National Aeronautics
and Space Administration

MRAM Technology and Status

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What is an MRAM?

MRAM = <u>Magnetoresistive</u> RAM

- **WRITE using <u>magnetic hysteresis.</u>**
- **READ using <u>magnetoresistance.</u>**
- **Built on CMOS. TSOP packages (or ceramic flat-pack for space)**
- **Architecture similar to SRAM.**
- **First memory to use magnetic structures exploiting electron <u>SPIN</u> as well as CHARGE.**
- **Future technologies have potential for very HIGH DENSITIES.**
- **MEMORY CELLS are nonvolatile (unlimited retention) and immune to radiation-induced upset. Also unlimited endurance.**

MRAM: The Ideal Memory?

- DRAM Density
- SRAM Speed
- NAND Nonvolatility
- Rad-Hard Memory Cells

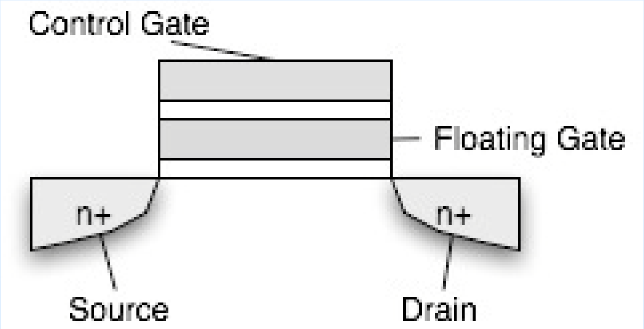
Potential to be first nonvolatile Gb memory with unlimited endurance and 20+ year retention (and SEU immunity bonus)

Spintronics

MRAM, The Spintronic Memory

Traditional Memory

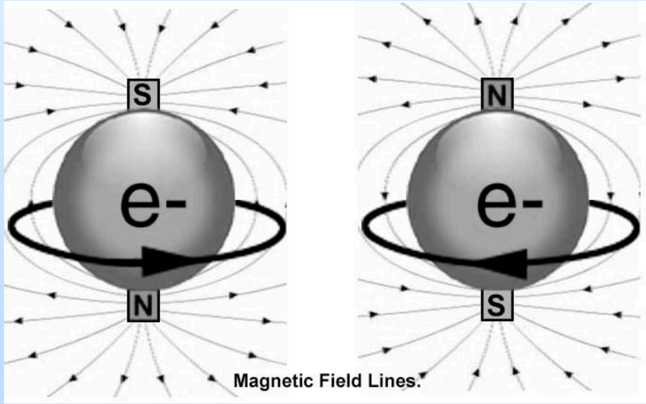
- **Bulk Movement/Storage of Electrons**



Ref [1]

Spintronics

- **Exploitation of Electron *Spin* and Resulting Magnetic Moment**



Ref [1]

Information is carried by electron spin in addition to, or in place of its charge.

Read: Magnetoresistance (MR)

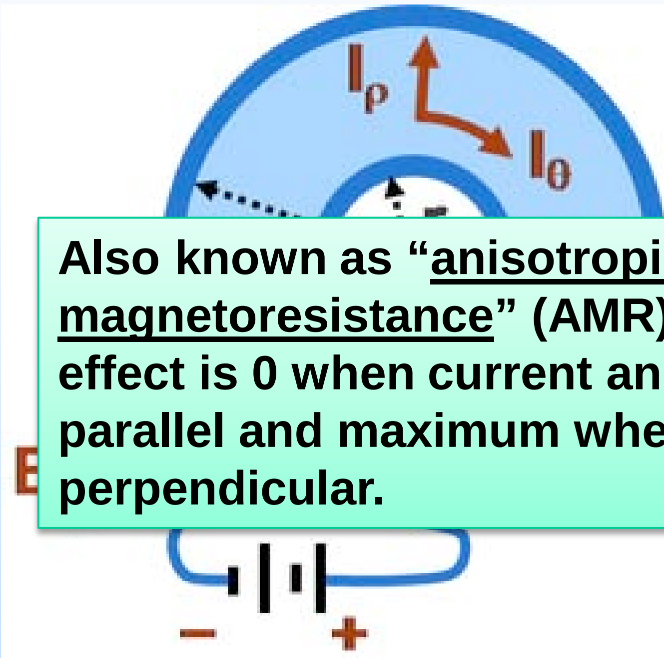
Types of magnetoresistance (MR):

Name	Increase in Resistance
Ordinary (OMR)	2%
Giant (GMR)	50%
Colossal (CMR)	99.9%
Tunnel (TMR)	200%

Modern "MTJ" MRAMs

"Ordinary" Magnetoresistance Effect

Resistance of material changes with applied magnetic field.



Also known as "<u>anisotropic magnetoresistance</u>" (AMR) because effect is 0 when current and B are parallel and maximum when perpendicular.

Ref [2]

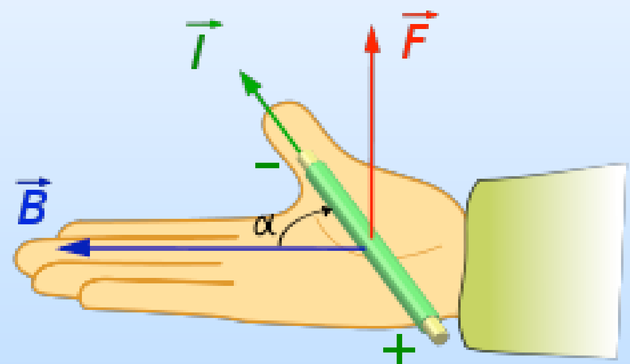
Corbino Disc

Magnetic field adds circular current component I_θ and creates resistance to radial component I_ρ.

Effect discovered by Lord Kelvin in 1856.

Increased resistance is due to <u>Lorentz Force</u>:

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$



Ref [3]

Change in resistance is proportional to B^2 (<u>Kohler's Rule</u>):

$$\frac{\partial \rho}{\rho} \propto a \left[\frac{H}{\rho} \right]^2$$

“Giant” Magnetoresistance

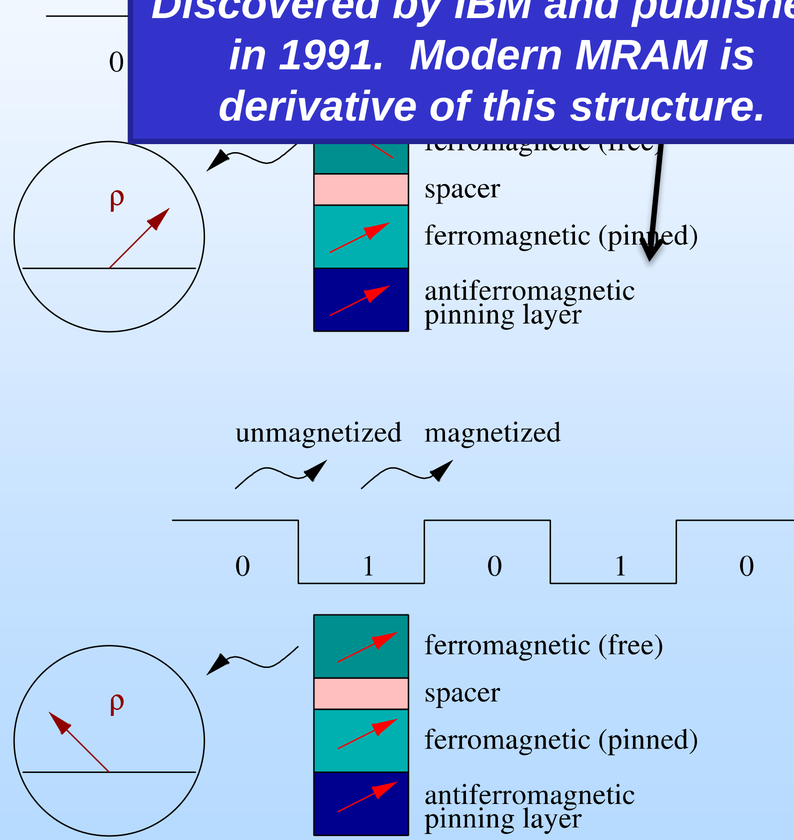
Birth of “spintronics”

Using pinning layer also known as “spin valve” structure

- **A much larger magnetoresistance effect (up to 50%) observed in thin-film structures composed of alternating ferromagnetic and non-magnetic layers (e.g. Fe/Cr/Fe). Thicknesses in nm.**
- **Current passes parallel to layers: current in plane (CIP).**
- **Resistance of material is affected by alignment of magnetic moments of magnetic materials which creates changes in scattering of spin up or spin down electrons.**
- ***In practical application as memory cell, change in resistance is too small (4-8%). Not good enough for high density memory.***

Disc Head Readers

Discovered by IBM and published in 1991. Modern MRAM is derivative of this structure.



Ref [4]

*The **2007 Nobel Prize** in physics was awarded to Albert Fert and Peter Grünberg for the discovery of GMR, which they did (independently) in the 1980s.*

"Colossal" Magnetoresistance

- **Very large change in resistance under magnetic field observed mostly in certain manganese oxide compounds**
- **First seen in 1950s by Jonker and Stanten (Philips)**
- **Effect not well understood**
- **Materials not to be seen in MRAM (or any other electronics) any time soon**

sistance has recently been discovered in La_{1-x}
. The largest effects have been observed for x=(
effects observed, on the order of $\Delta R/R(H)$ = 125,
resistance changes by 99.9% Figure 14 shows
sistivity of the material undergoes a low temp
ic behavior. The colossal magnetoresistance effec
arch has shown that the insulating to metal transi
mperature. HP has produced high quality CMR f
ce of about 95%. This resistance reduction is rel
egrees (Figure 16). These results were reported
s National Laboratory in February, 1995 [Ref. 8].
materials is the field dependence of the resistance
btain the large effect. These issues will be the foc

Ref [5]

"Tunnel" Magnetoresistance and the MTJ

Magnetic Tunnel Junction (MTJ) Cell Structures

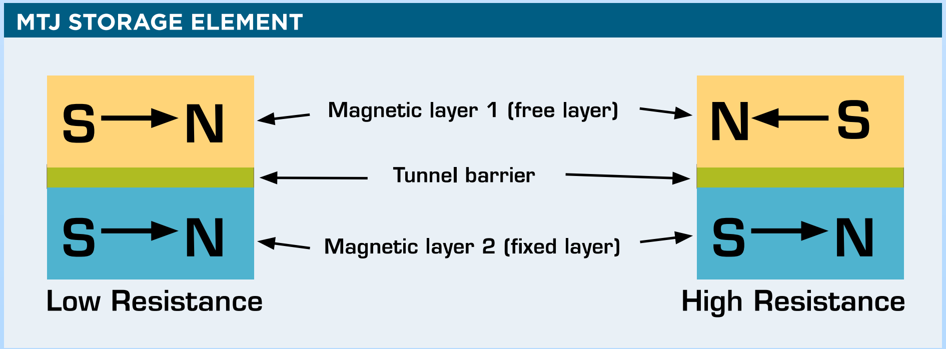
- **Two layers of magnetic metal (such as cobalt-iron) separated by a layer of insulator (typically aluminum oxide, ~1 nm)**

- **Tunneling Magnetoresistance**
  - **Consequence of spin-dependent tunneling**

Ref [6]

MTJ Operation

Ref [6]

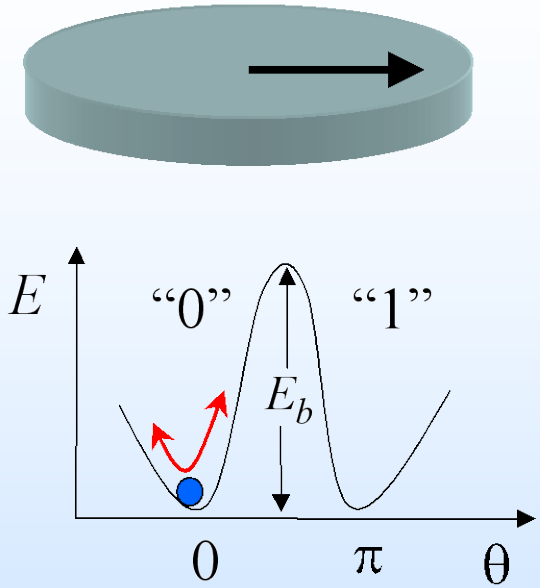


Ref [7]

MTJ Drawbacks

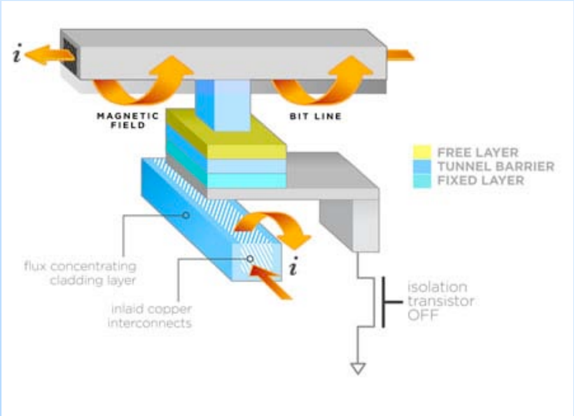
Scaling Issues

– Smaller bits are more susceptible to thermal fluctuations



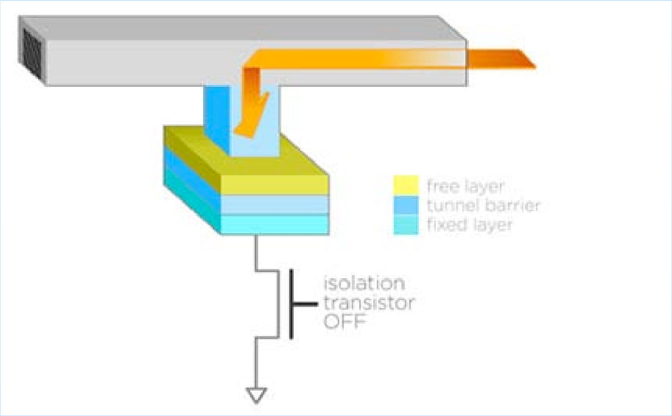
Ref [8]

Complicated Lithography



Ref [9]

1st Gen: MTJ Cell



Ref [9]

2nd Gen: STT Cell

MRAM Future: Thermally Assisted Switching (TAS)

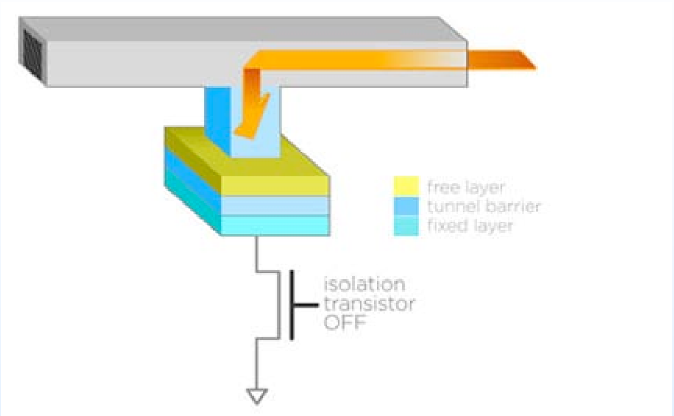
- **Idea is to heat the cell, which lowers the strength of the required magnetic fields for switching**

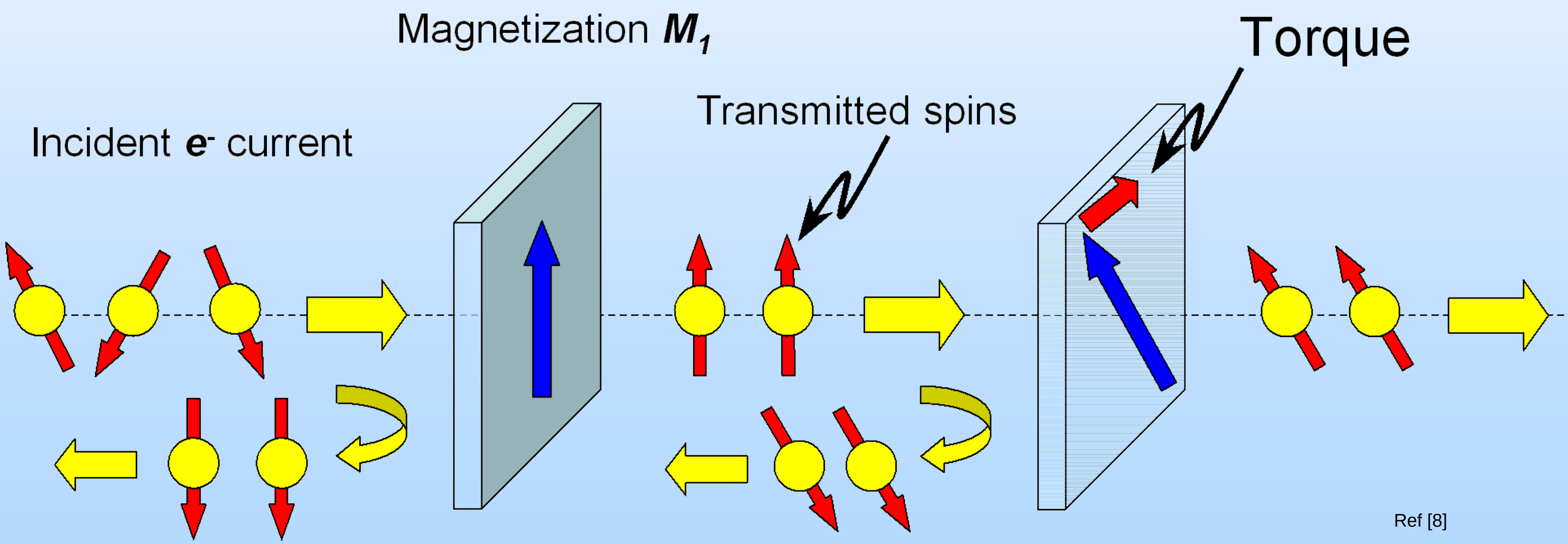
- **Advantages:**
  - **Eliminates write selectivity problems: write select is temperature driven**
  - **Lower power: only one magnetic field required for write**
  - **It is thermally stable due to the exchange bias of the storage layer.**

- **Main Advocate: Crocus (Spintec spin-off): Just received $300M to build factory in Russia.**

MRAM Future: Spin Torque Transfer (STT)

- **Advantages:**
  - **Lower Power Consumption**
  - **Better Scalability**
  - **Simpler Cells**

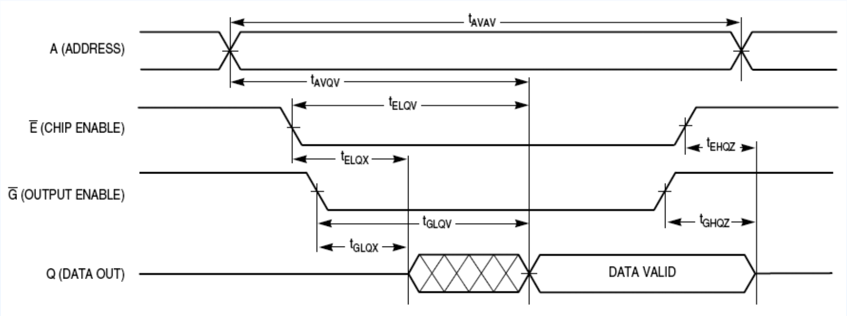




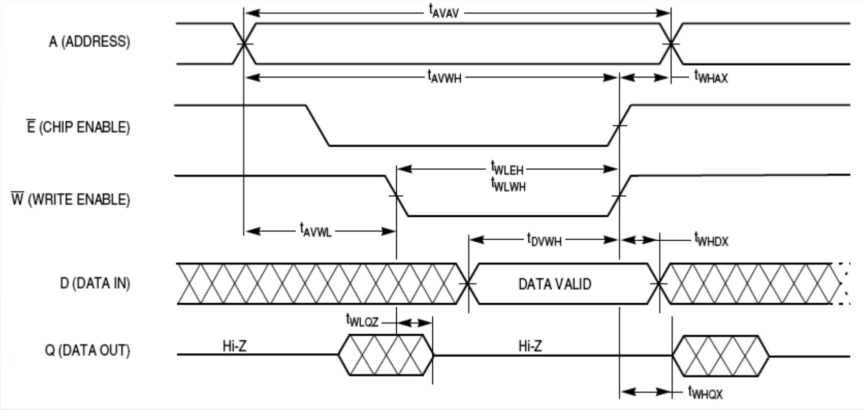
Ref [8]

SRAM-like Operation

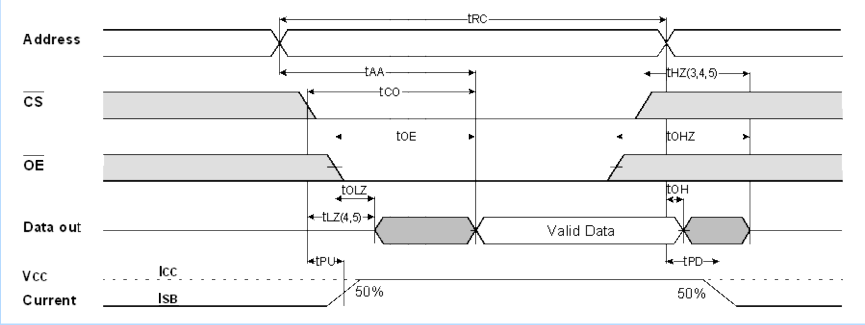
MRAM Read



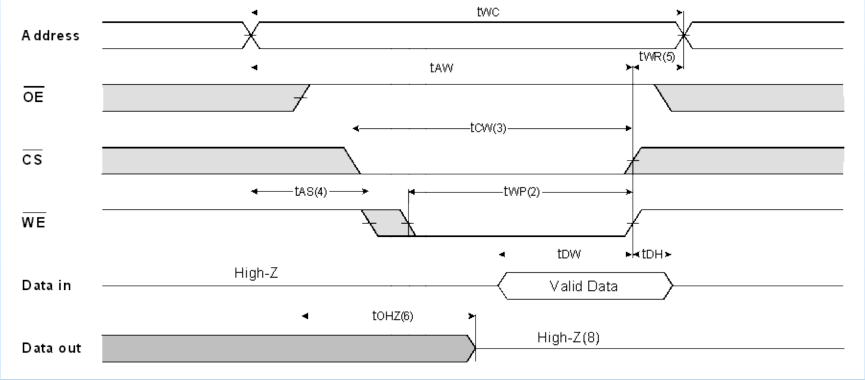
MRAM Write



SRAM Read



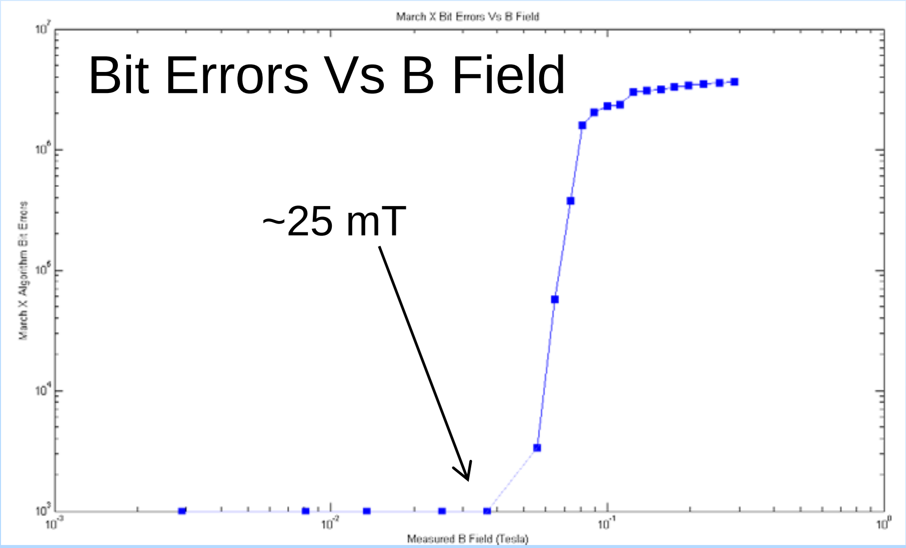
SRAM Write



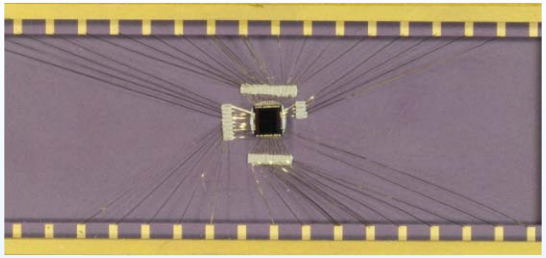
Device Reliability: 1 Mb Everspin (JPL)

- Unlimited Endurance
- 20+ year Retention
- Low susceptibility to external magnetic fields
- -55 to 125 C operation (E2V upscreen)
  - Sold by Everspin as -45 to 130C

B field measurements at JPL



Radiation Effects - JPL



A 1 Mbit MRAM die packaged in a 40-pin dual-in-package (DIP) for SEL testing (top) and thin-small-outline-package (TSOP) for TID testing (bottom).

Run #	Device	Energy (MeV/AMU)	Energy (MeV)	Ion	Eff. LET	Run Time (s)	Fluence
1	1	25	1766	Kr	21.2	177	2.0E+05
2	1	25	1766	Kr	21.2	242	3.0E+06
3	1	25	1766	Kr	21.2	45	5.0E+06
4	1	25	313	Kr	39	54	5.0E+06
5	1	25	1077	Xe	56	51	5.0E+06
6	2	25	1077	Xe	56	61	5.0E+06
7	2	25	1077	Xe	56	62	5.0E+06
8	2	15	2429	Au	84.1	89	1.0E+07
9	3	15	2429	Au	84.1	79	1.0E+07
10	4	15	2429	Au	84.1	54	1.0E+07

Ref [10]

Ion beams used for SEL testing.
No latchup observed during any testing.

Ref [10]

Memory Comparison

	SRAM	DRAM	NOR Flash	NAND Flash	FRAM	PRAM	MTJ MRAM	STT MRAM
Density	144 Mb	8 Gb	1 Gb	64 Gb	4 Mb	512 Mb	16 Mb	Gb?
Access Time	<1 ns	260 ps	25 ns	20 ns	55 ns	16 ns	35 ns	<10?
Standby I (mA)	2	150	<1	<1	<1	<1	<1	<1
Read I (mA)	100	1000	20	25	<10	16	30	15?
Write I (mA)	100	1000	50	25	<10	20	30	15?
Endurance	Infinite	Infinite	100k	0.5-100k	10^{14}	10^{6}	Infinite	Infinite
Retention	~0	~0	>10 yrs	>10 yrs	>10 yrs	>10 yrs	>20 yrs	>20 yrs
Cell Size (F^2)	100	8	6	5	10	6	10	<4?
Rad-Hard Cell	✖	✖	✖	✖	✔	✖	✔	✔
Cost/Mb ($)	2	.0004	.01	.0002	10	.05	1.5	?

Applications

Wherever nonvolatility, quick booting, high endurance, and/or radiation-hardness are important.

- **Home Computing**
  - **Quick boot discs, similar to Flash**
- **Mobile Computing**
  - **Nonvolatility**
- **Military/Space**
  - **Nonvolatile, Rad-Hard**
- **RFID**
  - **Embedded MRAM**

MRAM Players (Past and Present)

NVE CORPORATION
MOTOROLA
freescale semiconductor
EVERSPIN TECHNOLOGIES
IBM
infineon
Micron
intel
GRANDIS
RENESAS Everywhere you imagine.
CYPRESS PERFORM
NEC
FUJITSU
SAMSUNG
CROCUS Technology
spintec SPIN IN ELECTRONICS
TOSHIBA
Honeywell
AEROFLEX
Avalanche Technology
Spin Transfer Technologies An Allied Minds Company
e2v

MRAM Areas of Focus

Commercial MTJ Vendors

- Everspin
- E2V (Everspin Upscreen)

Commercial Rad-Hard MTJ

- Honeywell
- Aeroflex

MTJ IP

- NVE
- Spintec

Thermally Assisted Technology (TAS) R&D

- Crocus, IBM
- Spintec

Inactive

- Motorola (2005, spun off Freescale)
- Freescale (2008, spun off Everspin)
- Infineon (~2006)
- Cypress (2005)
- Micron (MTJ) (2003)

Spin Transfer Torque (STT) R&D

- IBM
- Samsung
- Hynix-Grandis
- Everspin
- Avalanche Technology (CA start-up)
- Spin Transfer Technologies (NYU start-up)
- Intel
- NEC
- Renesas
- Fujitsu
- Toshiba
- Micron, A*Star (Singapore)

MRAM Product Roadmap

Year	Device	Manufacturer
2004	4 Mb MTJ	Freescale
2005	1 Mb MTJ Rad-hard	Honeywell
2005	STT MRAM Prototype	Sony
2009	32 Mb STT MRAM Prototype	Hitachi
2010	4/16 Mb MTJ Rad-hard	Aeroflex
2012?	16/64 Mb Rad-hard QML Class V	Aeroflex/Honeywell
2015?	Gb STT	Toshiba

Flight Heritage - SpriteSat

- SpriteSat – Tohoku University, Japan
- Various Payloads/Launches Since 2008
- 4 Mb Freescale devices
- Replacing Flash and SRAM with MRAM

Flight Heritage – CubeSat - COVE (JPL)

- Launch October 2011 (Ref: 11)
- CubeSat On-board Processing Validation Experiment, "COVE"
- Secondary Payload on University of Michigan M-Cubed CubeSat
- Included:
  - Xilinx Virtex-5QV FPGA
  - Everspin MR4A16B MRAM (4 Mb)
  - Numonyx P5QPCM PRAM (128 Mb)
- First attempt: NPOESS Prepatory Project (NPP)
- M-Cubed did not separate from another CubeSat, Explorer 1-Prime
  - *Although beacons have been heard, University of Michigan team has been unable to send commands to satellite.*

Sources/References

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