Tunneling Magnetoresistance: Physics and Applications for Magnetic Random Access Memory and Magnetic Sensors

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- Magnetic Tunneling Junctions
  - Very high Magnetoresistance – up to ~50% at RT
  - Highly polarized current – >50% at 0.25 K
- Magnetic Random Access Memory
  - Attractive: Non-volatile, dense and high-speed
- Tunnel Junctions for Field Sensors (Recording Heads)
  - Voltage dependence of MR
  - Noise

Supported in part by the United States
Defense Advanced Research Project Agency
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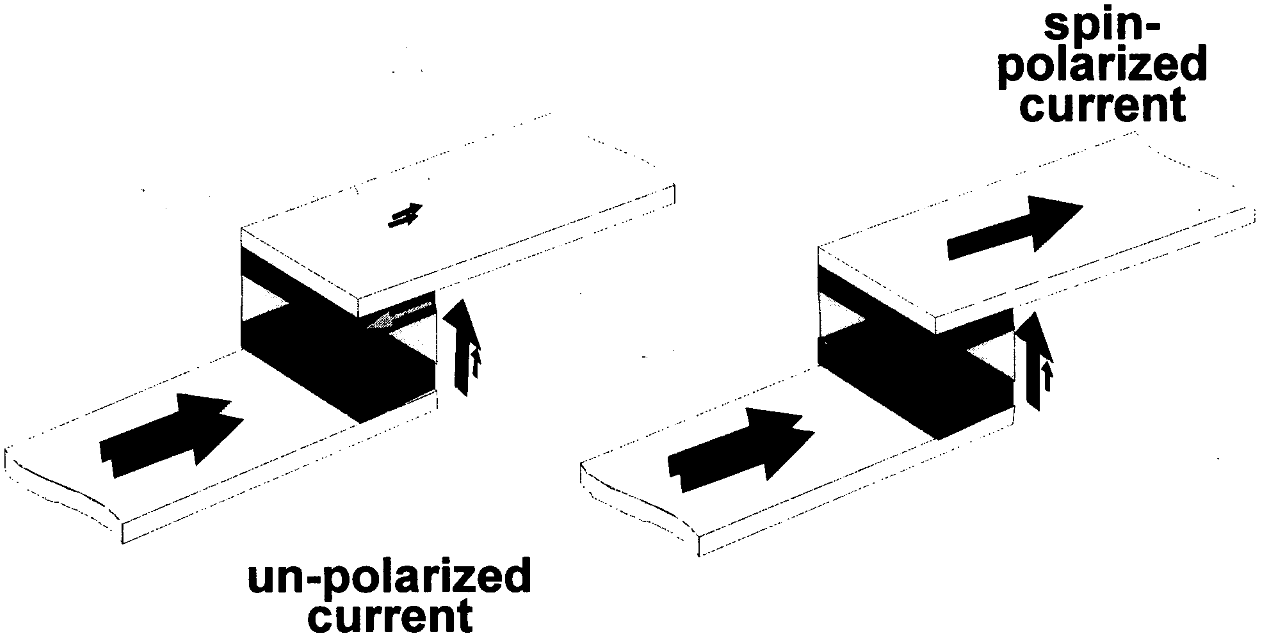
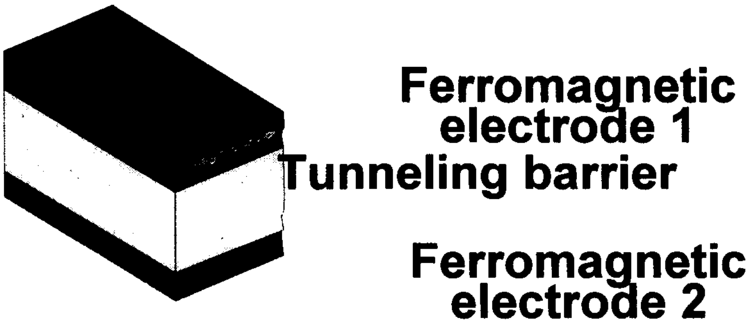
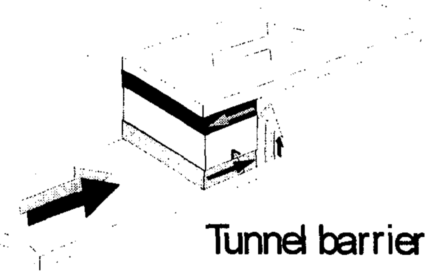
Magnetic Tunnel Junction





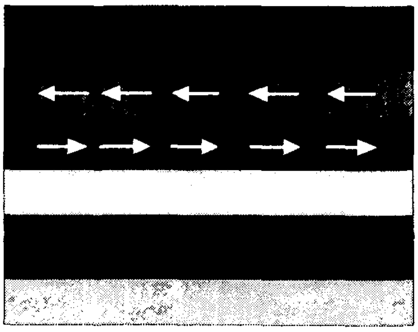
first ferromagnetic electrode acts as spin filter
second FM layer acts as spin detector

Magnetic Tunnel Junctions: History



1975: Juliere - first demonstration
  Fe/Ge/Co, $\Delta R/R \sim 14\%$ at 4.2 K
1982: Maekawa and Gafvert
  Ni/NiO/Ni, Fe, Co, $\Delta R/R \sim 0.4\text{-}2\%$ at 4.2 K
1990~1993: Miyazaki et al.
  NiFe/Al-Al_2O_3/Co, $\Delta R/R \sim 2.7\%$ at RT
1995: Miyazaki et al. - first large RT MR
  Fe/Al-Al_2O_3/Co, $\Delta R/R \sim 18\%$ at RT
1995: Moodera et al. - large RT MR
  Co-Fe/Al-Al_2O_3/Co, $\Delta R/R \sim 10\%$ at RT
1996: Parkin et al. - large RT MR
  >25% in shadow masked and patterned junctions
1998: Parkin et al. - extraordinarily large RT MR
  >35% in sub-micron junctions
  >47% in shadow masked junctions
  wide range of specific resistance ~20 to $>10^9$ $\Omega(\mu m)^2$
  high thermal stability (>300 °C)

Structure of Exchange-Biased MTJ device



Top lead

Tunnel barrier

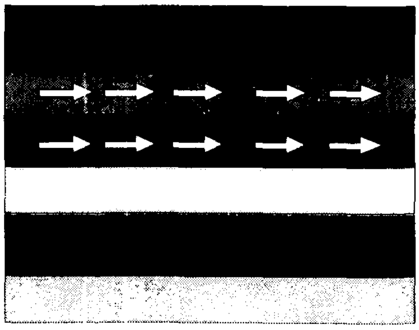
Free ferromagnet

Pinned

Antiferromagnet

Bottom electrode

Substrate



Ti, Ti/Pd or Ta/ Pt

CoFe/NiFe

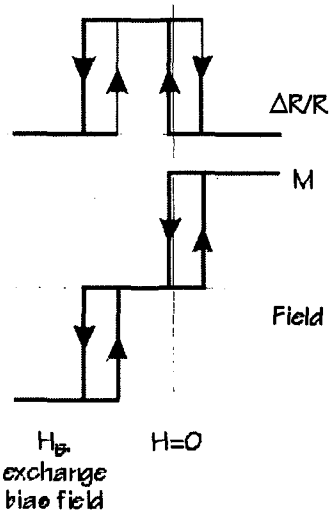
Al_2O_3

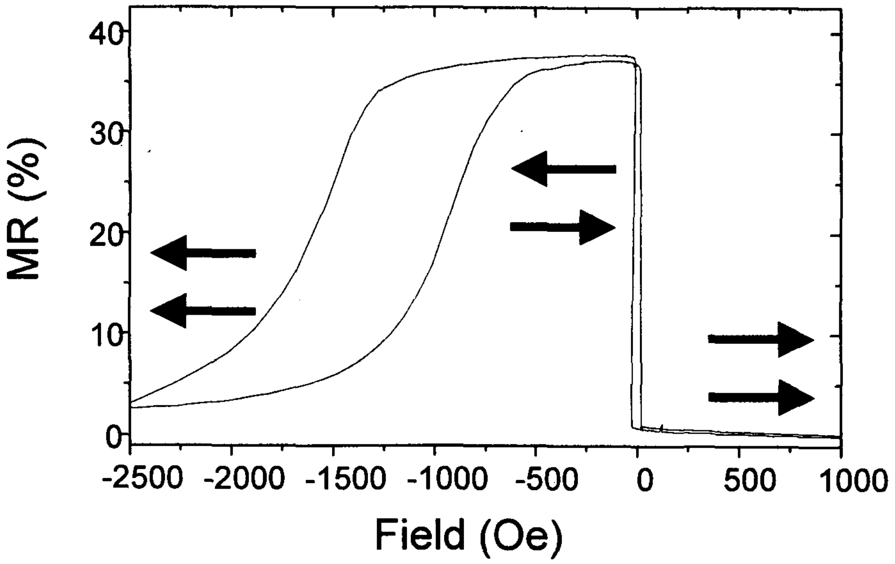
CoFe or NiFe/CoFe

Antiferromagnet

Underlayer

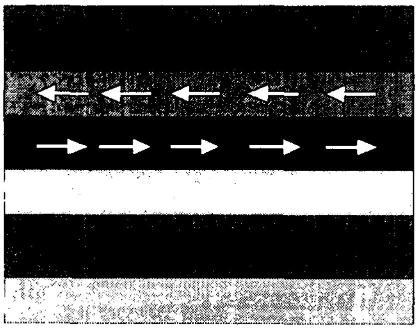
Si, quartz, N58





MR ~36%; Switching field of free layer ~ 20 Oe

Structure of Exchange-Biased MTJ device



Top lead

Free ferromagnet

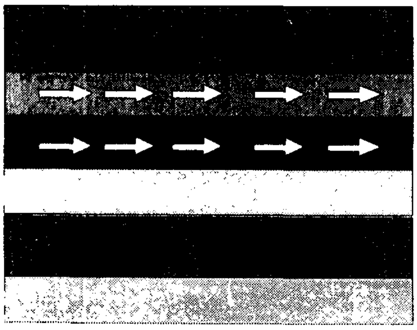
Tunnel barrier

Pinned

Antiferromagnet

Bottom electrode

Substrate



Ti, Ti/Pd or Ta/ Pt

CoFe/NiFe

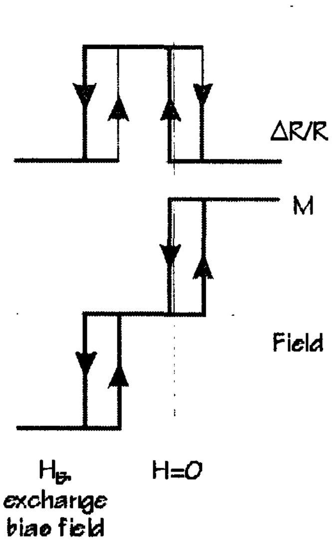
Al_2O_3

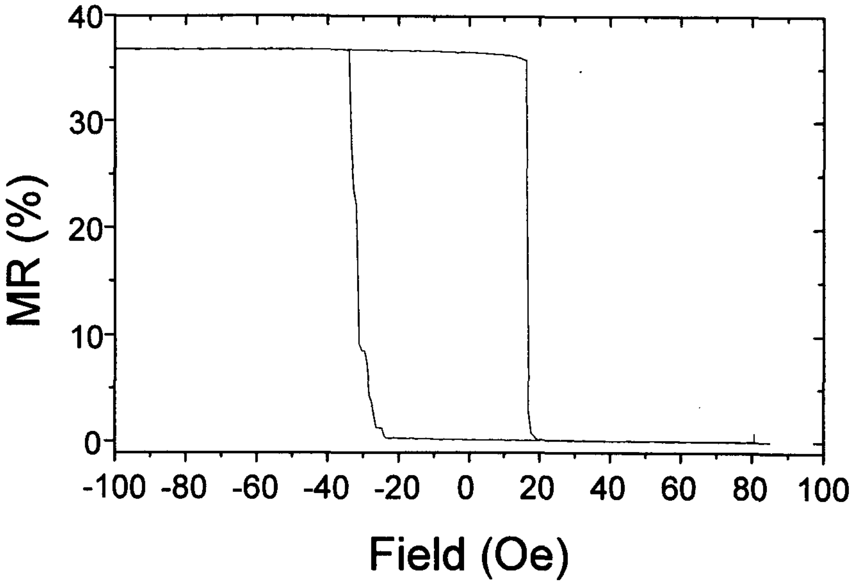
CoFe or NiFe/CoFe

Antiferromagnet

underlayer

Si, quartz, N58





Typical MR vs field hysteresis loop for shadow masked junction.

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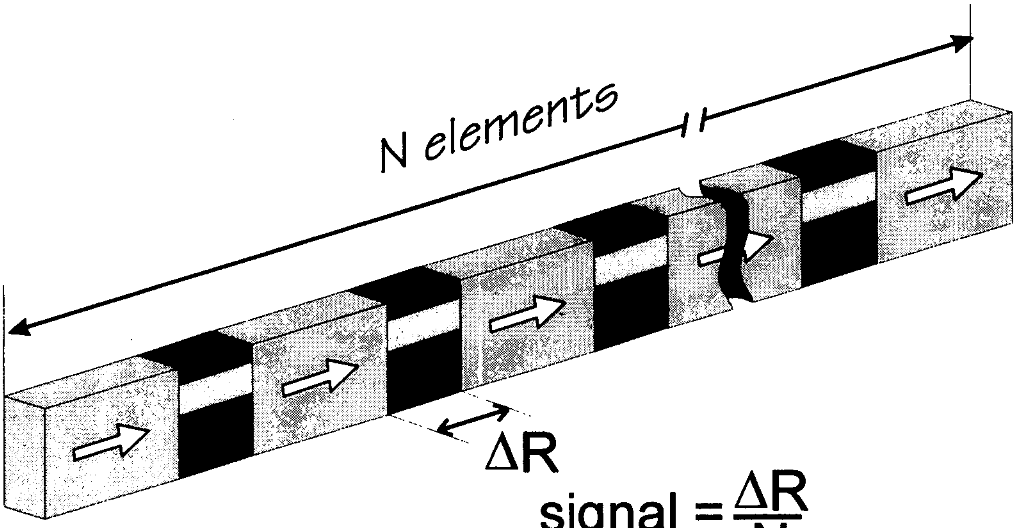
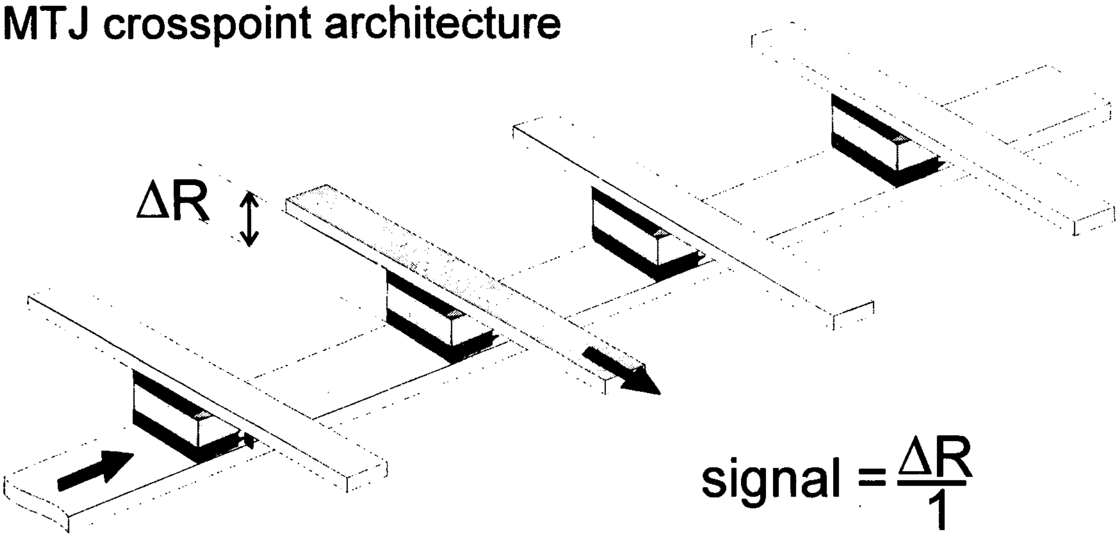
Series vs Crosspoint Architecture

AMR, GMR series architecture



$$\text{signal} = \frac{\Delta R}{N}$$

MTJ crosspoint architecture



$$\text{signal} = \frac{\Delta R}{1}$$

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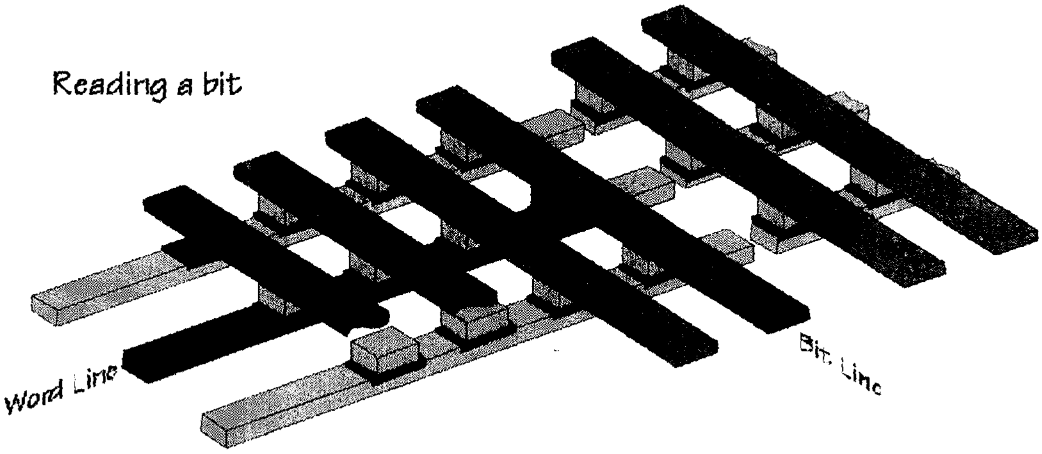
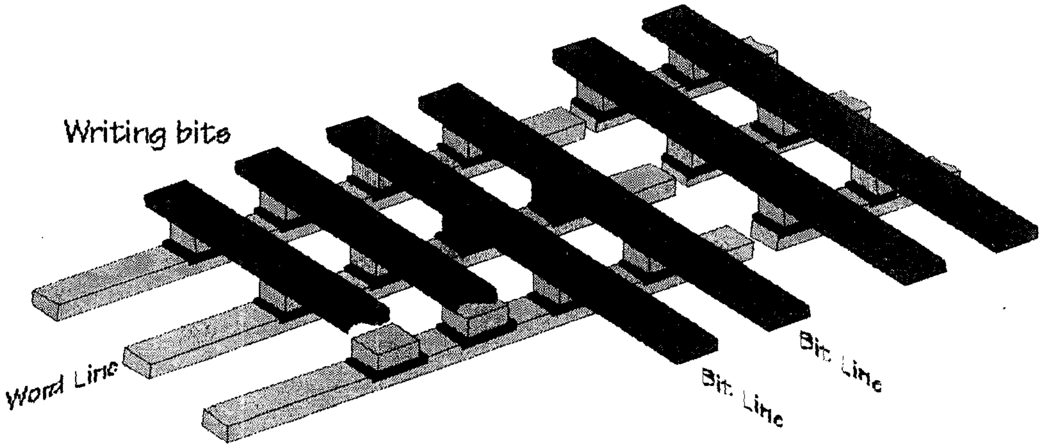
Magnetic Random Access Memory



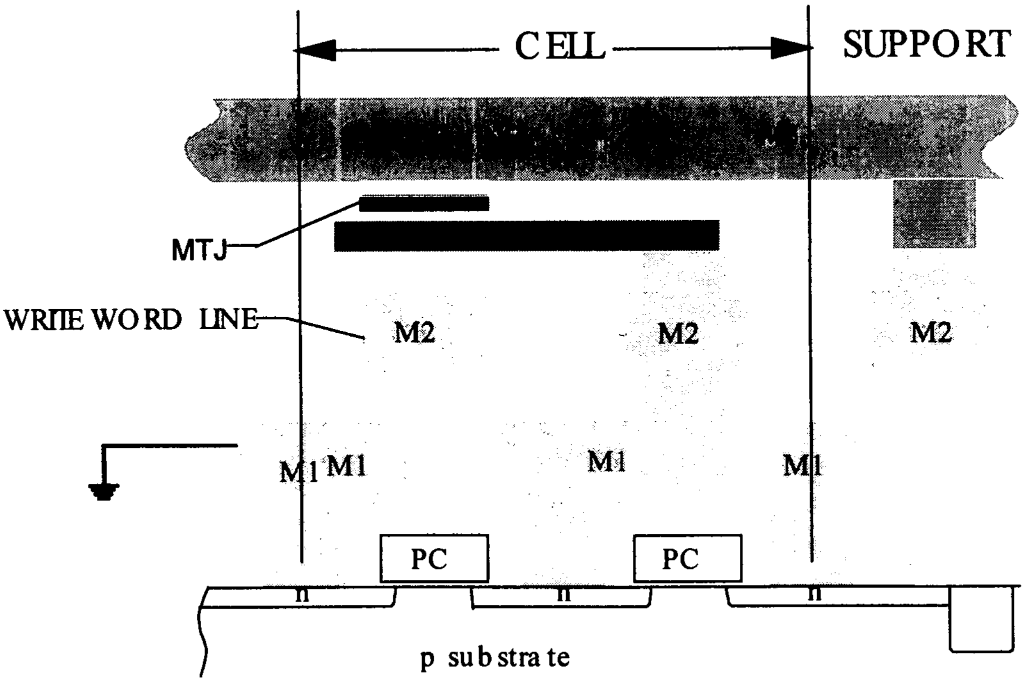


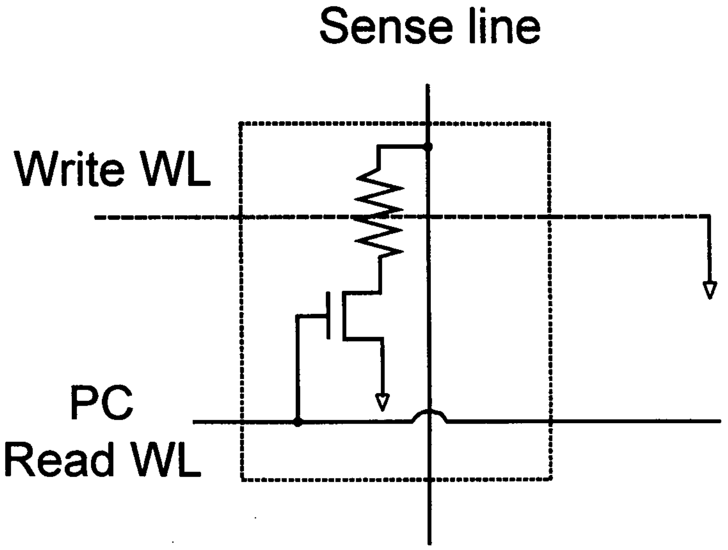
Storage cell is a Magnetic Tunnel Junction (MTJ)

Optimally dense Cross-point architecture

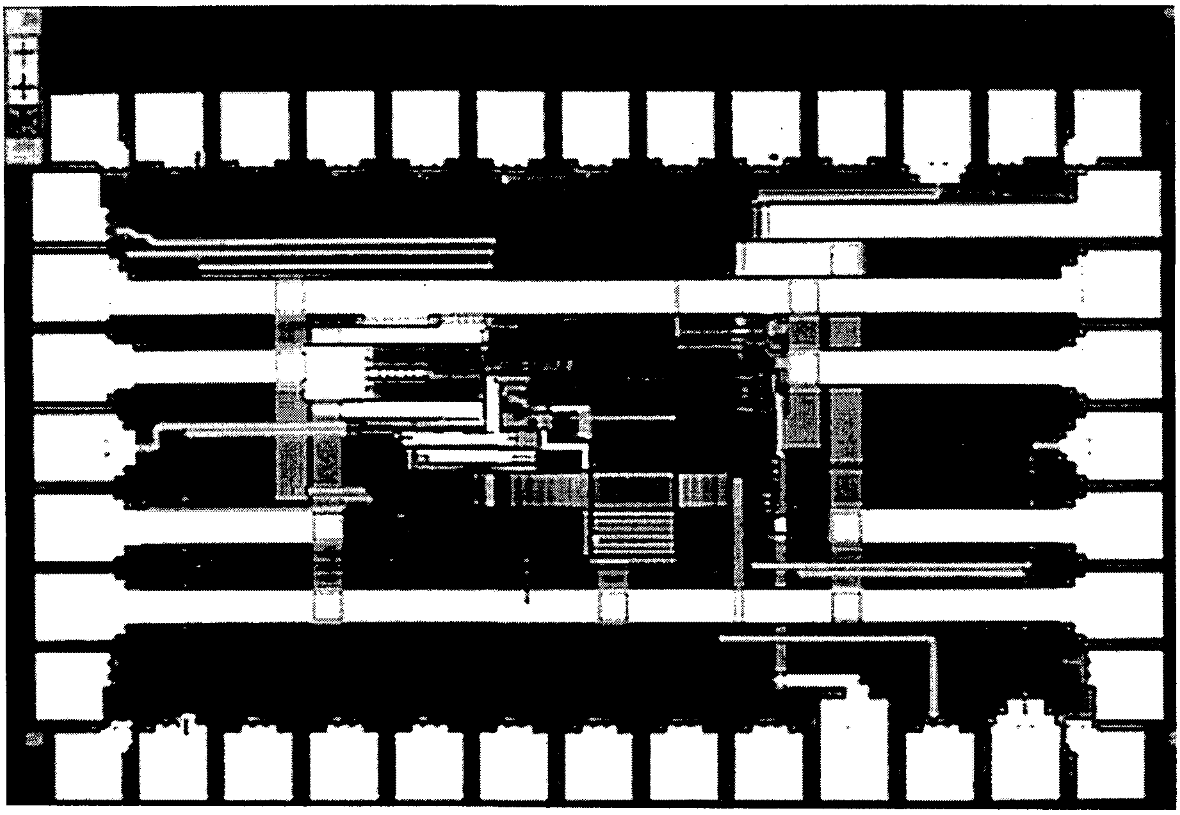
- diode enables reading of any cell

MTJ Cell with FET switch:
Grounded Source Cell





IBM 1 Kbit MTJ MRAM Chip



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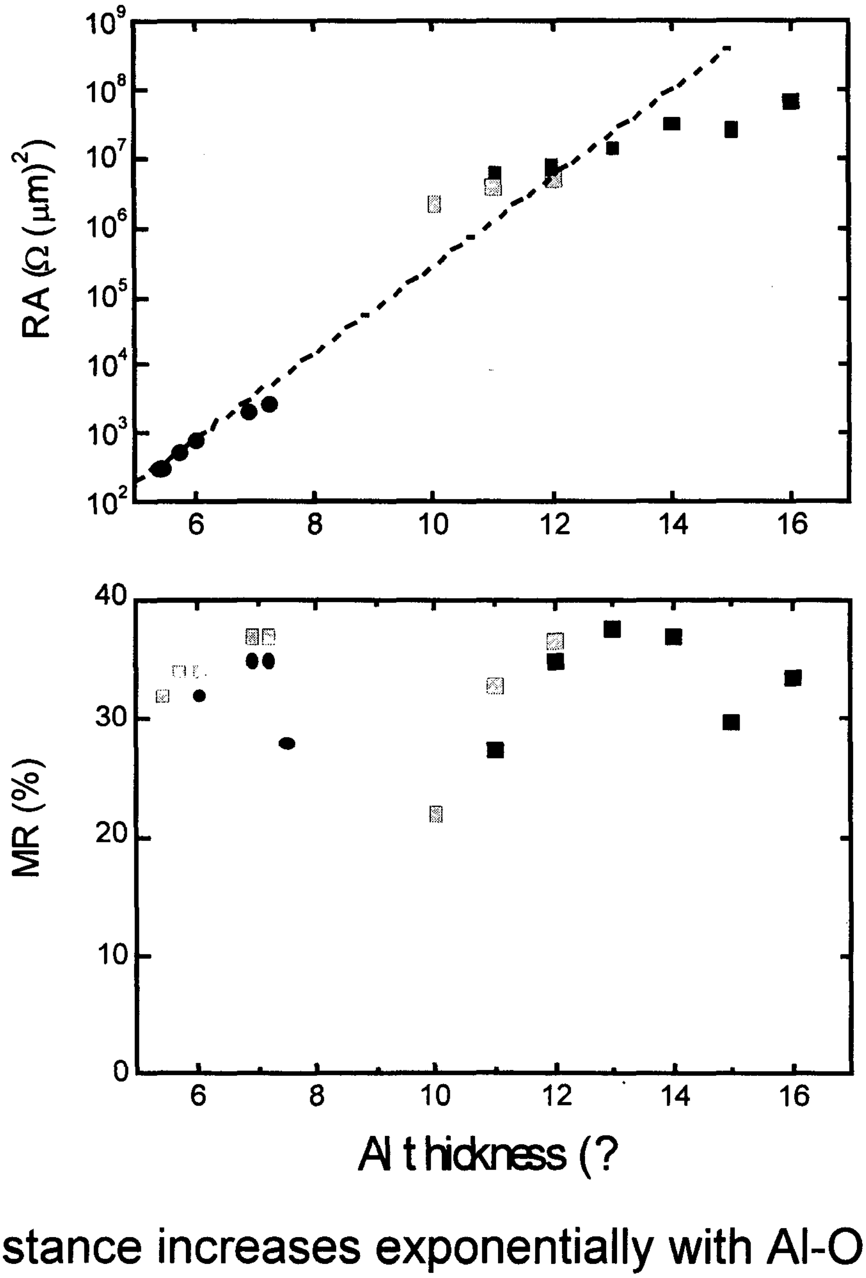
Comparison of Memory Technologies

	SRAM	DRAM (non-embedded)	FLASH	MTJ-MRAM (1st gen.)	FRAM
Cell size (Min. Lith squares – front end)	130 ·	8 ·	15 ·	35 ·	30 ·
Retention time	∞ (with power)	500 ms	10 yr	10 yr	10 yr
Read time	2 ns	60 ns	10 ns	3 ns	60 ns (8 ns burst)
Program time	2 ns	60 ns	10,000 ns (erase 100 ms)	3 ns	60 ns
Endurance	∞ (100 khr)	∞ (100 khr)	10^5 writes	∞	$>10^{12}$ reads/writes
Read energy /bit (pJ) (0.5 μm tech.)	13	5.3 + restore	1	3	>DRAM
Write energy /bit (pJ) (0.5 μm tech.)	6.6	11	0.01(tunneling) 20,000 (hot electron) + erase	33	>DRAM

Dependence of MR and R on Al thickness



- Resistance increases exponentially with Al-O thickness
- MR independent of barrier thickness
  - assuming barrier completely oxidized
  - no oxidation of underlying ferromagnetic electrode

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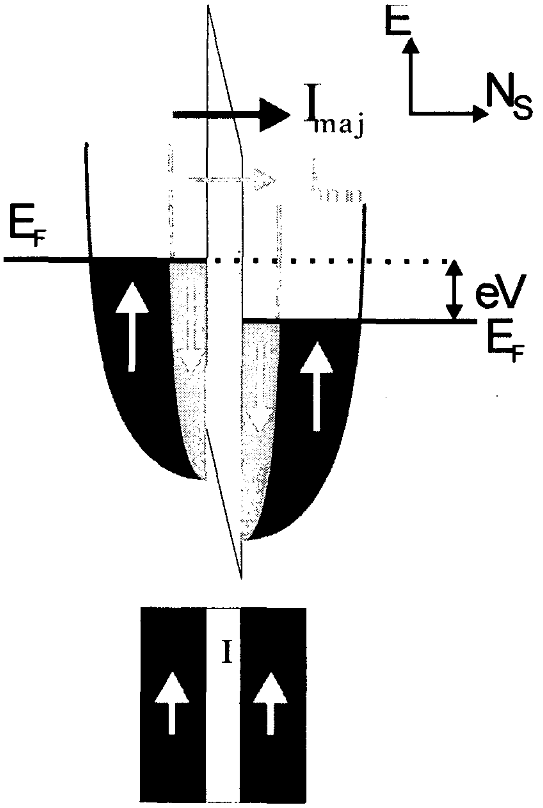
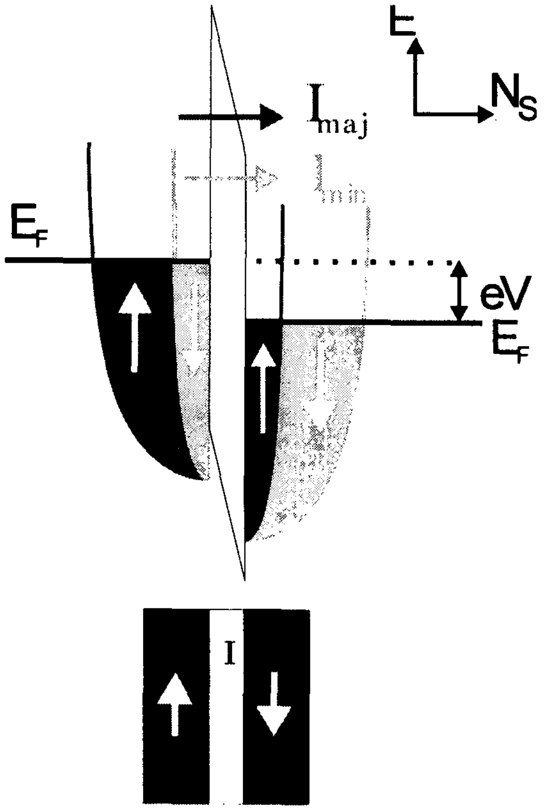
Spin Polarized Electron Tunneling: FM-I-FM



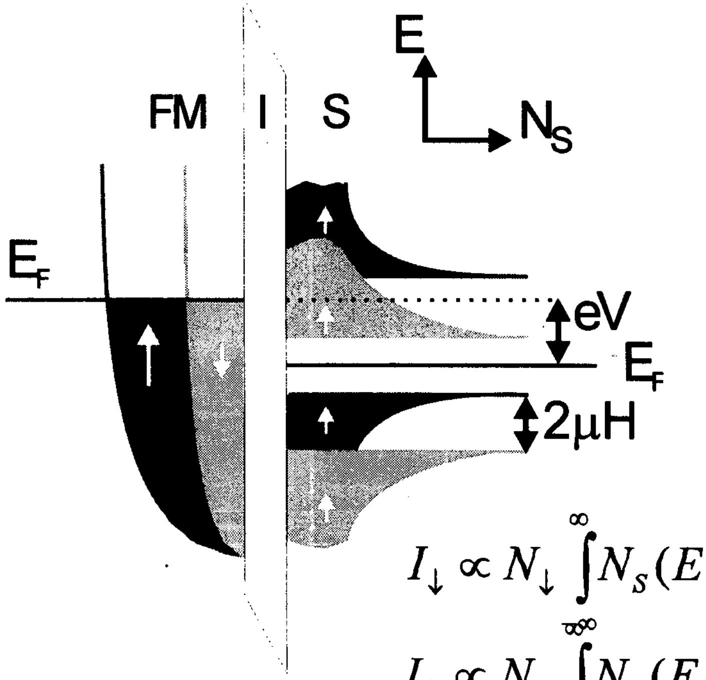


$$I_P \approx N_\uparrow^1 N_\uparrow^2 + N_\downarrow^1 N_\downarrow^2 \qquad I_{AP} \approx N_\uparrow^1 N_\downarrow^2 + N_\downarrow^1 N_\uparrow^2$$

$$MR = \frac{R_{AP} - R_P}{R_P} = \frac{2P_1P_2}{1 - P_1P_2} \text{ with } P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

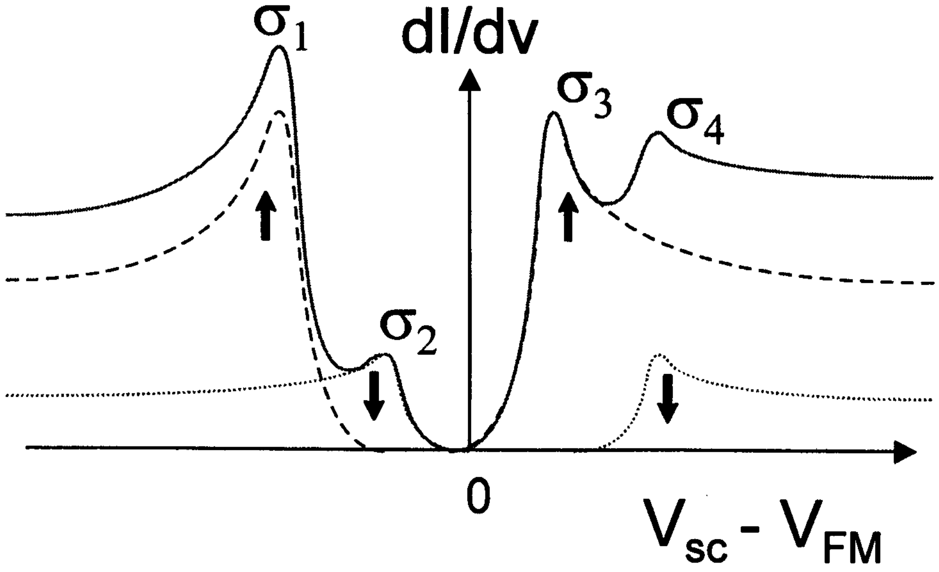
Spin Polarized Electron Tunneling: FM-I-S

(Meservey and Tedrow 1971)

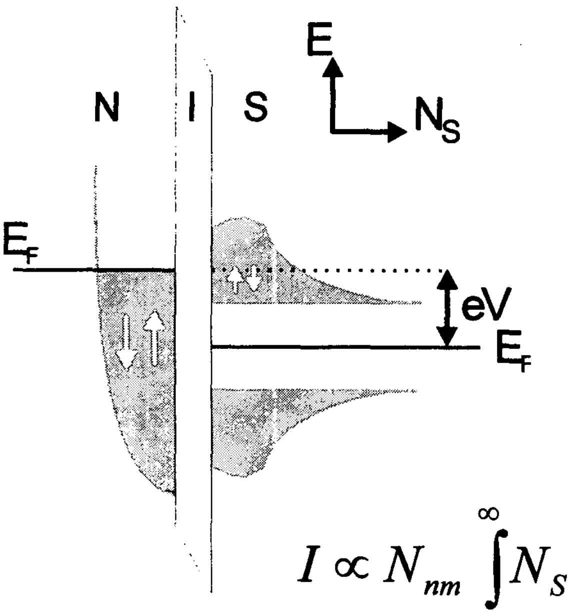


$$I_\downarrow \propto N_\downarrow \int_{-\infty}^{\infty} N_S(E-\mu H)\cdot[f(E+V)-f(E)]dE$$

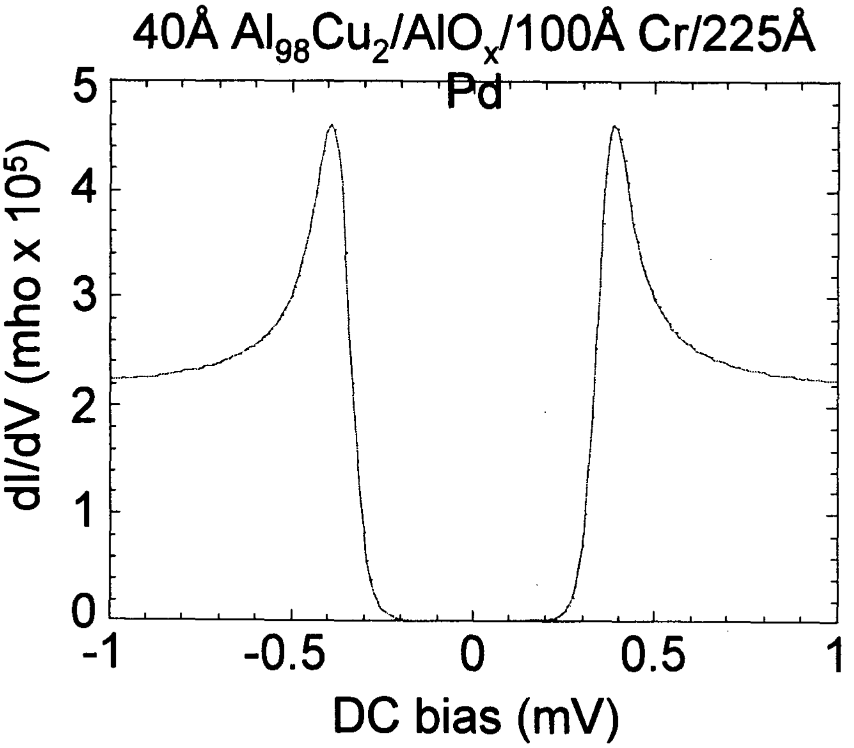
$$I_\uparrow \propto N_\uparrow \int_{-\infty}^{\infty} N_S(E+\mu H)\cdot[f(E+V)-f(E)]dE$$



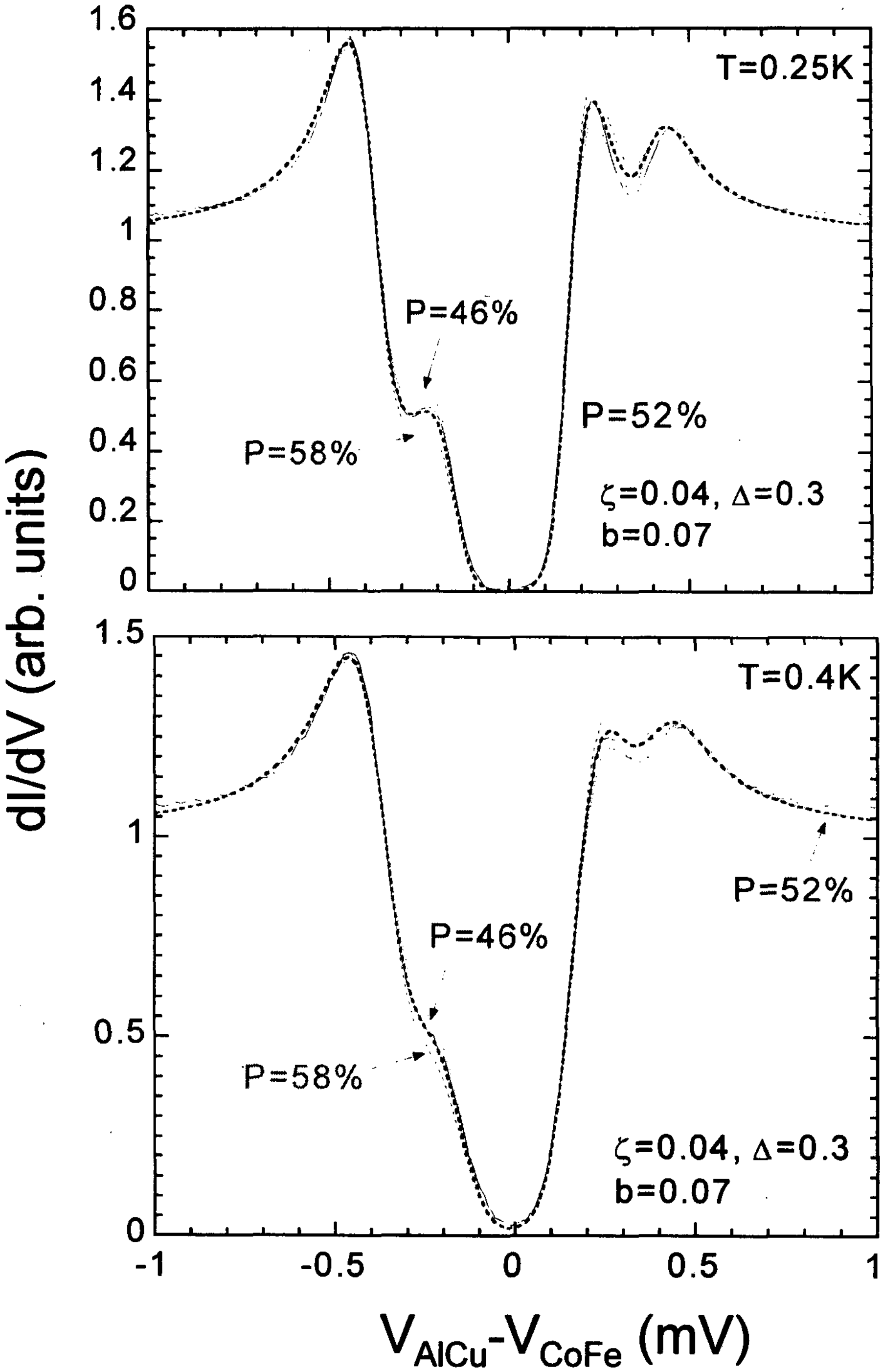
Electron Tunneling: N-I-S



$$I \propto N_{nm} \int_{-\infty}^{\infty} N_S(E) \cdot [f(E+V) - f(E)]dE$$



Determination of Spin Polarization from Dynamic Conductance Curves for $Al_{98}Cu_2/Al_2O_3/Co_{84}Fe_{16}$



Spin Polarization Values

FM	P_{fi} %	P_u %	$P_{l,f}$%	$P_{l,u}$ %	M υ_B/atom (4.2K)
Co	42	52	32	35	1.65
$Co_{84}Fe_{16}$	52	62			1.99
$Co_{60}Fe_{40}$	50	61			2.25
$Co_{50}Fe_{50}$	50	60		55	2.23
$Co_{40}Fe_{60}$	51	61			2.43
Fe	45	55	35, 40*	44	2.15
$Ni_{25}Fe_{75\backslash}$			40, 42	47	2.11
$Ni_{40}Fe_{60}$	55	65		53	1.8
$Ni_{60}Fe_{40}$	53	64			1.46
$Ni_{81}Fe_{19}$	45	57			0.94
$Ni_{90}Fe_{10}$	36	47			0.81
$Ni_{95}Fe_{5}$	34	44			0.70
Ni	31	40**		29	0.59

MR= $2P_1P_2/(1-P_1P_2)$:

- maximum MR observed at 4.2K ~ 70%: corresponds to $P_1=P_2$~50%
- Ideally $P_1=P_2$=55% gives MR~87%
  - MTJ: FM/Al_2O_3/FM: depends on P_1 and P_2
  - SIF: Al/Al_2O_3/FM: measure P_2
    - FM /Al_2O_3/Al: typically shorted
- Interface influences polarization value in some cases
  - Ni and Ni alloys particularly sensitive

Dependence of Spin Polarization on Magnetic Moment

FM	Spin Polarization (%)	Moment (μ_B) 1000Å thick films
Fe	55	2.15
Co	52	1.65
Ni	35*	0.6
$Co_{40}Fe_{60}$	61	2.43
$Co_{50}Fe_{50}$	60	2.23
$Co_{60}Fe_{40}$	61	2.25
$Co_{84}Fe_{16}$	62	1.99
$Ni_{40}Fe_{60}$	64.5	1360 emu/cm^3
$Ni_{60}Fe_{40}$	63.8	1055 emu/cm^3
$Ni_{81}Fe_{19}$	57	807 emu/cm^3

* Ni polarization decays with time

Polarization weakly dependent on M

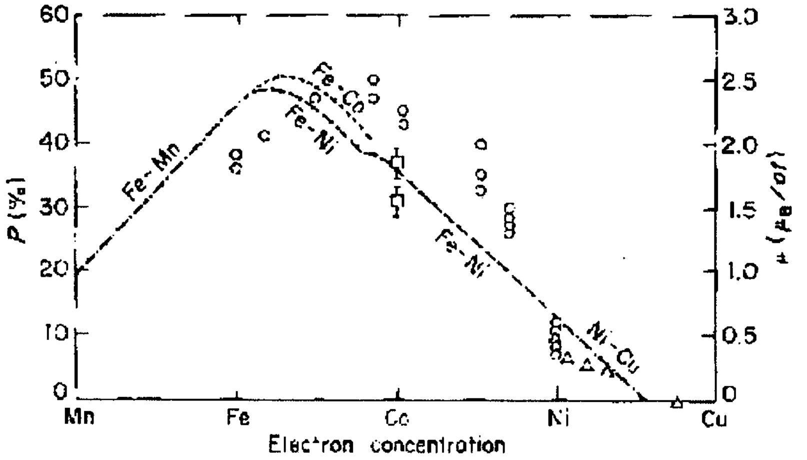
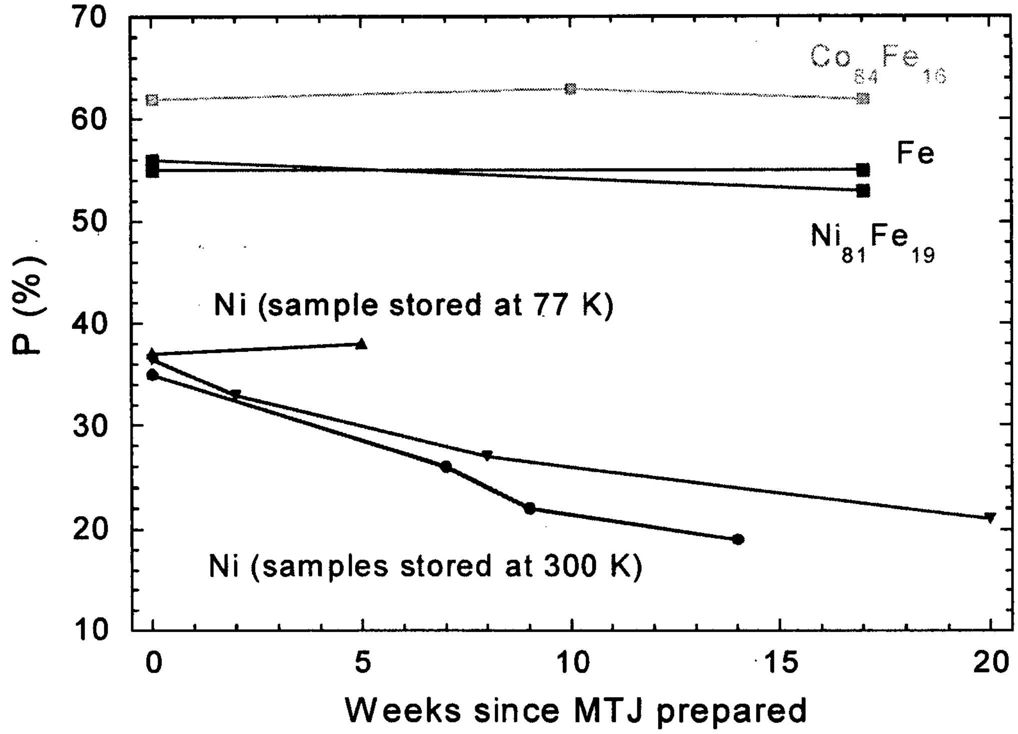


Fig. 8.9. Survey of spin polarization determinations by electron tunneling among elements and alloys of the 3d transition series. (After Meservey, 1978.)

Literature:

$P \propto M$

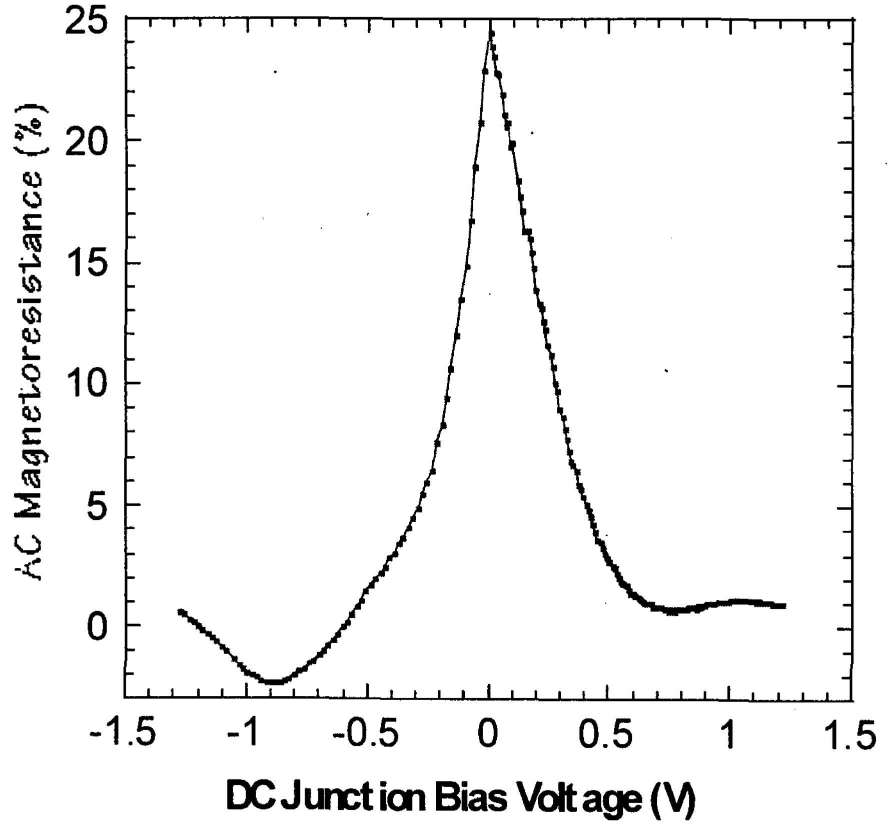
Temporal Decay of Spin Polarization
(uncorrected data)



- Spin polarization of Ni electrode decays with time
  - No decay for samples stored at 77 K
  - Most likely due to oxidation of Ni
  - Probable explanation for widely varying values of Ni polarization in literature

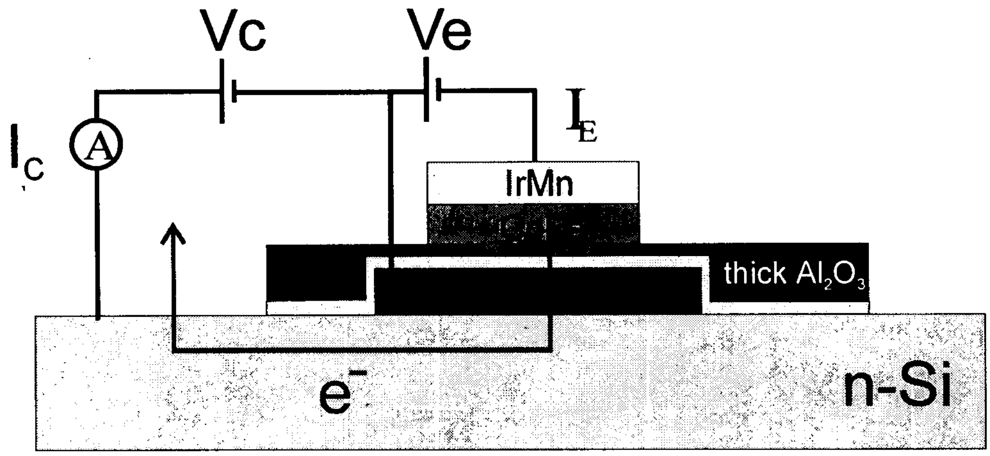
Oscillatory variation of MR with Bias Voltage

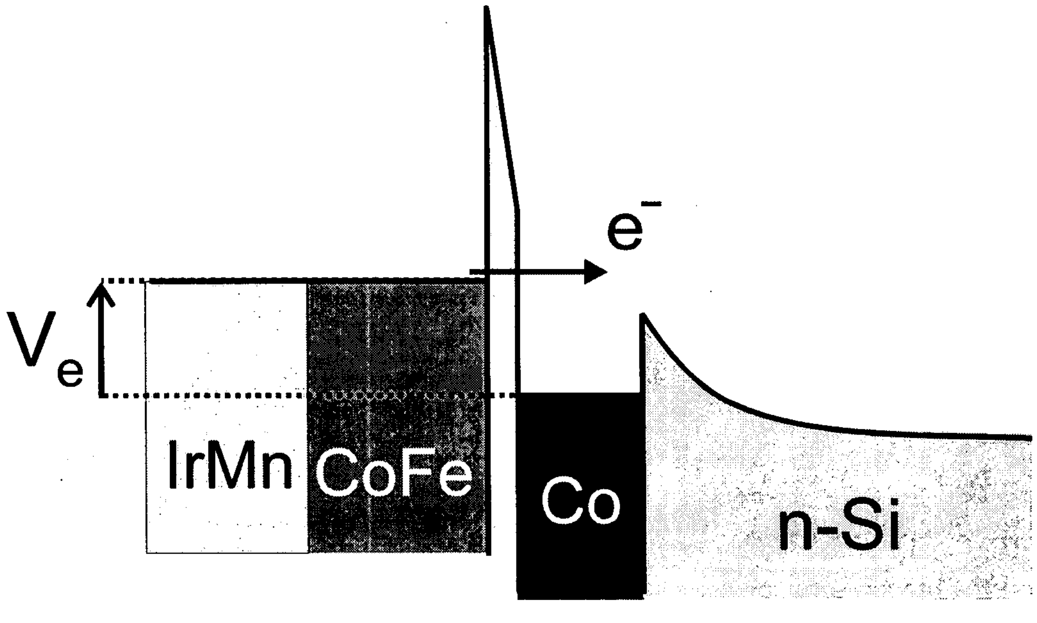
Si/ 70Å Pd/100ÅCo/20Å Al_2O_3 / 300NiFe



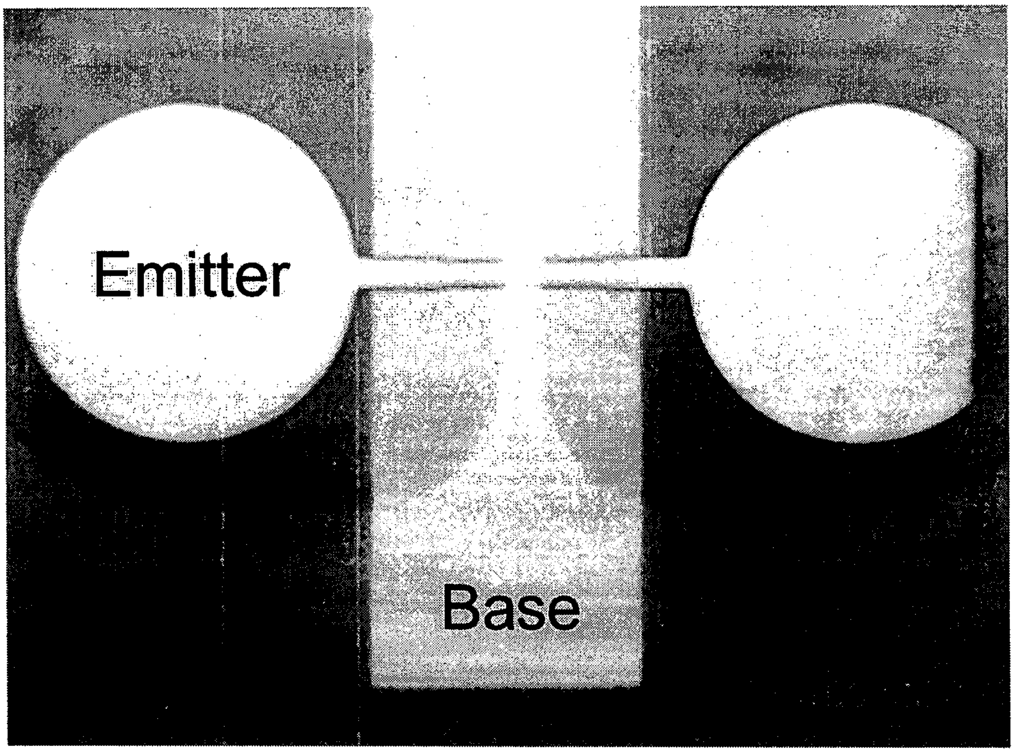
- Magneto-conductance determined from ac conductance vs dc bias voltage curves for parallel and anti-parallel alignment of ferromagnetic layers
- MR oscillates through zero MR for negative bias voltage
- Weak MR oscillation for positive bias voltage

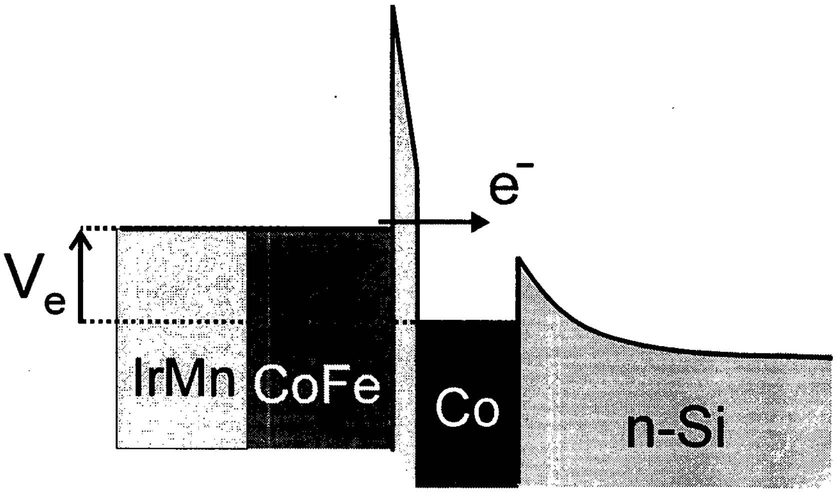
Spin Valve Transistor (SVT): common base operation





Spin Valve Transistor with Tunnel Injector Fabricated using Metal Shadow Masks





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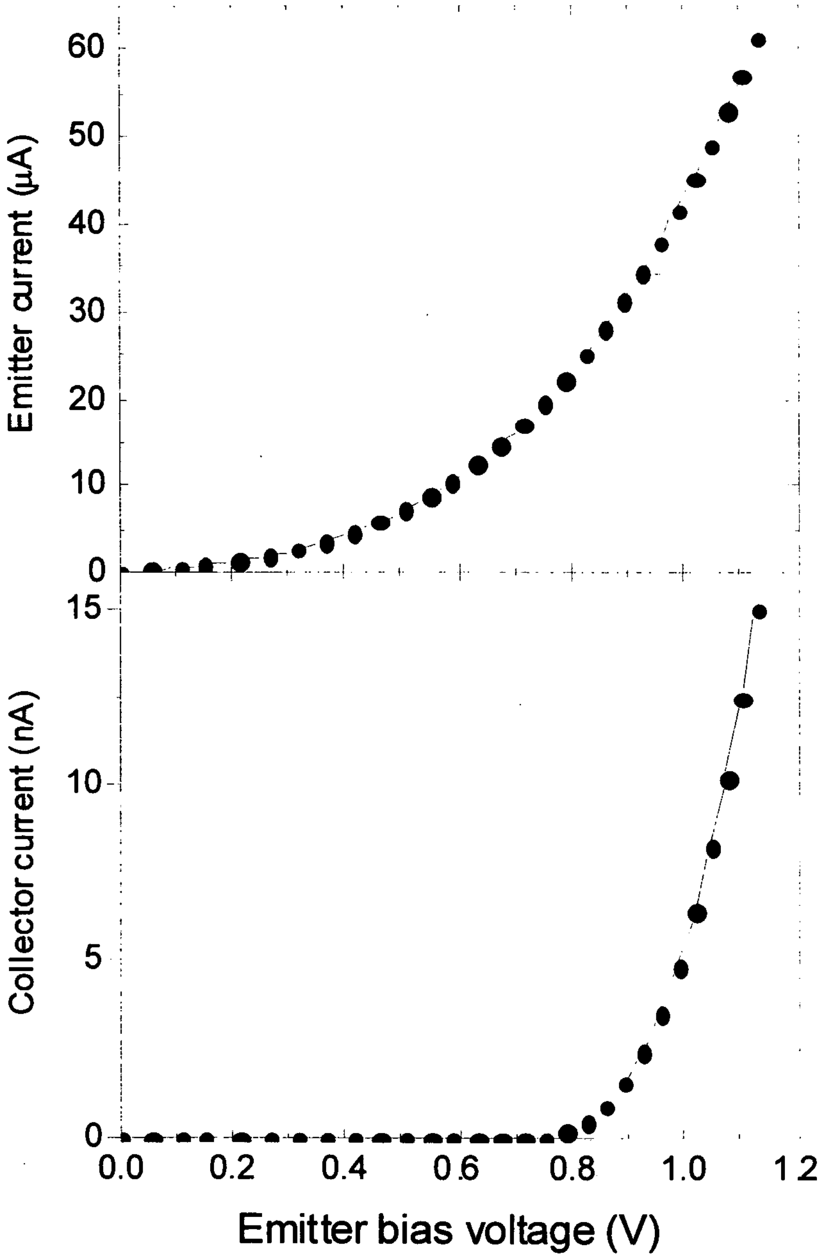
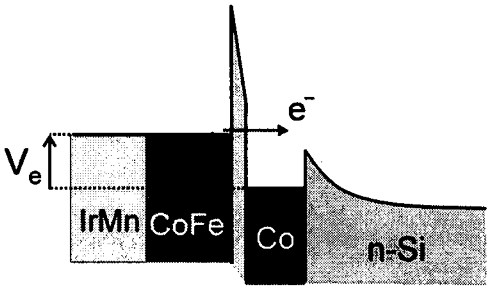
Emitter and collector current vs MTJ bias

Si/100ÅNiFe/18ÅAl-oxidized/CoFe/IrMn



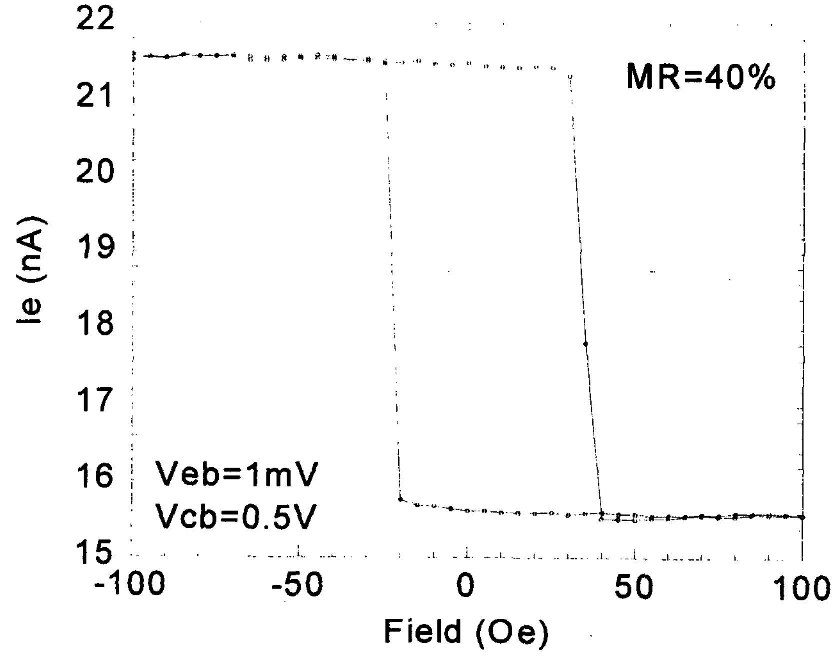
Emitter current
vs emitter bias
V: Typical
IV characteristic
of MTJ



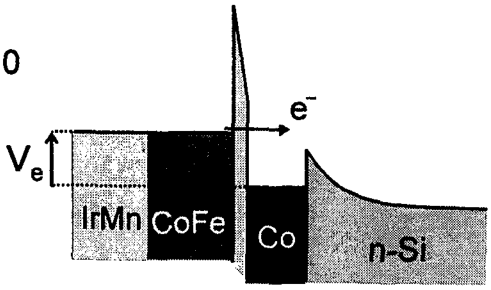
Collector current
vs emitter bias
V:
Typical
IV characteristic
of Schottky
barrier, ~0.8 V

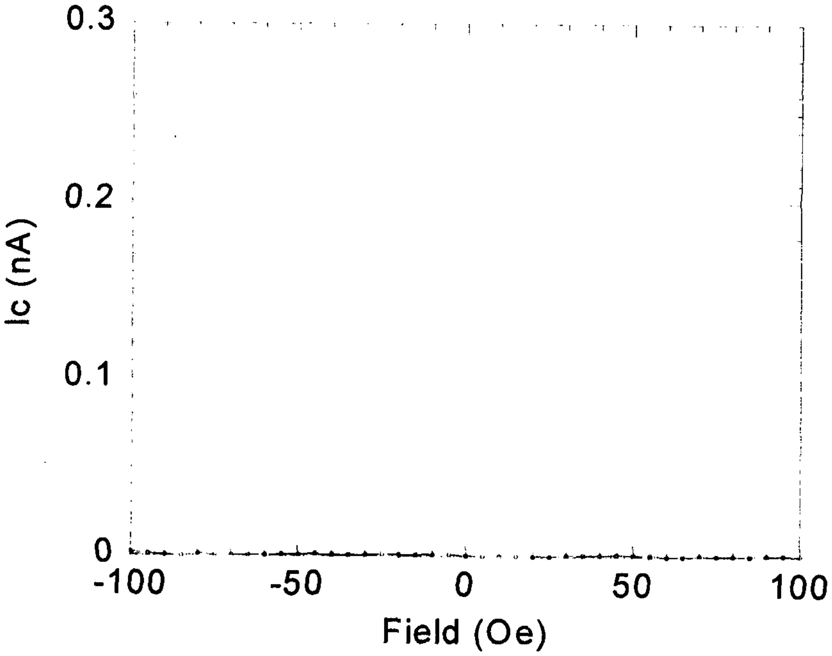
Emitter and Collector Current vs Field: 1 mV emitter bias voltage

Si/ 70Å Pd/100ÅCo/20Å Al_2O_3 / 100Å $Co_{84}Fe_{16}$/ IrMn



Emitter current vs field: Typical characteristic of MTJ at high bias voltage- high MR

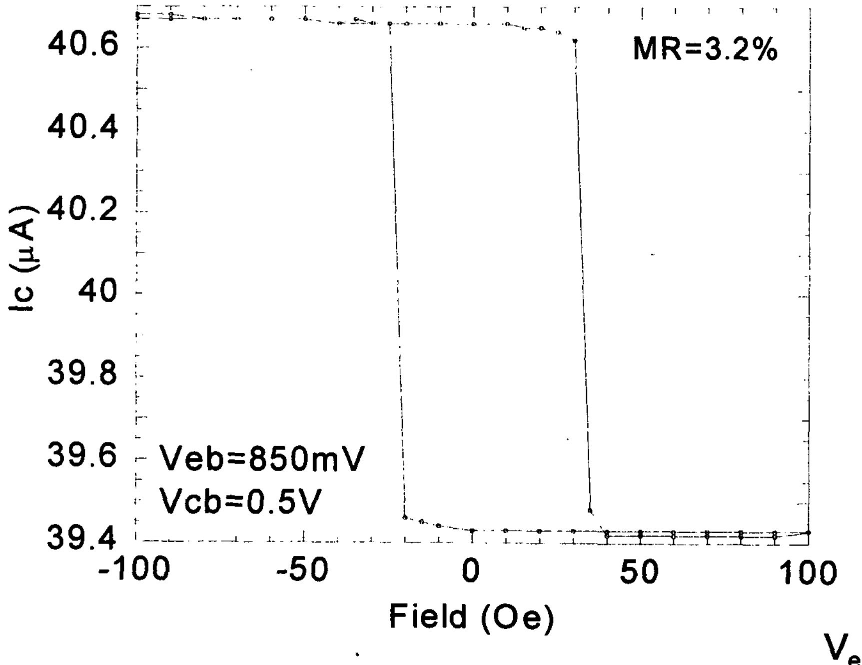




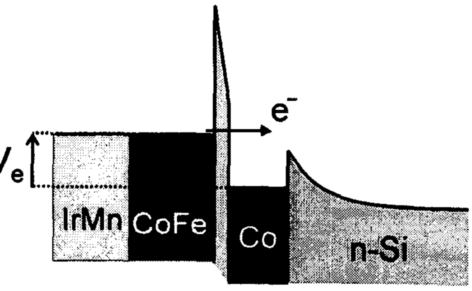
Collector current vs field: No current: electron energy too small to cross Schottky barrier, ~0.8 V

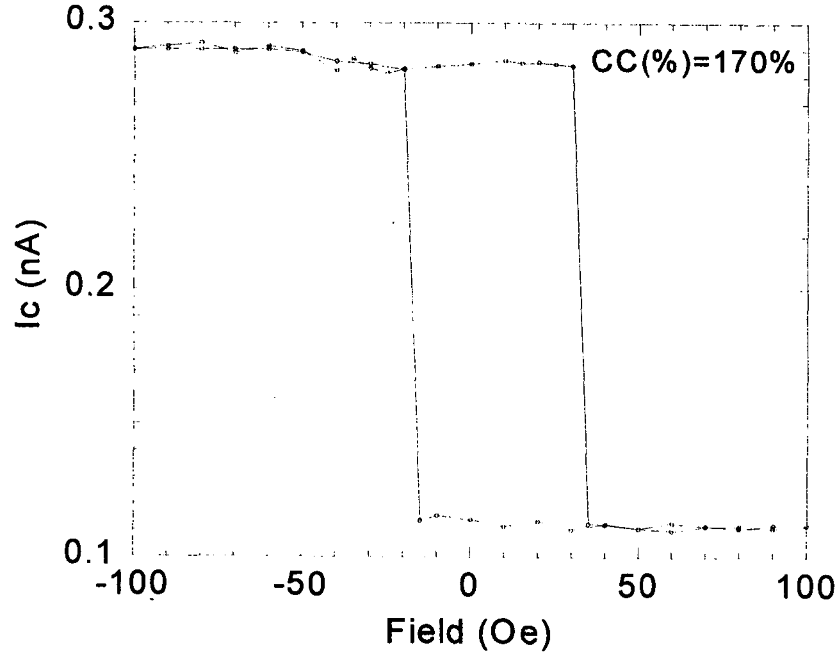
Emitter and Collector Current vs Field: 850 mV emitter bias voltage

Si/ 70Å Pd/100ÅCo/20Å Al_2O_3 / 100Å $Co_{84}Fe_{16}$/ IrMn



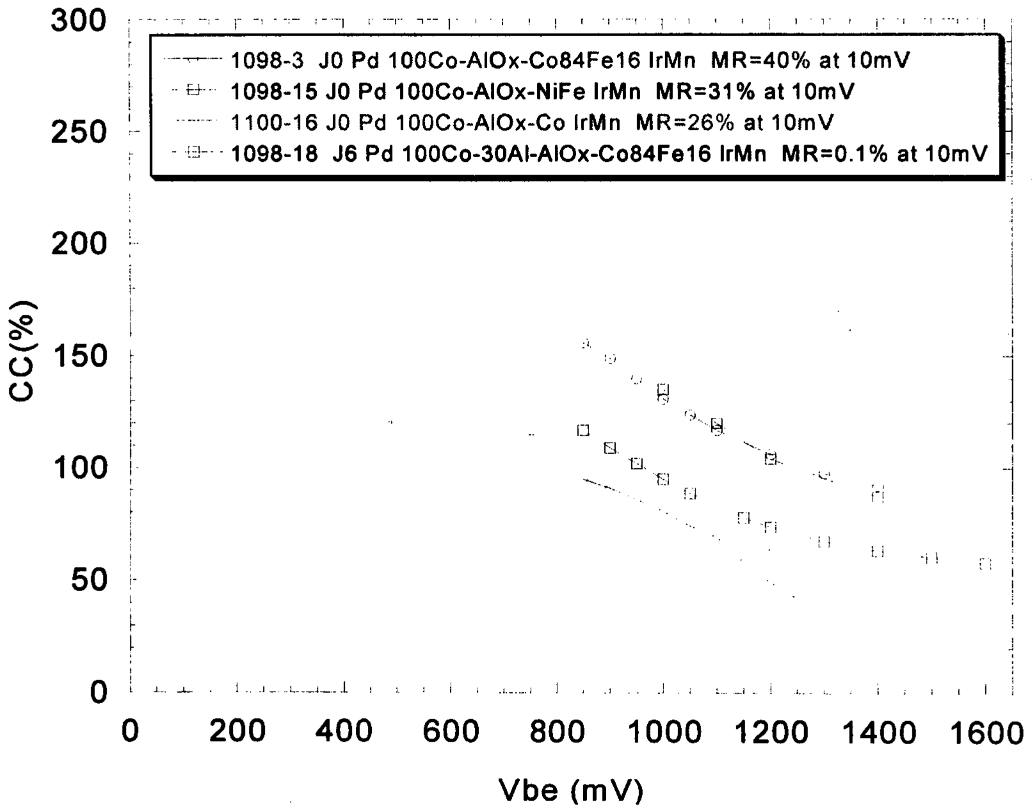
Emitter current vs field:
Typical characteristic of MTJ at high bias voltage- low MR





Collector current vs field:
Significant current and large change electron energy large enough to cross Schottky barrier, ~0.8 V

Collector Current Change CC(%) vs Emitter Bias



Extrapolated zero bias polarization for samples with Co lower FM

Si/ 70Å Pd/ 100ÅCo/ 20Å Al_2O_3 / FM/IrMn

- Co84Fe16: P=58%
- Ni81Fe19: P=55%
- Co: P=42%

But

for sample with Al interface layer beneath tunneling barrier

Si/ 70Å Pd/ 100ÅCo/ 30ÅAl/ 20Å Al_2O_3 / FM/IrMn

- Co84Fe16: P_1=58%

Summary

- MRAM
  - High performance MRAM using MTJs demonstrated
    - fully integrated MTJ MRAM with CMOS circuits
    - write time ~2.3 nsec; read time ~3 nsec
    - Thermally stable up to ~350 C
    - Switching field distibution controlled by size & shape
- Magnetic Tunnel Junction Properties
  - Magnetoresistance: ~50% at room temperature
    - enhanced by thermal treatment
  - Negative and Positive MR by interface modification
  - Spin Polarization: >55% at 0.25K
    - Insensitive to FM composition
  - Resistance x Area product
    - ranging from ~20 to $10^9 \Omega(\mu m)^2$
- Spin valve transistor
  - Tunnel injector: fabricated using shadow masks
  - High injected spin polarization for "hot" electrons
    - Decrease of MTJ MR at high bias originates from anode

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