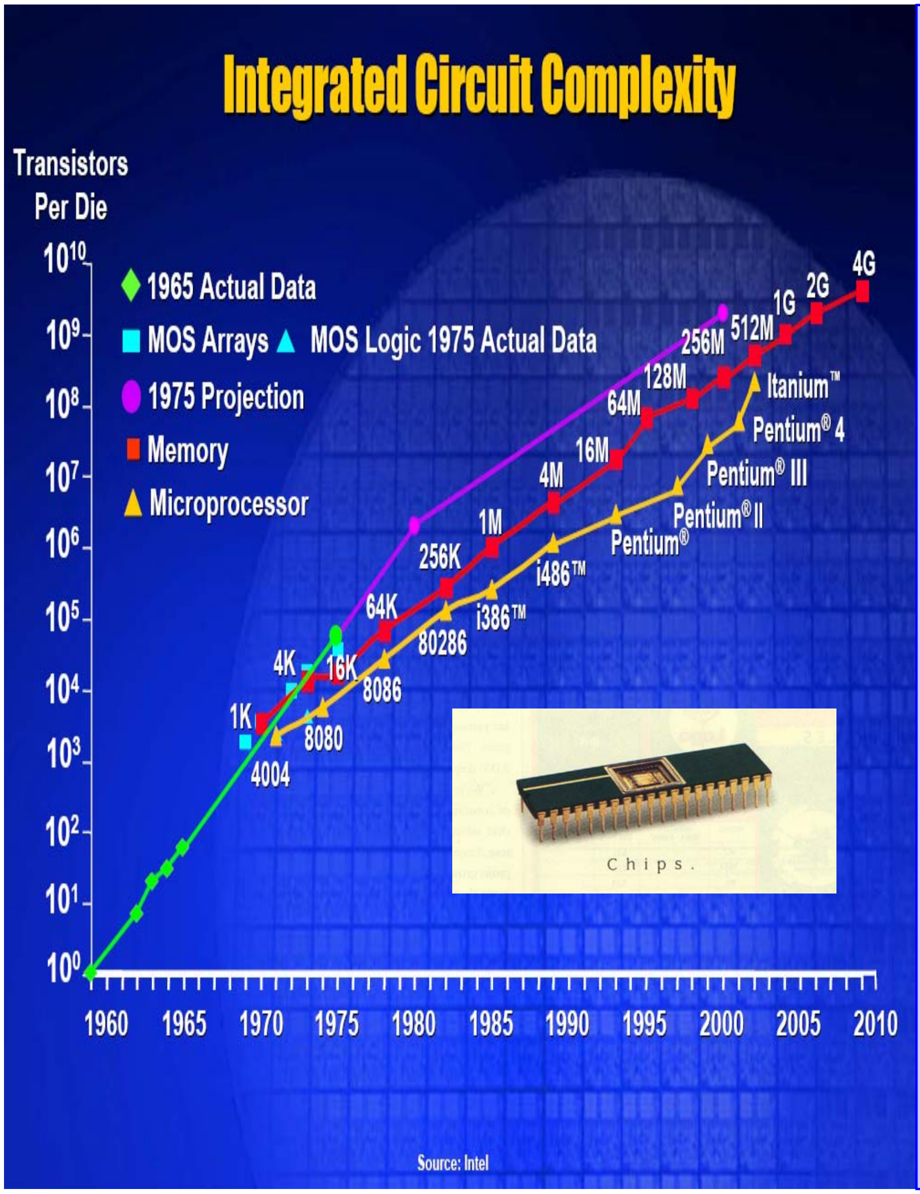
Spintronics and Nanomagnetics

Nate Newman
School of Materials

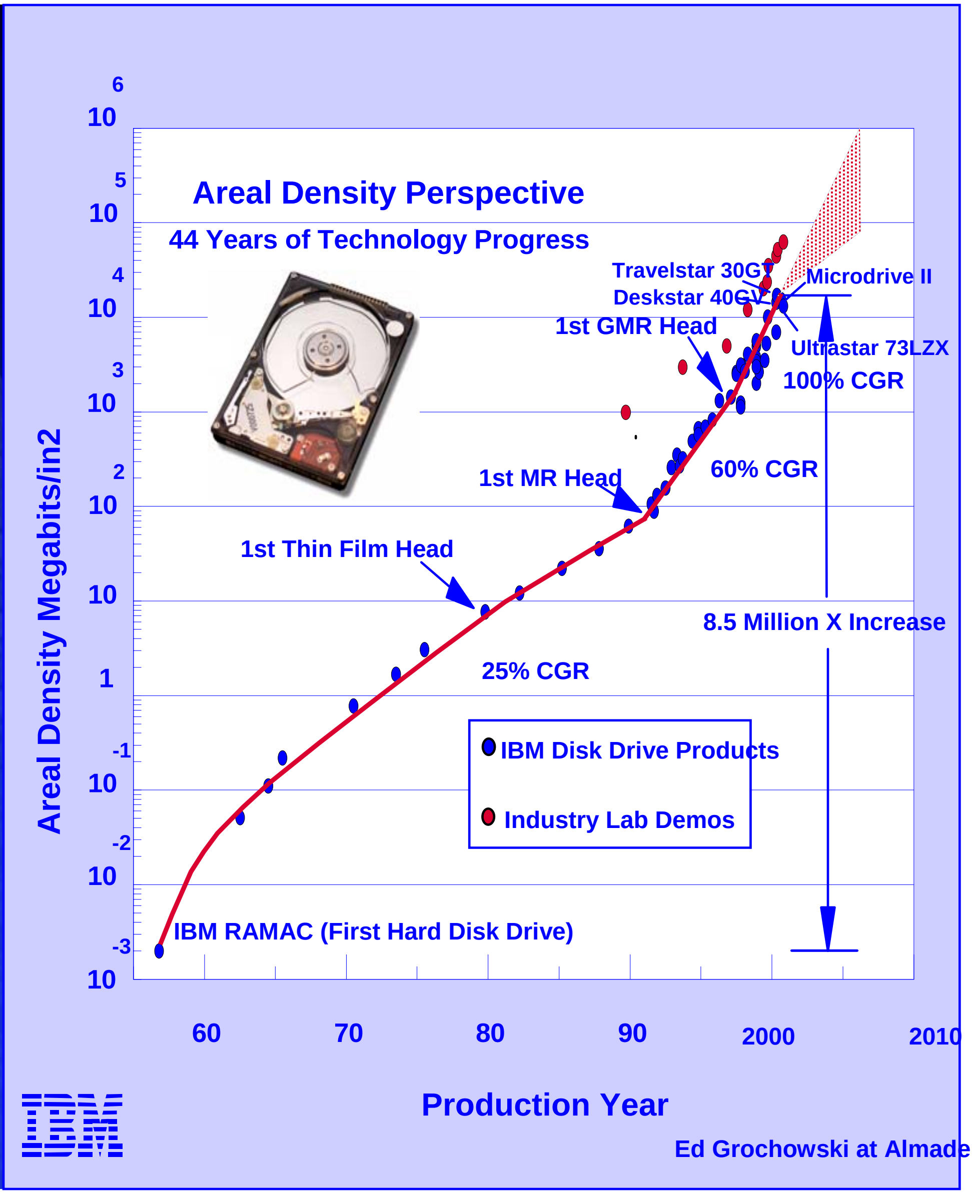
Why focus on nano when discussing magnetics?
Some current issues and how we might address them.

Scaling

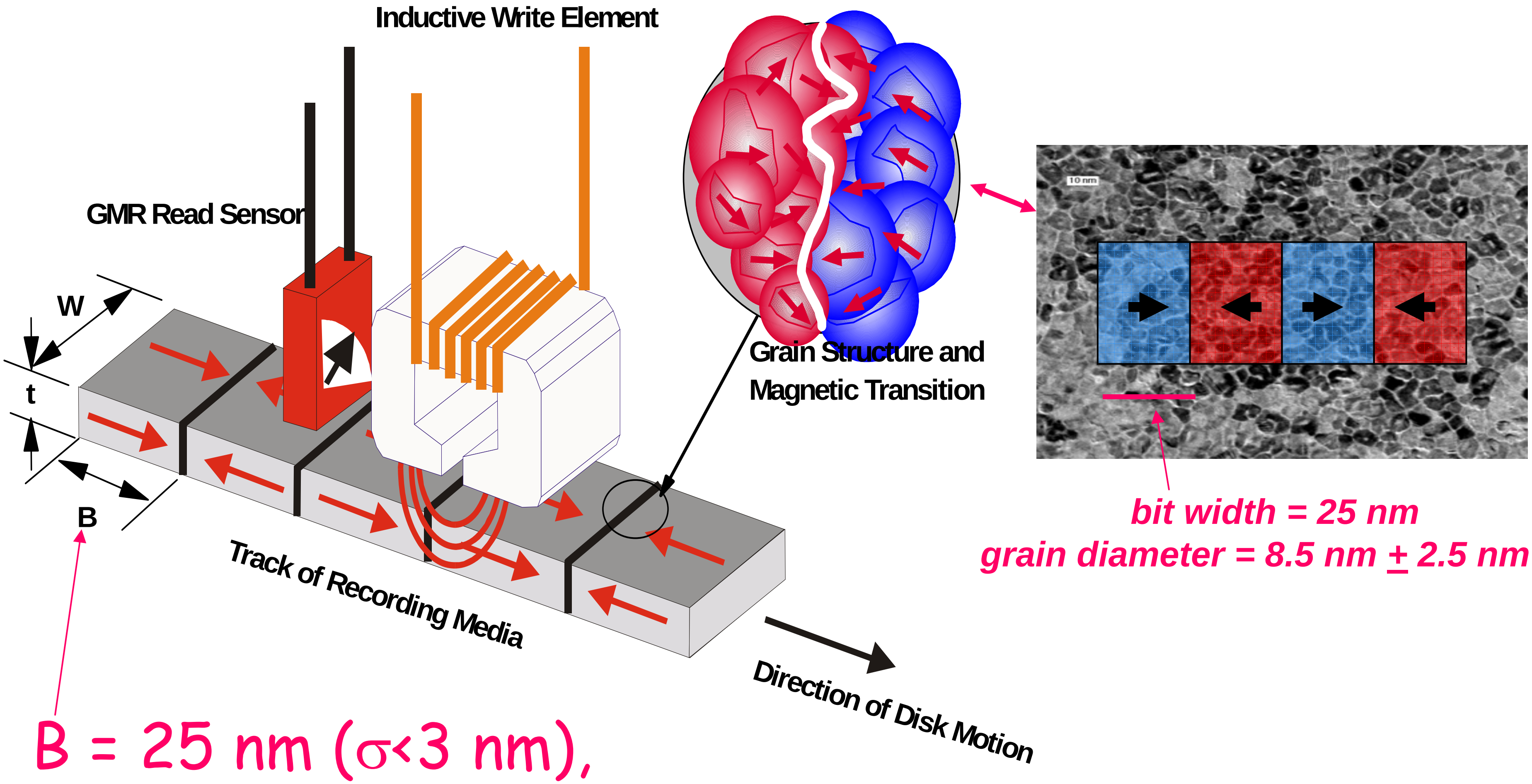
Semiconductor devices- Moore's law



Magnetic memory- Kryder's Law



Hard drives- nm scale



bit width = 25 nm

grain diameter = 8.5 nm ± 2.5 nm

B = 25 nm (σ<3 nm),
W=150 nm, t = 14 nm
data rate ~ GHz

Courtesy of Prof. Eric Fullerton,
UCSD

Thanks for the memories

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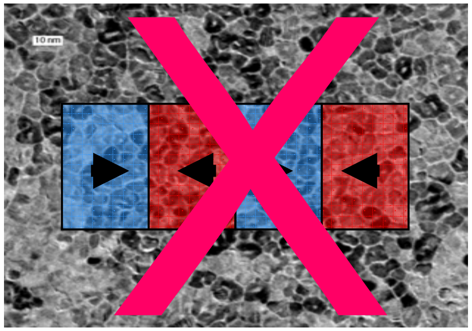
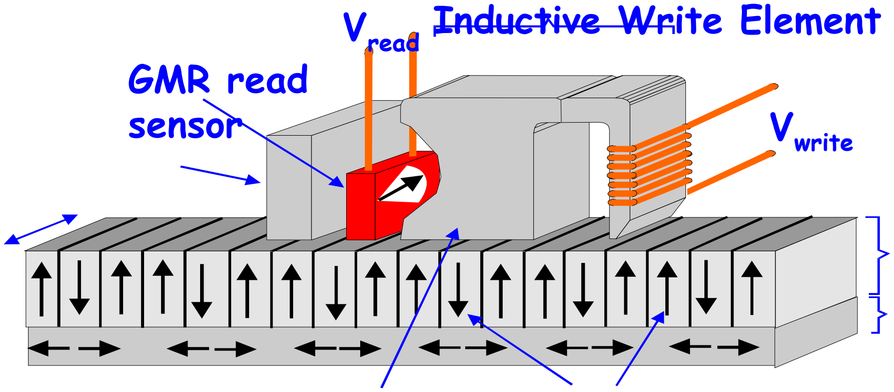
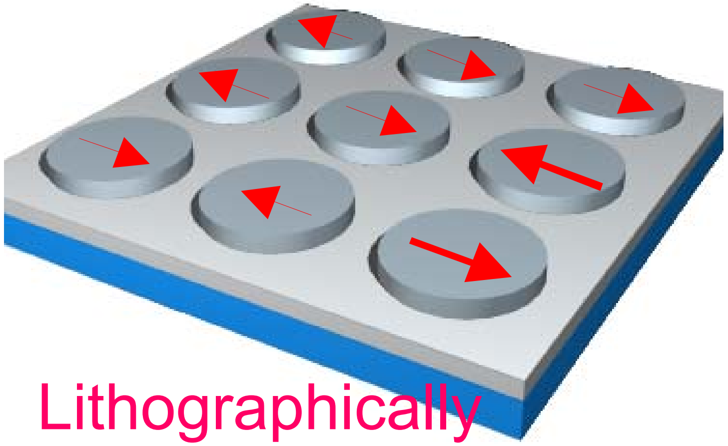
Advanced systems





Perpendicular recording

Product 2006
extend to ~ 500 Gb/in^2
maybe higher



Lithographically patterned media

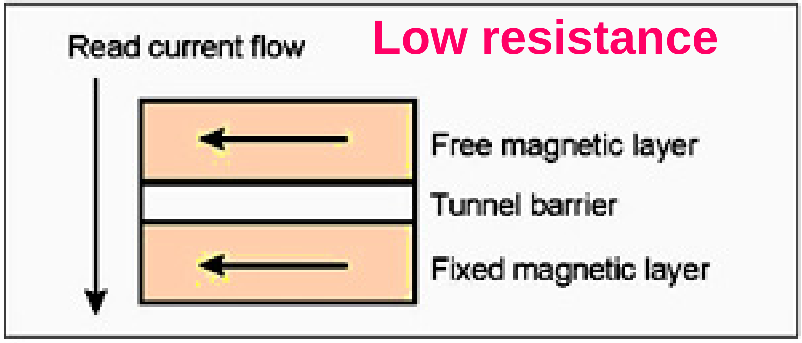
Ultimate Structure –

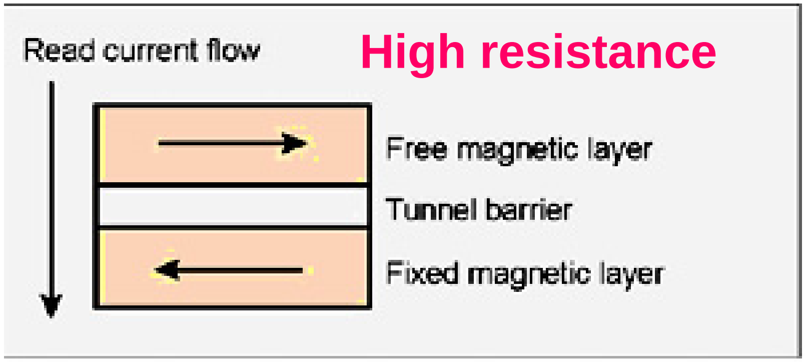
1 Grain of Magnetic Alloy per Bit

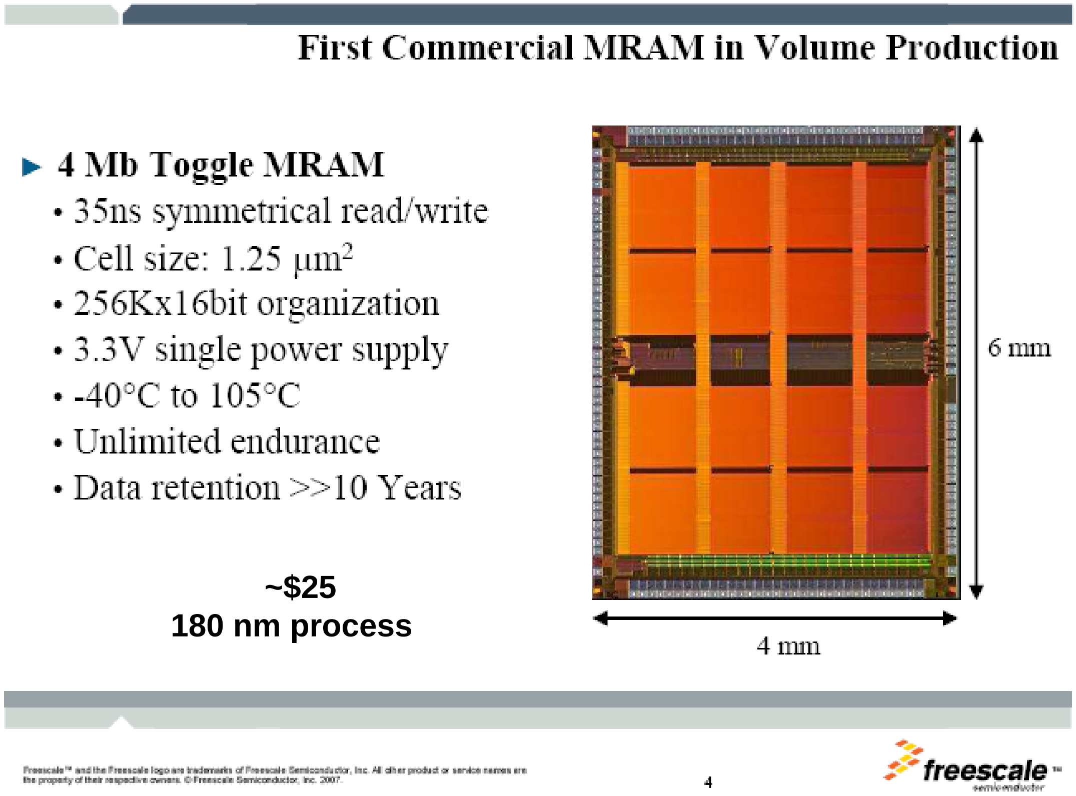
Courtesy of Prof. Eric Fullerton, UCSD

MRAM

Embeddable, density of DRAM , speed of SRAM , non-volatility of FLASH/hard drive & low power







First Commercial MRAM in Volume Production

- **4 Mb Toggle MRAM**
  - 35ns symmetrical read/write
  - Cell size: 1.25 μm^2
  - 256Kx16bit organization
  - 3.3V single power supply
  - -40°C to 105°C
  - Unlimited endurance
  - Data retention >>10 Years

~$25
180 nm process

4

freescale™ semiconductor

Courtesy of Dr. Nick Rizzo, Freescale

Embeddable memory

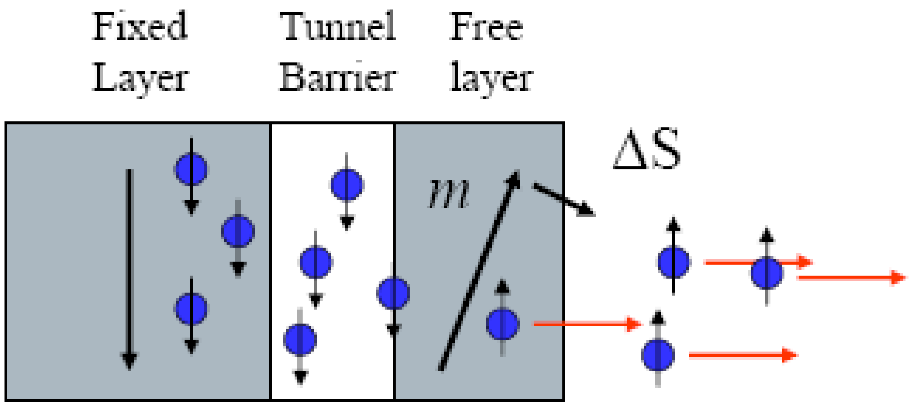
1. Combine semiconductor logic & memory
2. Random access capability (flash limitation)
3. >10 M cycles (limitation of flash memory)

Uses:

1. 4 MB- auto, replacing battery-backed SRAM
   a. airbag, crash & ABS recorders
   b. auto sensors need high # of write cycles (flash wears out)
2. Future- higher density needed
   a. Cell phone microprocessor & memory
   b. Immediate computer reboot

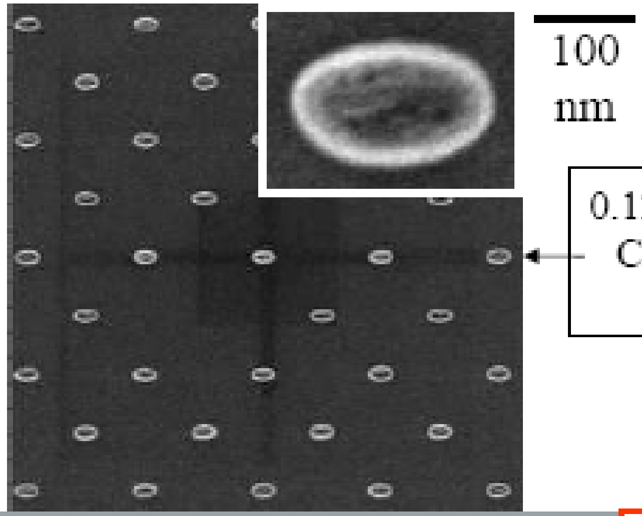
Spin Torque Programming for High Density, Low Power MRAM

- Use spin momentum from current to change direction of ***S***, ***m***.



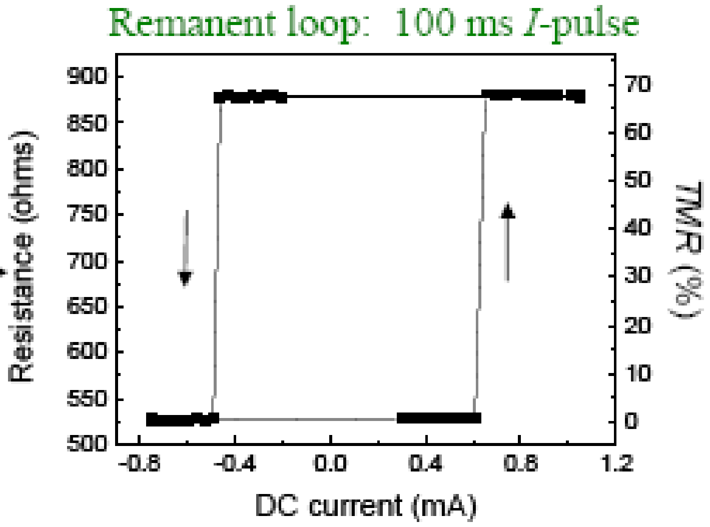
Net change in $S = \hbar$ per e⁻

$$\frac{\Delta S}{\Delta t} = Torque$$



0.12 μm x 0.19 μm CFB Free layer on MgO

Remanent loop: 100 ms *I*-pulse

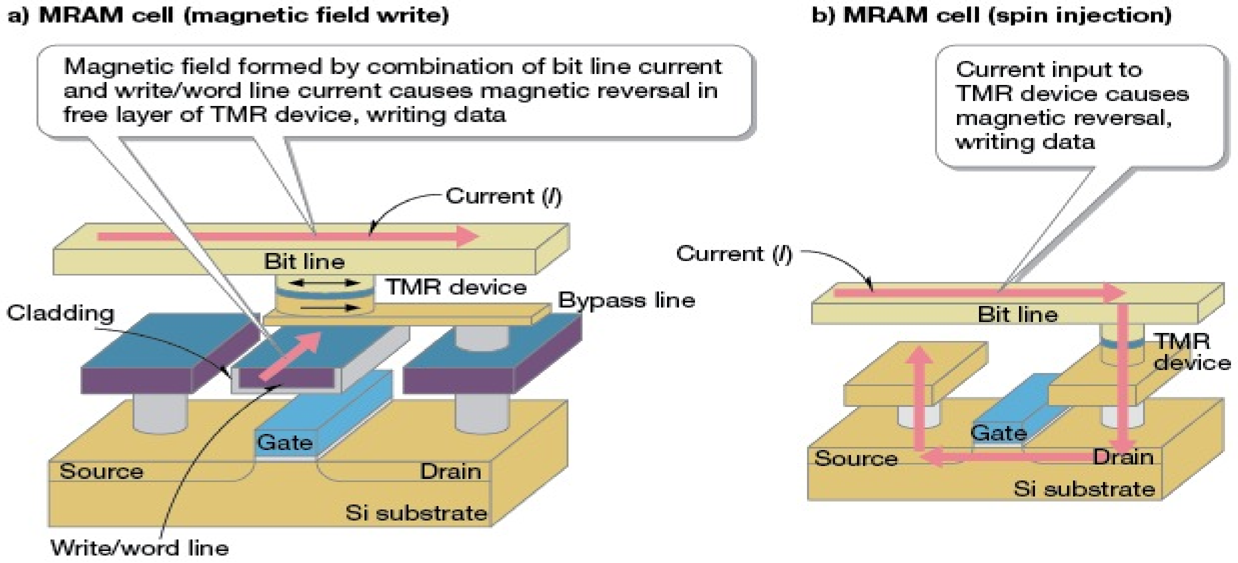


$J_c \sim 10^6\text{-}10^7$ A/cm²

Courtesy of Dr. Nick Rizzo, Freescale

half-select
problem

limited to
> 65 nm
due to
thermal
switching


a) MRAM cell (magnetic field write)

Magnetic field formed by combination of bit line current and write/word line current causes magnetic reversal in free layer of TMR device, writing data

b) MRAM cell (spin injection)

Current input to TMR device causes magnetic reversal, writing data

can be
made to
< 20 nm

c) Comparison

	Magnetic field write MRAM	Spin injection MRAM
Memory cell area (*F* is minimum feature)	$20F^2$ to $30F^2$	$6F^2$ to $8F^2$
Memory cell structure	Complex (requires bypass line and cladding write/word line)	Simple (does not need bypass line or write/word line)
Ease of reducing line width	Poor	Excellent
Write current	Inversely proportional to volume of magnetic body	Proportional to volume of magnetic body
Erroneous read	Relatively susceptible	Relatively resistant

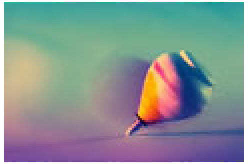
Fig 1 Smaller Memory Cells Facilitate Smaller Features Compared to the magnetic field write method of MRAMs now in volume production (a), the newly-proposed spin injection MRAMs (b) have smaller cell areas and are much easier to reduce line widths for (c). Diagram by *Nikkei Electronics* based on material courtesy Grandis

Toshiba claims to be the first to report a TMR device with vertical magnetization.

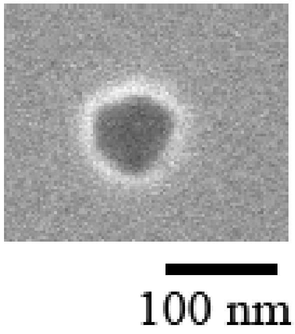
Toshiba & NEC have announced a 16 Mbit MRAM chip

In December 2005, Sony announced the first lab-produced spin-injection (torque-transfer) MRAM

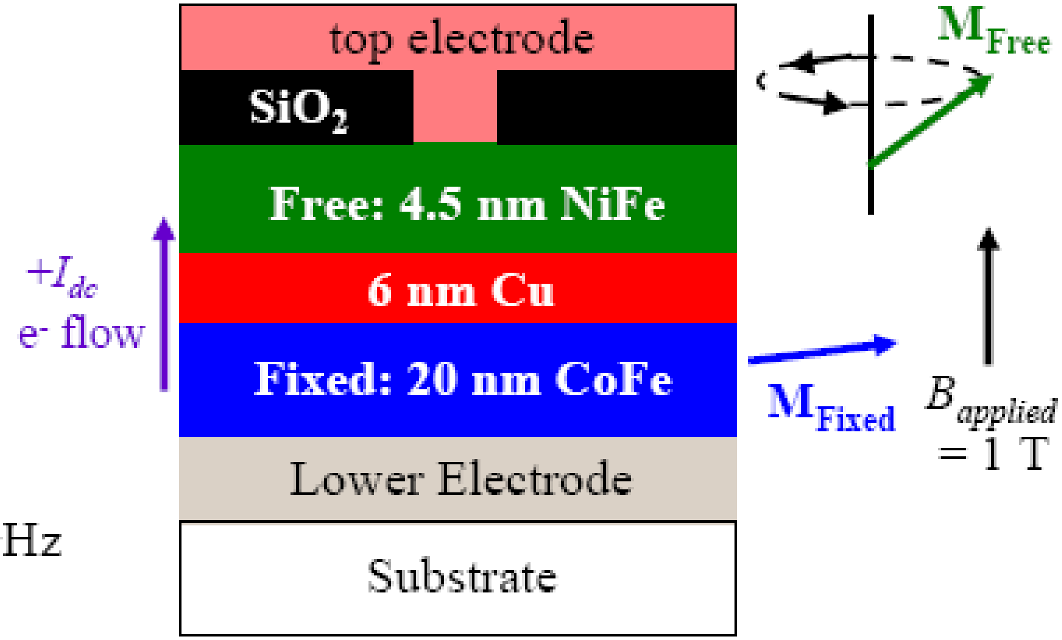
Spin Torque Nano-Oscillators



- GMR Point contact geometry



Point contact diameter: 50-300 nm

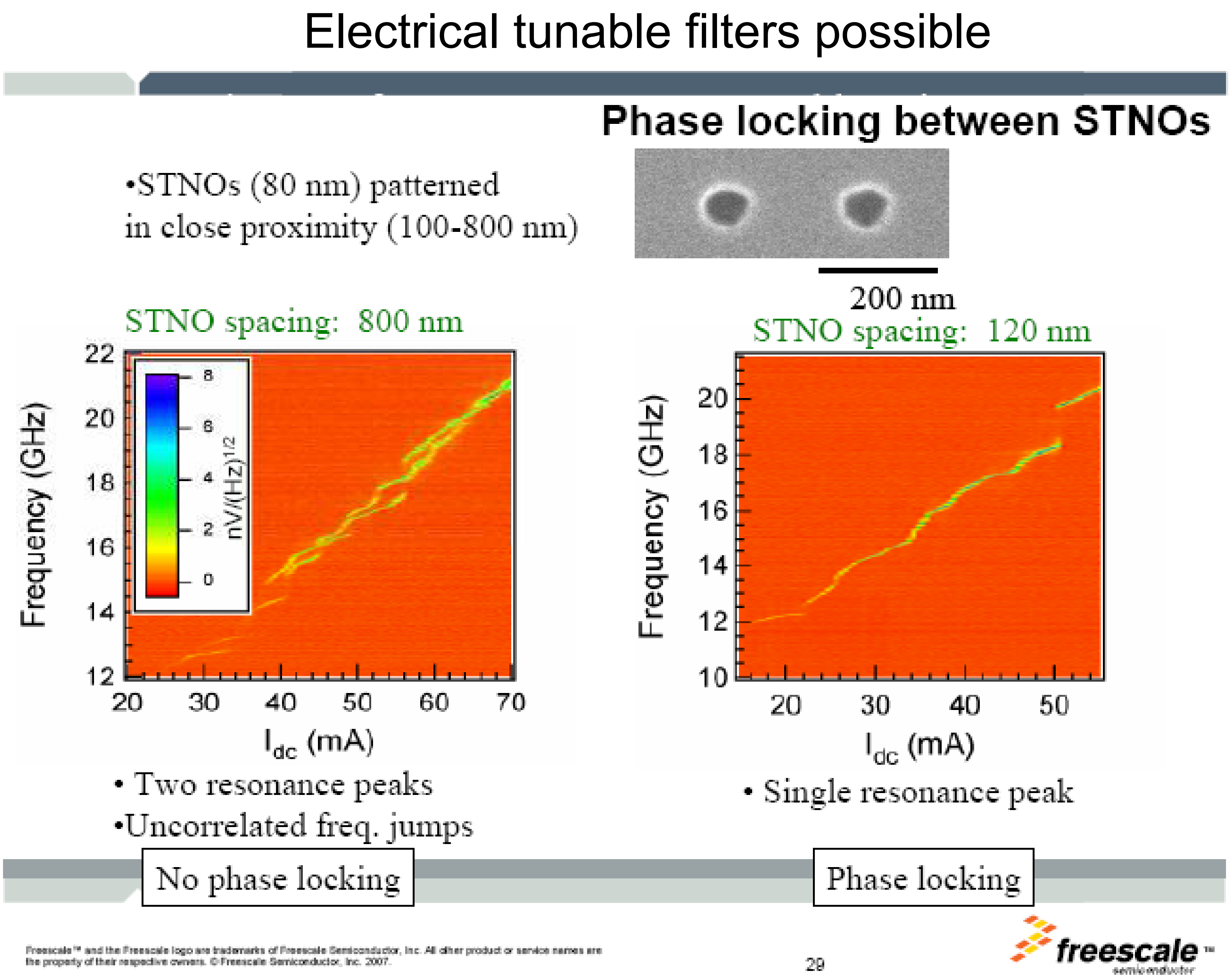


STNO attributes:

- Small size: ≈ 50-80nm
- Large tunable range: < 8 to >24 GHz
- High Q >~ 2000

•STNOs of interest for radar, signal processing, on-chip communications, low power magnetic excitations

Courtesy of Dr. Nick Rizzo, Freescale



Electrical tunable filters possible

Phase locking between STNOs

- STNOs (80 nm) patterned in close proximity (100-800 nm)

- Two resonance peaks
- Uncorrelated freq. jumps

No phase locking

- Single resonance peak

Phase locking

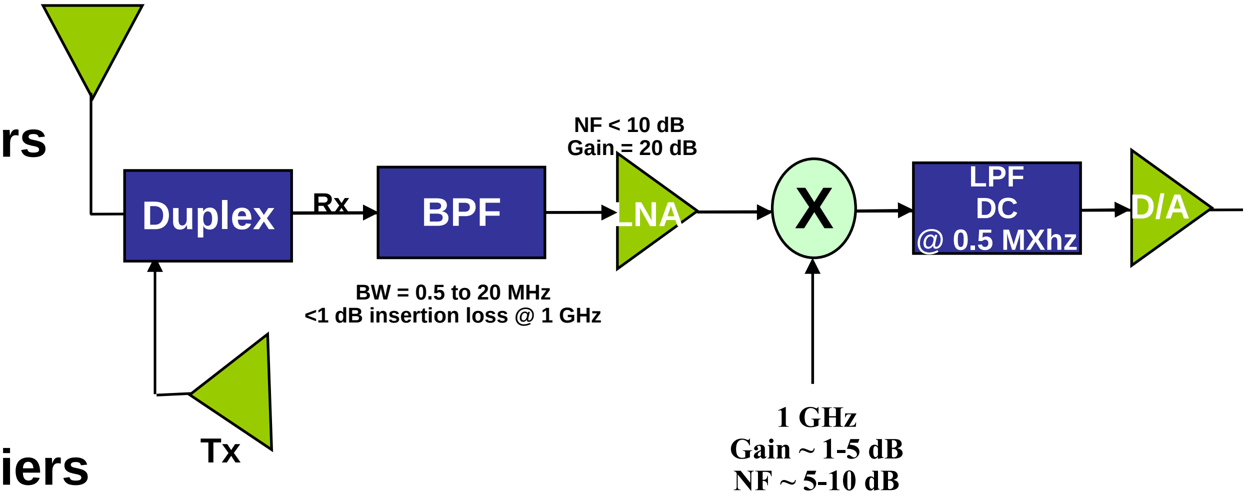
Courtesy of Dr. Nick Rizzo, Freescale

Radio receiver on a pinhead

**N. Newman, Clarence Tracy, Larry Cooper, Mark van Schilfgaarde,
Jim Aberle, Sayfe Kiaei, Ralph Chamberlin**

1. **We plan to develop the essential building blocks needed to demonstrate a revolutionary rf communication technology based solely on nanomagnetics**

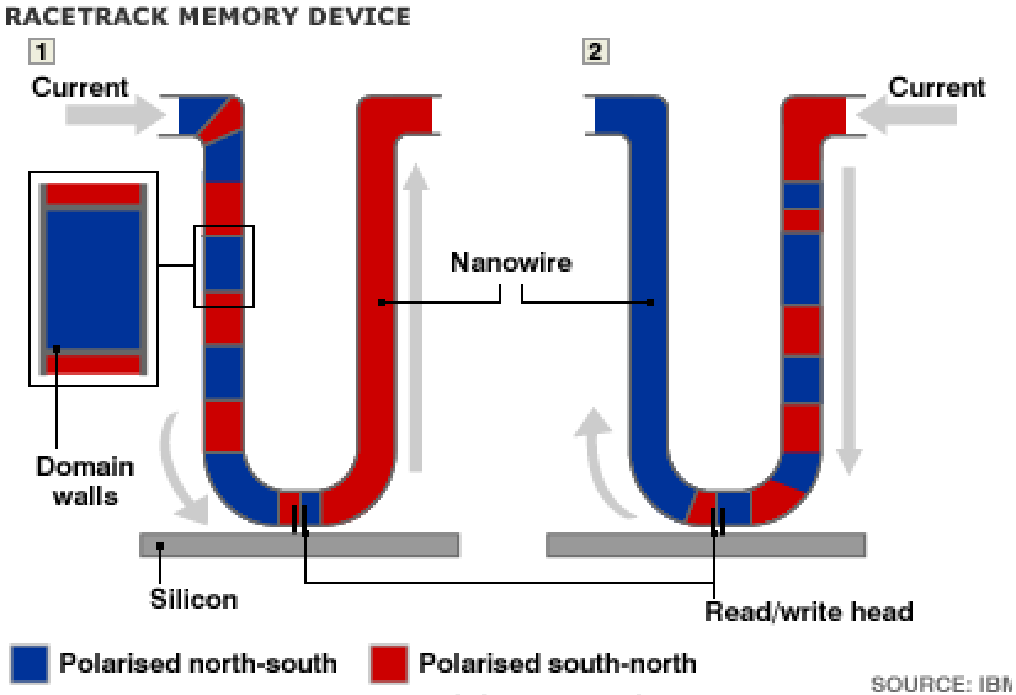
   a. frequency generators,
   b. resonators
   c. filters of various forms [lowpass, bandpass, bandstop, notch, chirp]
   d. attenuators
   e. phase shifters
   f. directional couplers
   g. frequency multiplexers
   h. mixing
   i. directional couplers
   j. circulators
   k. antennas
   l. amplifiers
   m. paramagnetic amplifiers



2. **We will then build a demonstration nanomagnetic rf radio receiver.**

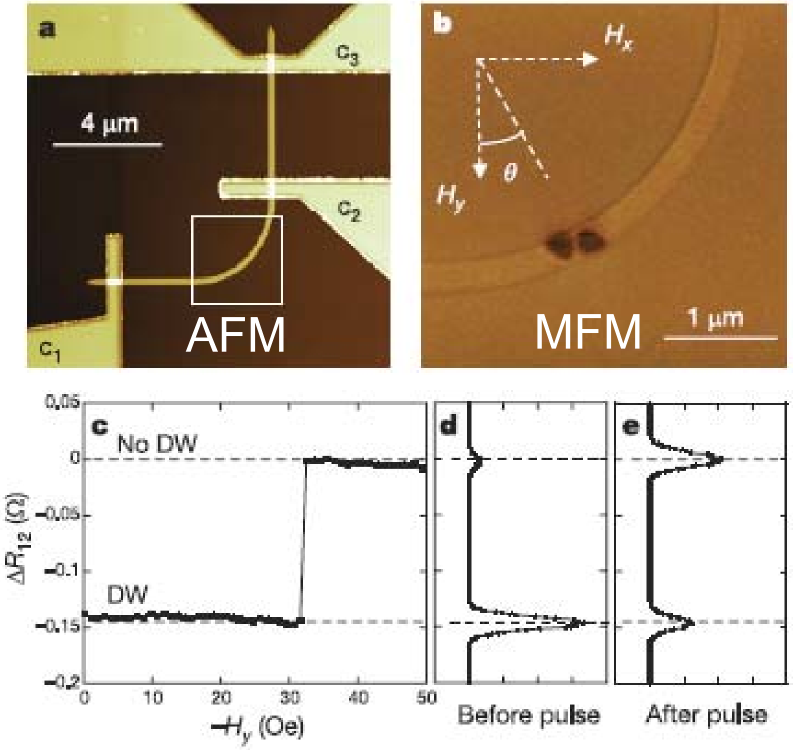
Drive domain walls with currents
Dynamics of Magnetic Nanowires

S.S.P. Parkin
IBM Almaden



SOURCE: IBM

news.bbc.co.uk

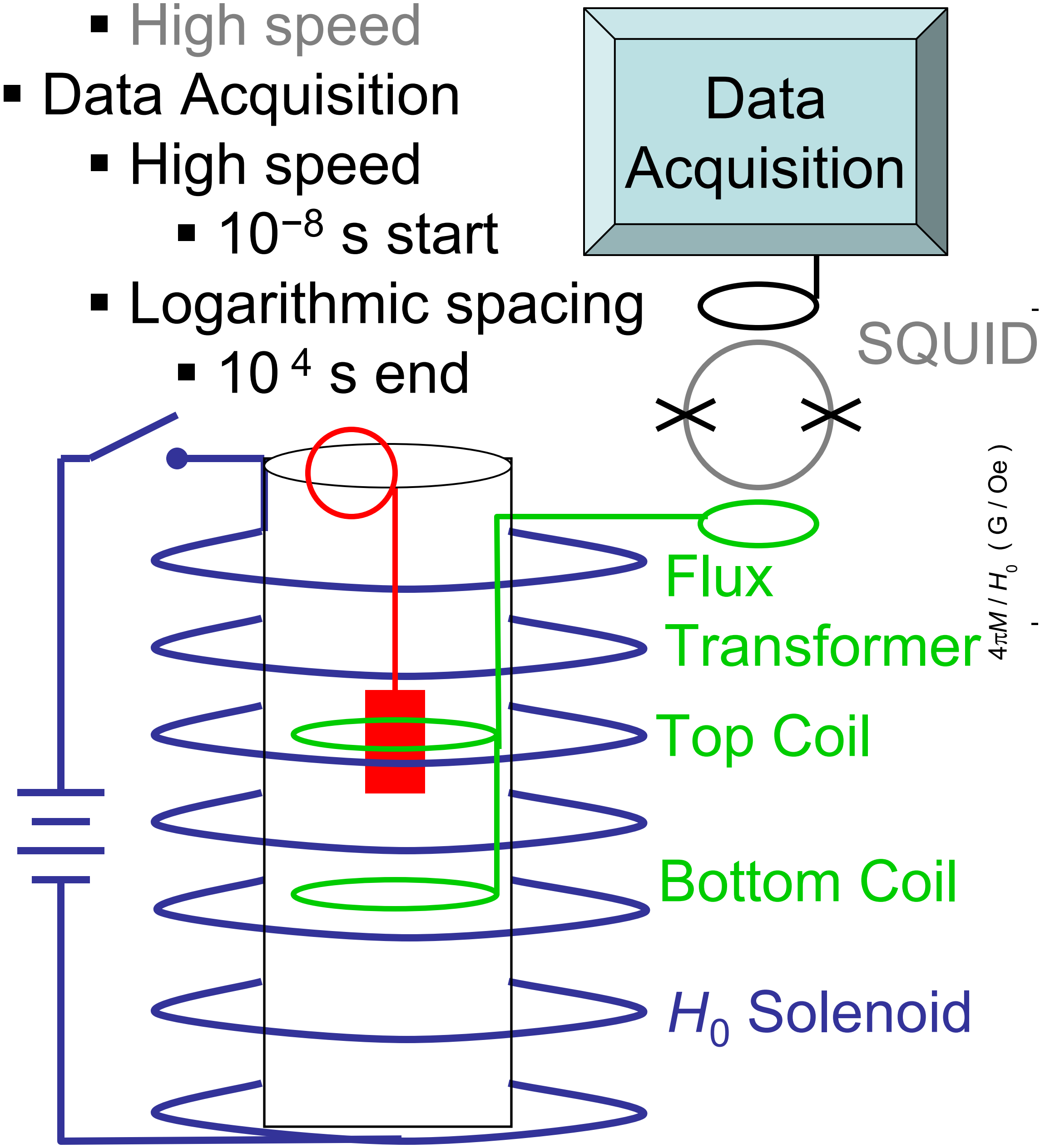


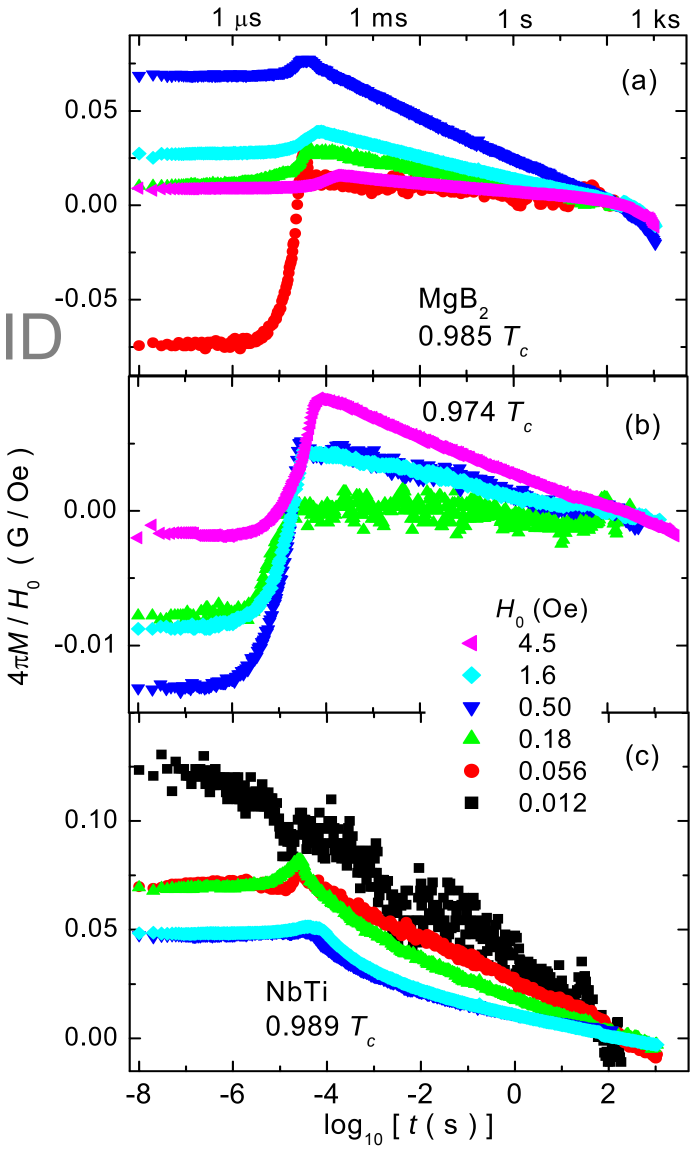
Thomas et al.
Nature, **443**,
197 (2006)

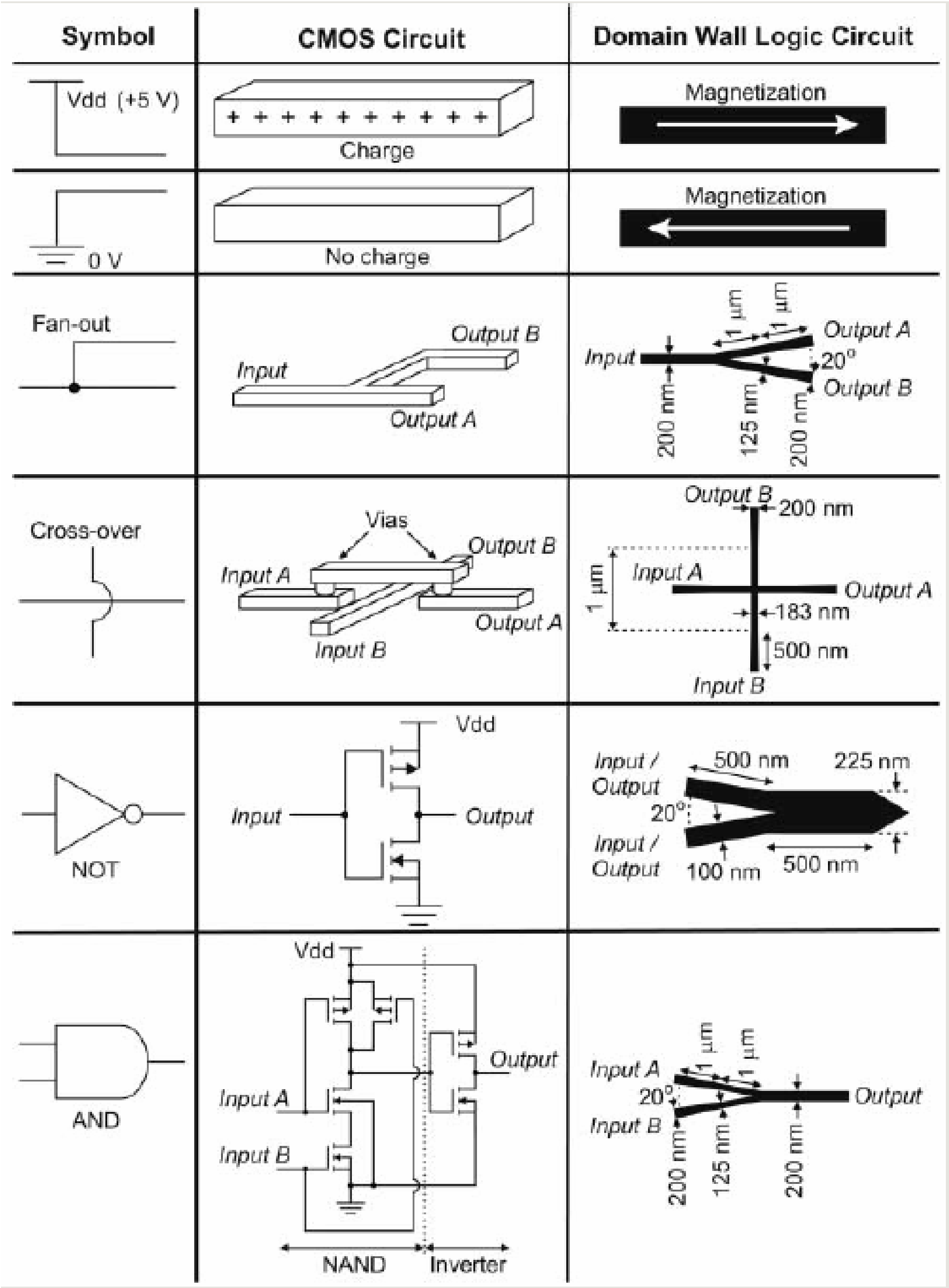
World-record fast SQUID Magnetometer

R. V. Chamberlin, L. Cooper, C. Tracy, N. Newman

- dc SQUID
  - Low noise
  - High speed
- Data Acquisition
  - High speed
    - 10^{-8} s start
  - Logarithmic spacing
    - 10^{4} s end

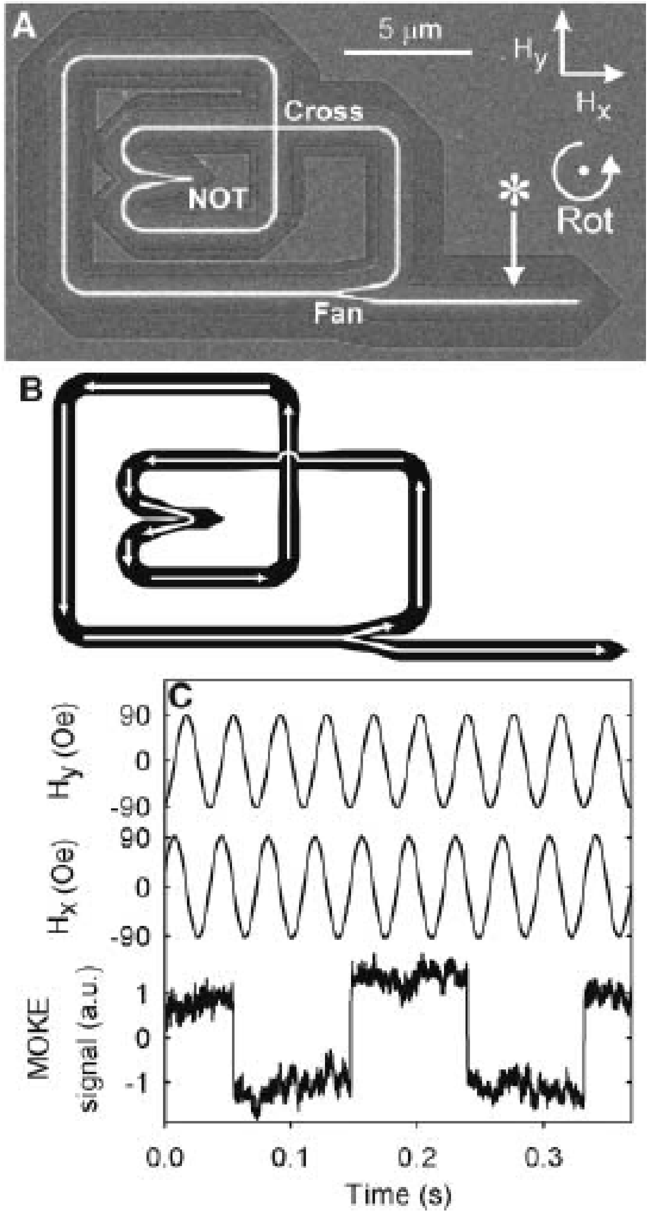






Domain-Wall Logic

R. P. Cowburn et al. *Science*
309, 1688 (2005)



Synthesis of dilute magnetic semiconductor materials

Nathan Newman, A Freeman, S Krishnamurthy, D Smith & M van Schilfgaarde

Approach

Synthesize semiconductors doped w/ transition-metals to create magnetic layers

Revolutionary concept

***Use spin of electron to transmit, manipulate and store information,**

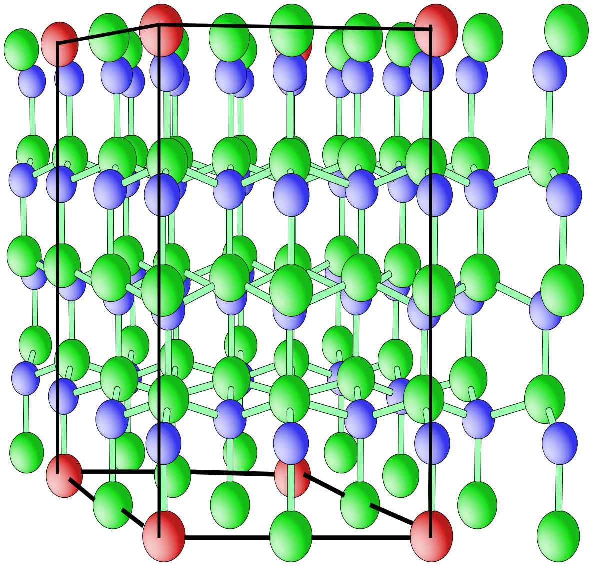
***Tremendous potential for reduction in speed, efficiency & functionality over current devices**

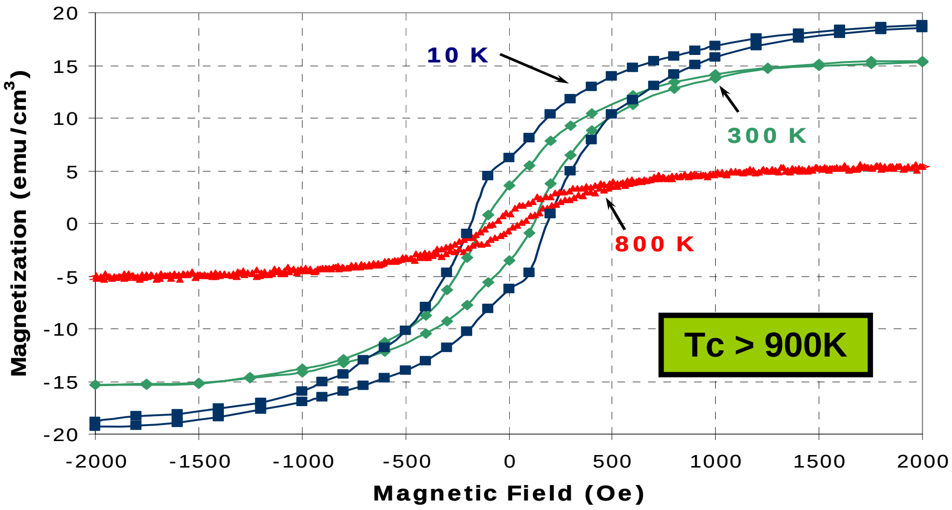
Room temperature Dilute Magnetic Semiconductor materials and devices

7% Cr - doped AlN: $T_c > 900$K , $M_s = 0.6\ \mu_B$/Cr

6.25 %

Mn or Cr





Synthesis of dilute magnetic semiconductor materials (cont.)

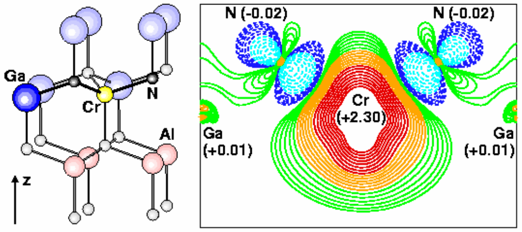
Program Objective

III-N semiconductors are ideal for spintronics

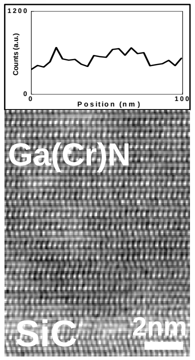
- **high T_c**
- **long spin mfp**
- **bandgap engineering of barrier**

Progress to-date

- **Ferromagnetic GaN & AlN w/ Tc>900K**
  - **microscopic proof Cr_{Ga} involved in magnetism**

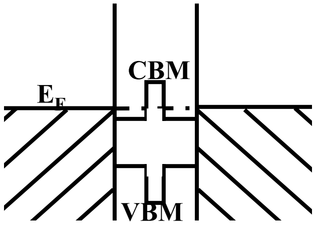


Geometry of energetically favored Cr in AlN/GaN heterostructure

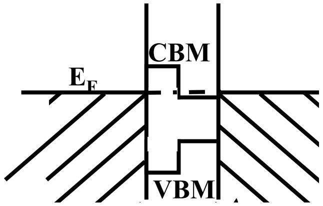


Å scale mapping of Cr distribution

High resolution TEM of GaCrN



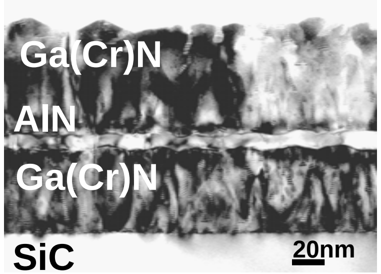
Minimize role of FM/III-N Interface (also using FM III-N electrodes)



Measure injection efficiency & transport through III-N layer

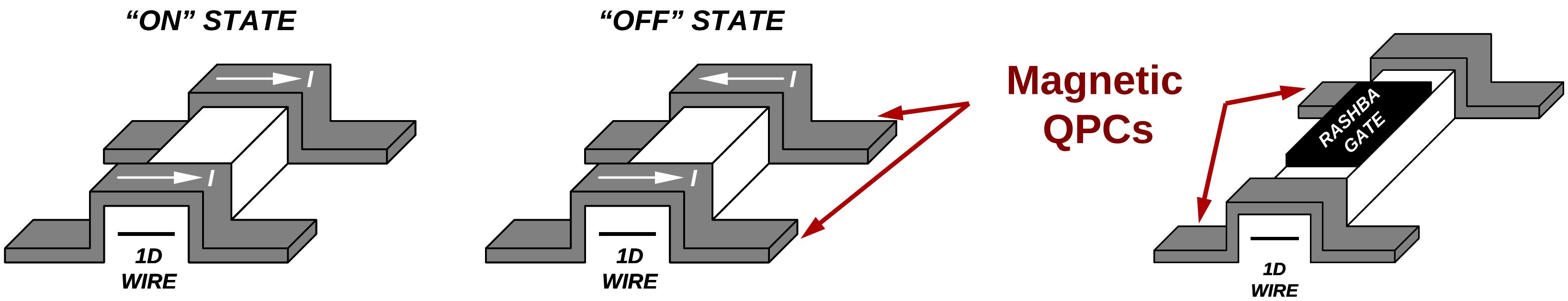
Plans

- **Fabricate magnetotunneling devices w/ bandgap-engineered barriers**
  - **Measure injection efficiency & mfp of spin-polarized electrons**
  - **Access potential for practical III-N MTJ SPINS devices**



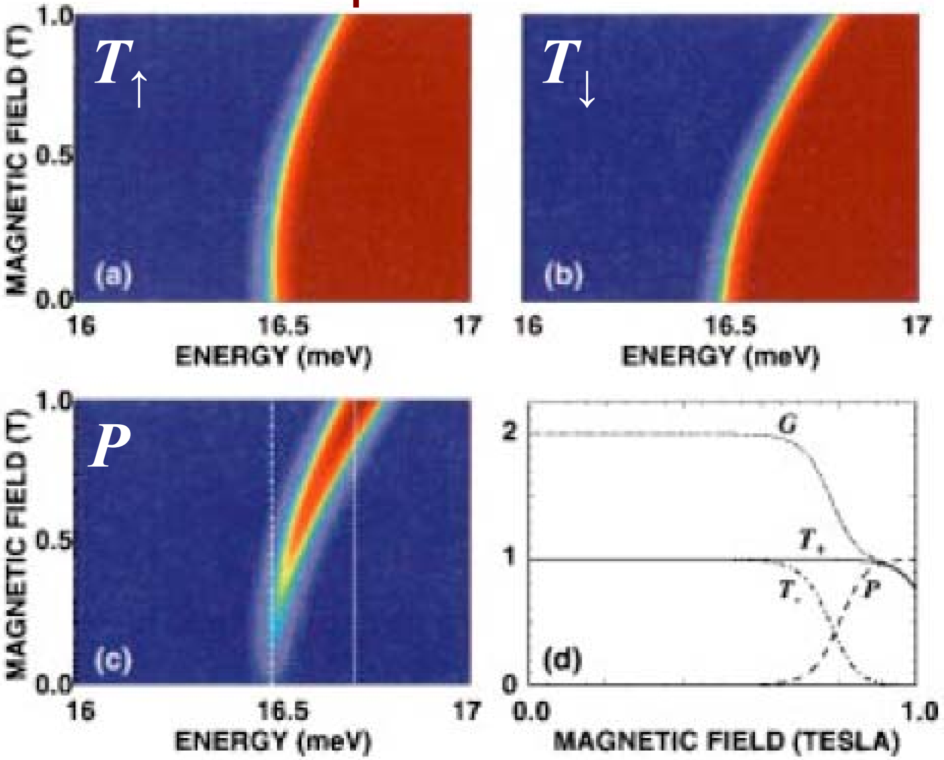
Fabrication of III-N Magneto-tunneling structures

1D Hybrid Spin-Valve/SpinFET: Operation



1D spin-valve

1D spinFET

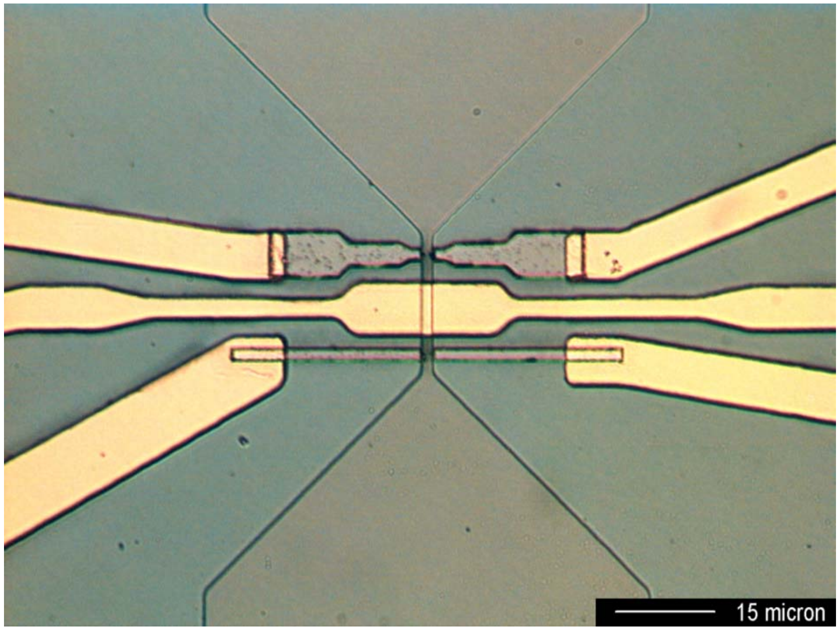


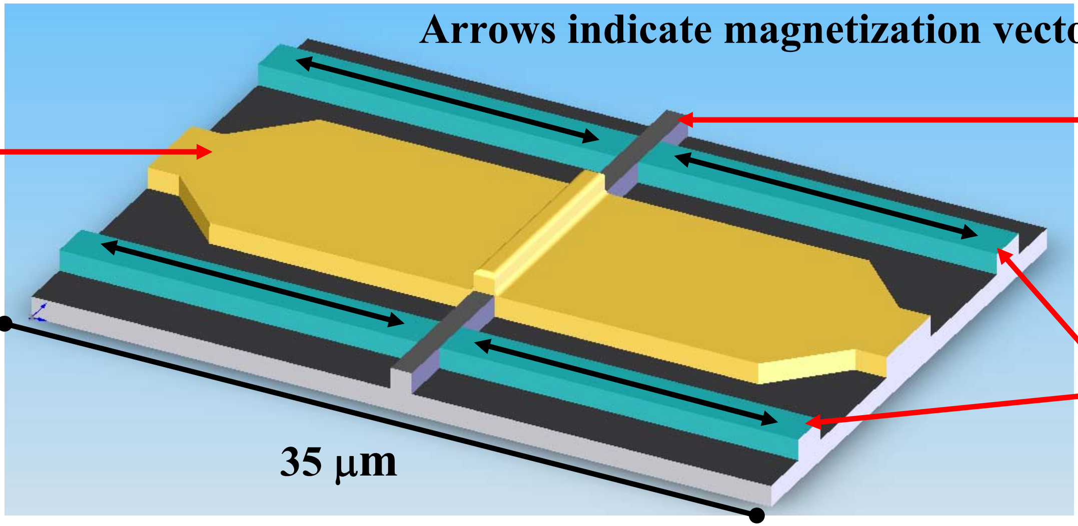
Gilbert et al. *Appl. Phys. Lett.* **77** 1050 (2000).

- "On" state is low resistance, "Off" state is high resistance
- Electrostatic potential and Zeeman Effect combine to act as a **spin filter**
- Spin-polarization of 100% predicted at 0.9 T
- Rashba gate can be added to form a three-terminal spinFET

1D Hybrid Spin-Valve/SpinFET: ASU Structure

- Ferromagnetic split-gates are magnetized parallel to the surface by an external magnetic field
  - Create magnetic field AND act as quantum point contact
- Non-magnetic Schottky gate patterned around wire
  - Manipulate the electric field to control the electron density and the Rashba effect





Arrows indicate magnetization vector

Non-Magnetic Schottky Gate

AlGaAs/GaAs Nanowire

Co Split-Gates

AlGaAs/GaAs heterostucture courtesy of Sandia National Laboratory

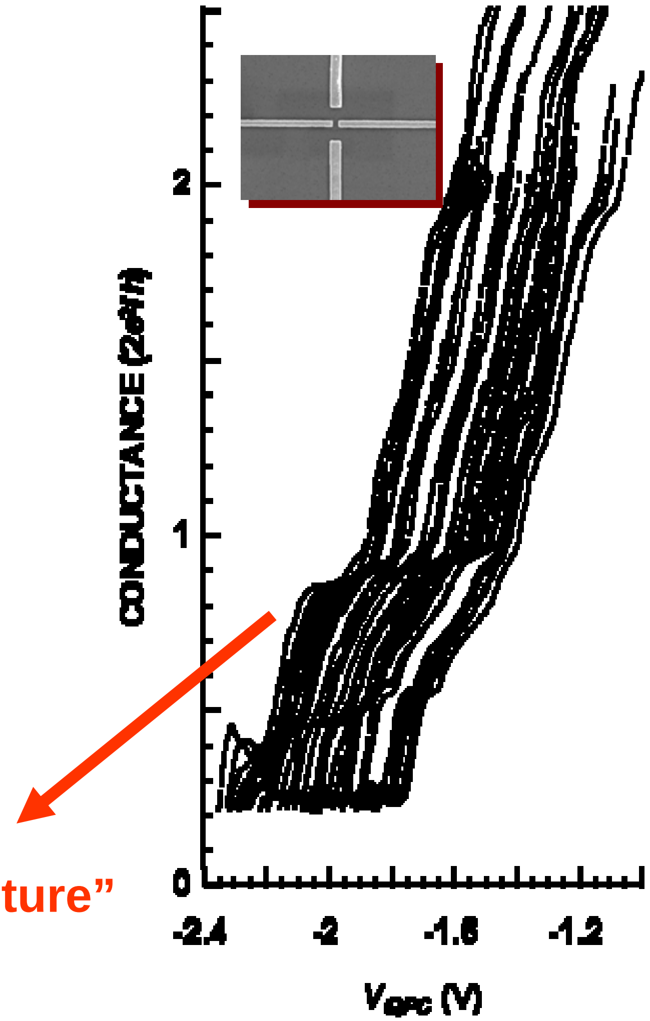
Simulation of Spin Filtering Effects in Quantum Point Contacts,
R. Akis, D. K. Ferry, Department of Electrical Engineering, ASU

Recently, there has been much interest in the **0.7 structure** that has been observed in numerous experiments on quantum point contacts (QPCs) and wires.

We have been performing simulations of quantum point contacts that incorporate density functional theory to see if we can determine what is leading to these effects.

Our results indicate that spin-filtering effects play a prominent role in the observed features.

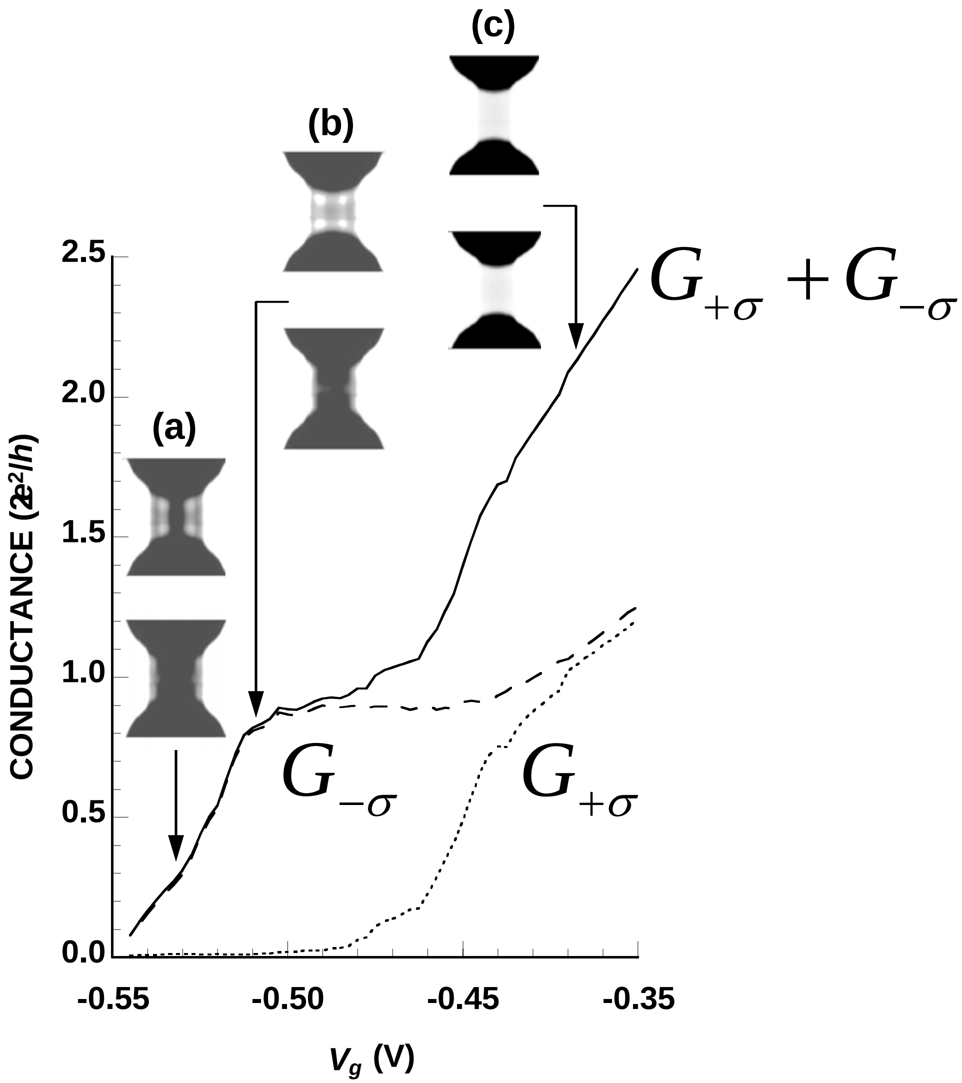
ASU QPC Experiment



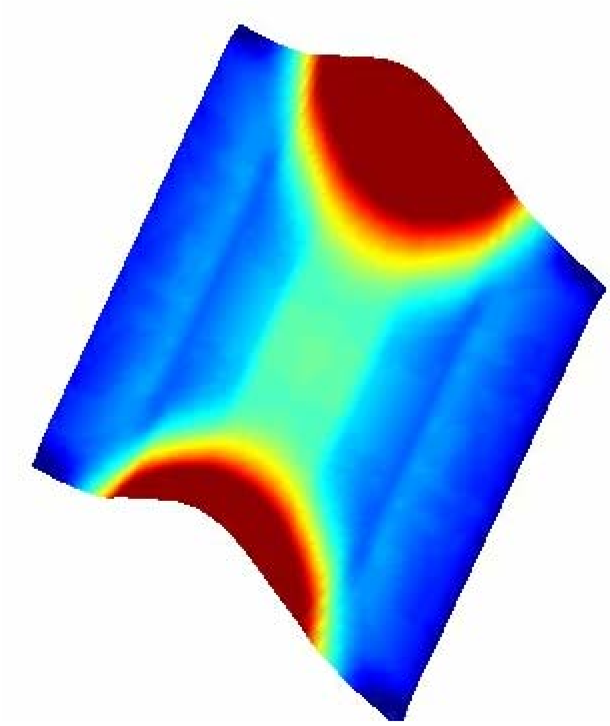
"0.7 structure"

A. Shailos, A. Ashok, J. P. Bird, R. Akis, D. K. Ferry, S. M. Goodnick, M. P. Lilly, J. L. Reno & J. A. Simmons, Journal of Physics, Condensed Matter, 18, 1715-1724 (2006).

Theory (spin down and up barriers shown)



3D plot of the density dependent spin-up potential barrier that forms at (a)



Barriers form in QPC region that depend on both spin and density. Spin up transport fully blocked at 0.7 feature - position (b) in figure