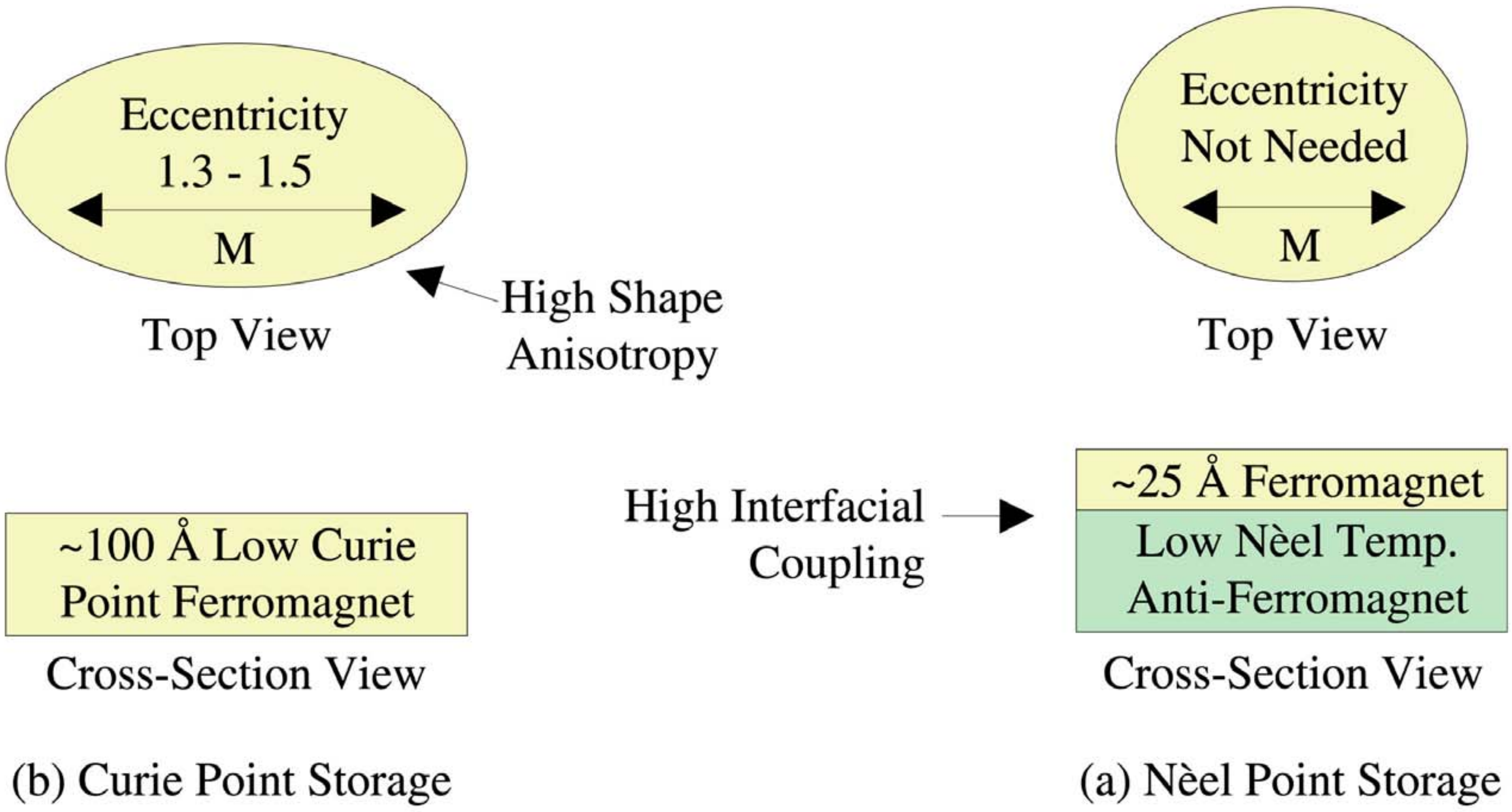
Spins in Semiconductors (SPINS)

- Ferromagnetic Semiconductors
- Light-Induced Spin
- LED Sensing
- Ferromagnetic Injection

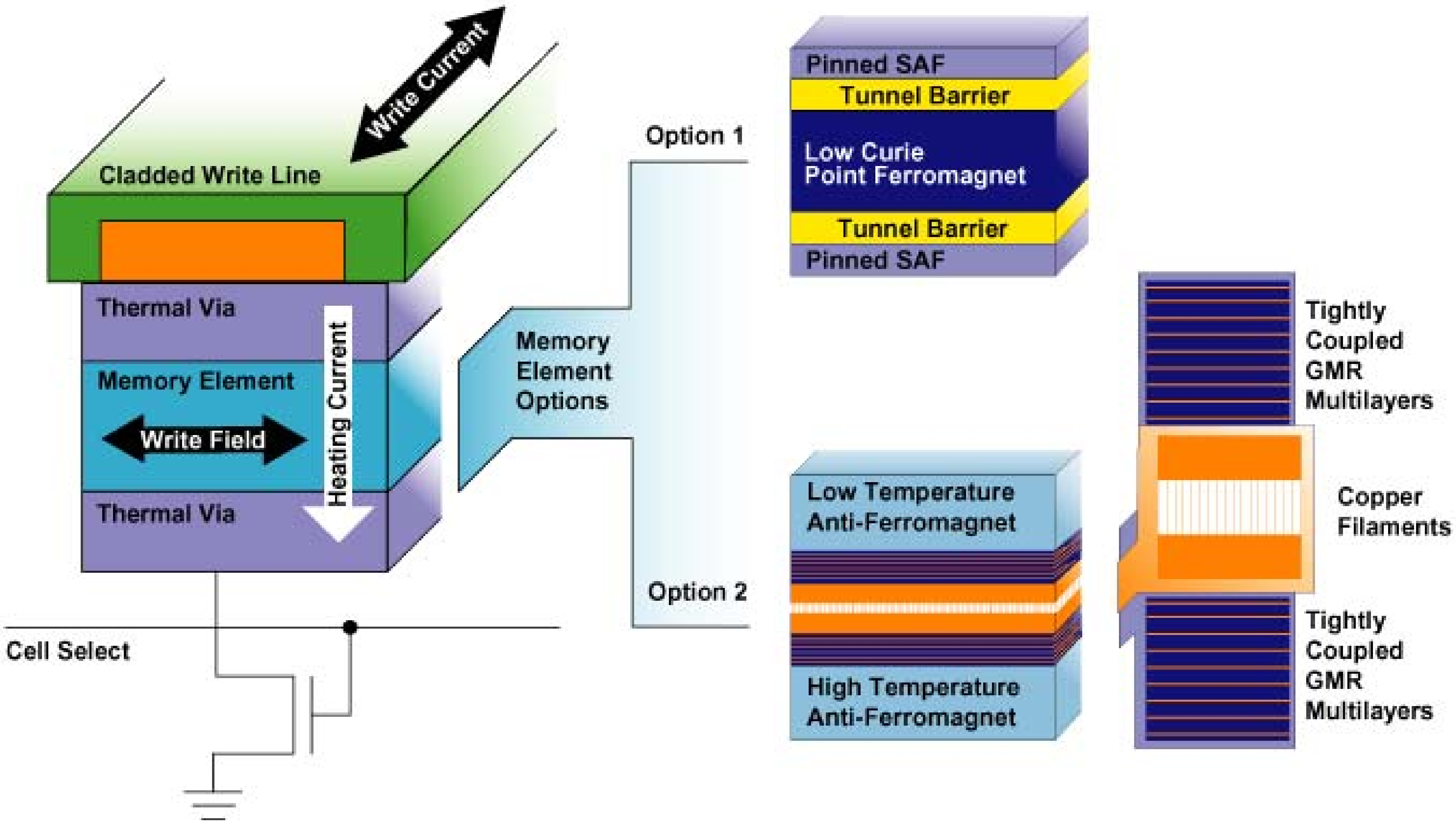
Thermally Assisted MRAM



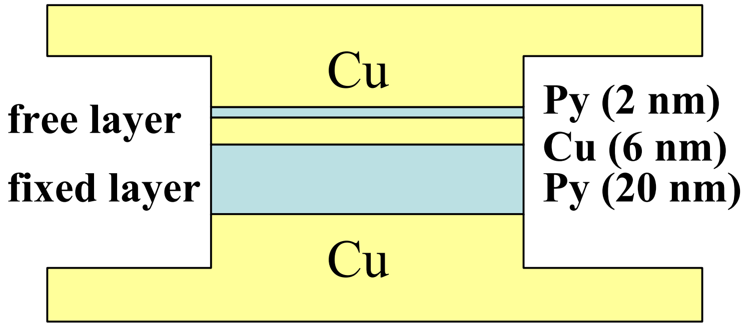
Two Methods For T-MRAM

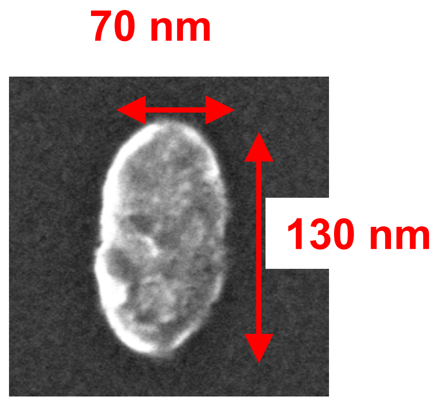


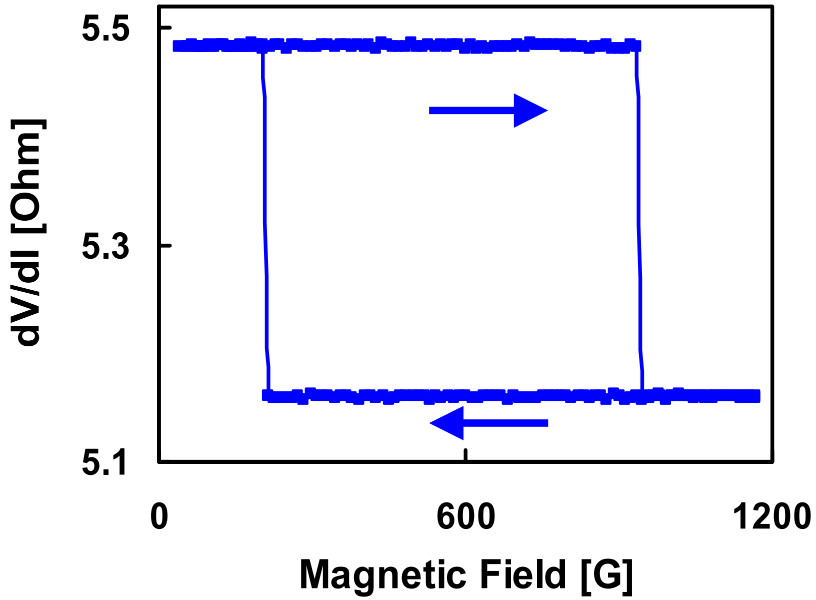
Possible Implementation

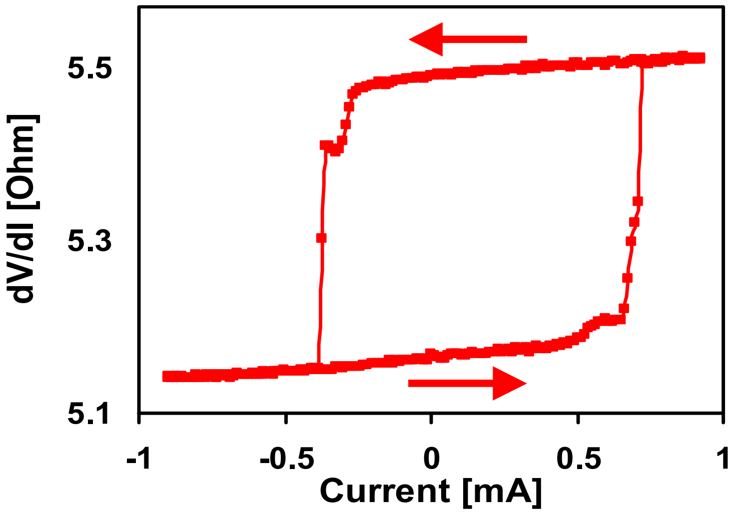


SMT Written MRAM









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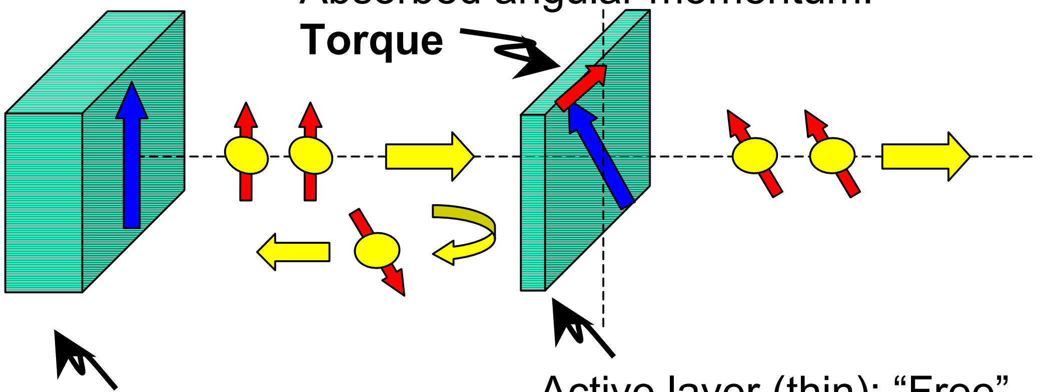
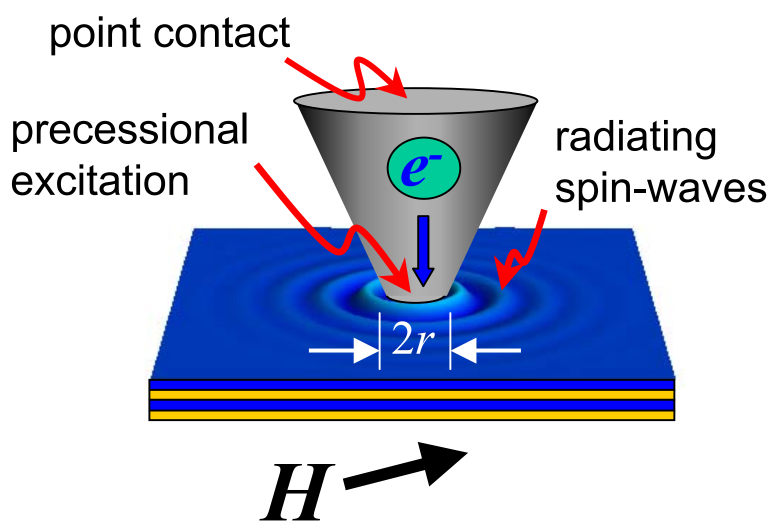
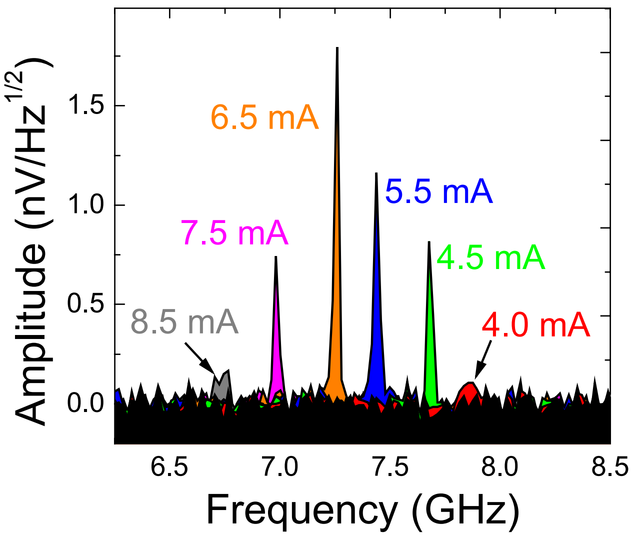
Spin Waves - Spin Transfer Oscillator





W. H. Rippard et al PRL **92**, 027201 (2004)



Future Products

- **High Density MRAM- Will Scale**
  - Thermally Assisted Writing
  - Spin Momentum Transfer
- **Magnetic Logic - High On/Off Ratio TMR**
- **SPINS Program (Spins In Semiconductors)**
  - Semiconductor/Light
  - Spin Transfer Oscillator
  - Magnetic Transistor- Storage