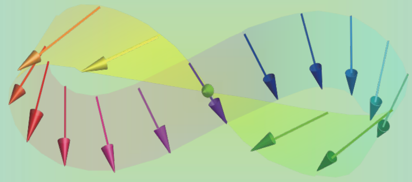
Nanoelectronics

12



Atsufumi Hirohata

Department of Electronic Engineering

THE UNIVERSITY *of York*

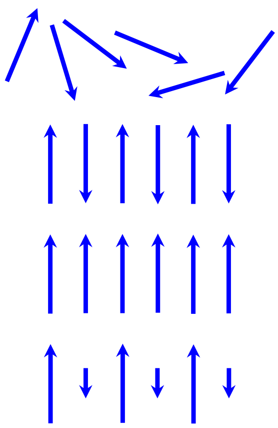
13:00 Friday, 24/February/2023 (P/T 005A)

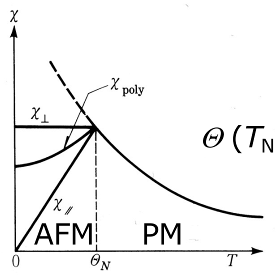
Quick Review over the Last Lecture

Origin of magnetism :

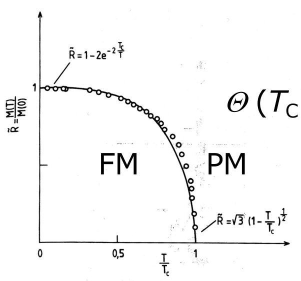
( ) is equivalent to a ( ).

Dipole moment arrangement :





Θ (T_N) : temperature



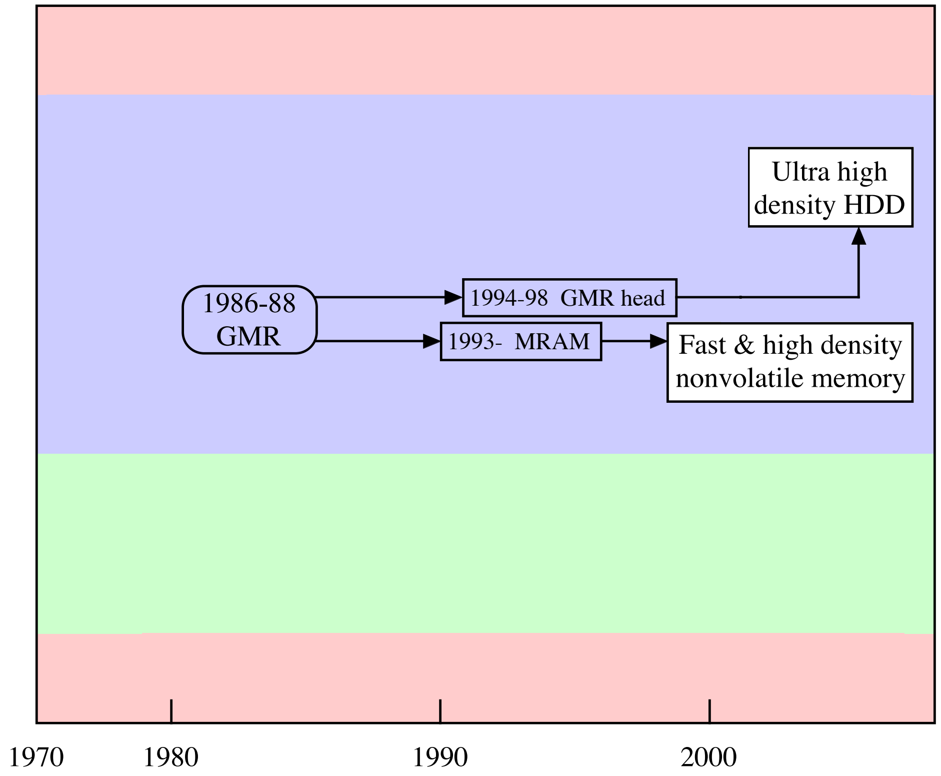
Θ (T_C) : temperature

Contents of Nanoelectonics

12 Spintronic Nanodevices

- Magnetoresistance
- Hard disk drive
- Magnetic random access memory
- Spin-polarised three-terminal devices

Recent Progress in Magnetoelectronics I - *Giant Magnetoresistance*

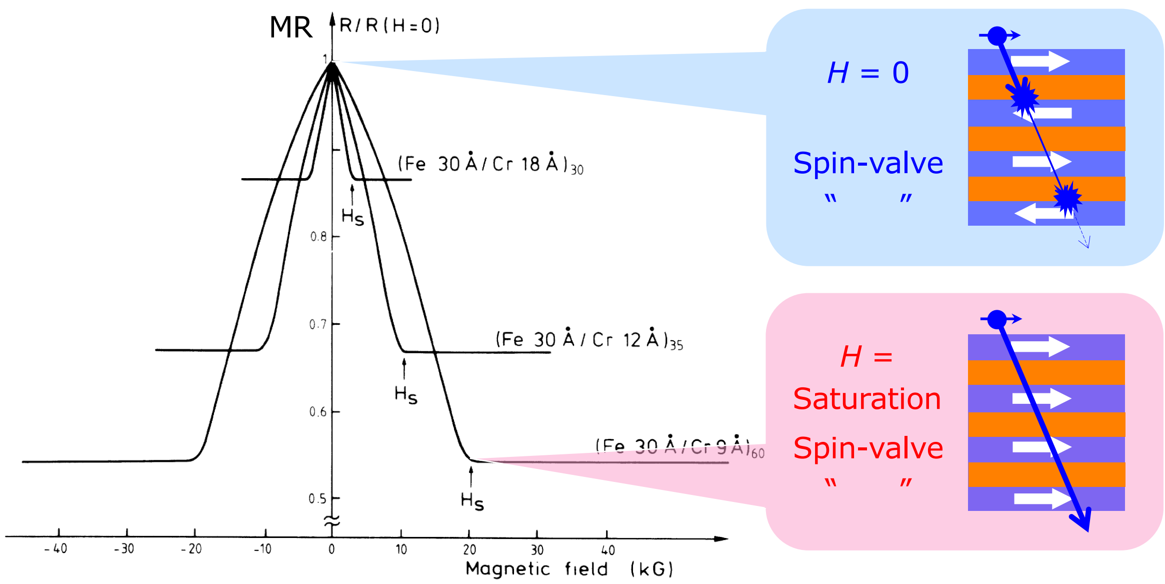


* *After* K. Inomata, *J. Magn. Soc. Jpn.* **23**, 1826 (1999).

Discovery of Giant Magnetoresistance

Giant magnetoresistance (GMR) :

[3 nm Fe / 0.9 nm Cr] × 60 *



50 % resistance change at 4.2 K

* M. N. Baibich *et al.*, *Phys. Rev. Lett.* **61**, 2472 (1988); P. Grünberg *et al.*, *Phys. Rev. Lett.* **57**, 2442 (1986).

Nobel Prize in Physics 2007

The Nobel Prize in Physics 2007

"for the discovery of Giant Magnetoresistance"

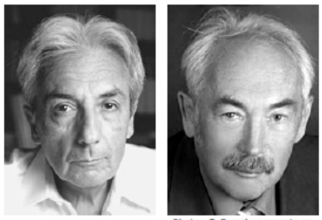


Photo: © Forschungszentrum

naturenews

Published online 9 October 2007 | Nature | doi:10.1038/449643a

News

The physics prize inside the iPod

Giant magnetoresistance secures Nobel.

Geoff Brumfiel (/news/author/Geoff+Brumfiel/index.html)

Two researchers who discovered an effect that has dramatically shrunk the size of magnetic storage devices have won the 2007 Nobel Prize in Physics.

Albert Fert of the University of Paris-South in France and Peter Grünberg of Jülich Research Centre in Germany split the prize for their 1988 discovery of an effect called giant magnetoresistance (GMR). The Royal Swedish Academy of Sciences announced the award on 9 October in Stockholm.

The effect has been heralded as one of the first major applications of the fields of nanotechnology and 'spintronics'.

"I am so proud and so happy," Fert said in a press conference via telephone from France. "Science is something marvellous."

At the heart of GMR are the spins of electrons, which generate a magnetic field and can be aligned either up or down. An electron can easily pass through a material whose electrons are similarly aligned, but will encounter resistance when it passes through one with electrons aligned in the opposite direction.

Spin doctors: Peter Grünberg (left) and Albert Fert.

NOBEL PRIZES

Effect that Revolutionized Hard Drives Nets a Nobel

If you work at a computer, play video games, or listen to music on an iPod, you've benefited directly from the efforts of the winners of the 2007 Nobel Prize in Physics. Albert Fert of France's national research agency, CNRS, in Orsay, France, and Peter Grünberg of the Jülich Research Center in Germany independently discovered an effect known as giant magnetoresistance (GMR) that fueled a dramatic increase in the capacity of computer hard drives. The discovery also laid the cornerstone of a new field known as spintronics, in which researchers try to exploit the fact that electrons spin like little tops to make novel devices.

"It's a physics discovery that has had real consequences," says Robert Buhrman, an applied physicist at ...ity. "Without ...d not be able ...le life around ... drive."

... the discovery ...hers knew that ...etic field to a ... iron or nickel ... conductivity. ...t would flow ...rallel to the ...h the material ...d and more ... Technologists ...ffect to make ..." that sensed ...e magnetized ...er hard drive. ..., known as ...agnetoresis- ... the resistance varied by a few percent.

In 1988, Grünberg and Fert found that they could greatly increase the change in resistance if they made layer-cake films with layers of iron separated by layers of nonmagnetic chromium only a few atoms thick. If two adjacent iron layers are magnetized in the same direction, then electrons spinning in one direction will pass along the film readily, whereas electrons spinning in the other direction will not. If, however, the iron layers are magnetized in opposite directions, then all electrons run into greater resistance, regardless of how they are spinning. That makes a GMR film an extremely sensitive magnetic field detector. As a result, all the bits and hardware in a disk drive can be made much smaller.

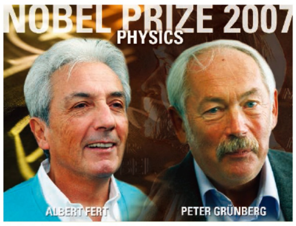
The basic quantum mechanical concepts behind GMR were understood in the 1970s, but at the time technology was not available to exploit them, Fert says. "I put this idea in the fridge," he says. "Then in the 1980s, it became possible to fabricate these materials." Grünberg could not be reached for comment when *Science* went to press.

Although Fert and Grünberg discovered the effect, Stuart Parkin of IBM's Almaden Research Center in San Jose, California, did much of the work to make GMR technologically useful. Stuart Wolf, a physicist at the University of Virginia, Charlottesville, says he was surprised that Parkin was not honored as well. But Tony Bland of the University of Cambridge, U.K., says that the Nobel committee apparently distinguished between the discovery and its cultivation. "This is properly a physics prize for a truly extraordinary and novel effect."

The advent of GMR helped launch the emerging field of spintronics, Wolf says. "This particular discovery seemed to crystallize a lot of people's interest in working in this area," he says. Their efforts may someday lead to myriad other devices, such as computer memory that can hold information even when it loses power and microchips that exploit spin to perform computations.

–ADRIAN CHO

With reporting by Daniel Clery.



Thanks for the memories. Physicists Albert Fert (*left*) and Peter Grünberg independently discovered an effect that vastly increased the capacity of computer drives.

www.sciencemag.org SCIENCE VOL 318 12 OCTOBER 2007
Published by AAAS

physicsworld.com

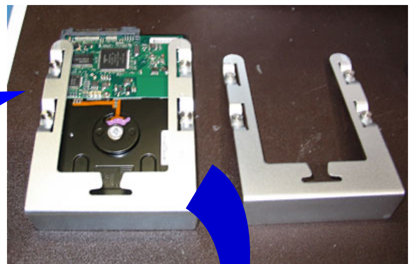
NEWS

Oct 9, 2007

Nobel prize recognizes GMR pioneers

The 2007 Nobel Prize in Physics has been awarded jointly to Albert Fert of the Université Paris-Sud in France and Peter Grünberg of the Forschungszentrum Jülich in Germany "for the discovery of giant magnetoresistance". Their discovery, which both physicists made independently in 1988, led to a dramatic rise in the amount of data that can be stored on computer hard-disk drives. Fert and Grünberg share prize money totalling 10 million Swedish krone (about $1.5m).

How Can We Find a Hard Disc Drive ?

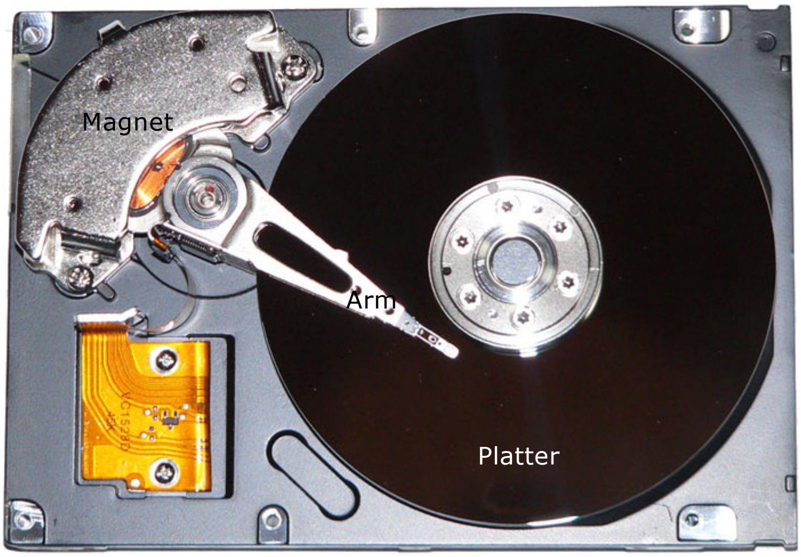


Open your computer …

This is a HDD !

Do NOT Try This at Home !

Open a metal frame of a HDD …



- Arm is operated by a linear motor with a very strong permanent magnet.
  - Arm moves ~ times/sec.
  - Platter records data.
  - Platter rotates rpm.

Where Can We Find a Hard Disc Drive ?

PC

Hard disc recorder

Video game

GPS navigation

Digital camera

Video camera

Data storage

PDA

mp3 player

Mobile phone

Most popular recording media now :

· ·

· ·

· ·

HDD in Cloud

In this lecture, ~ 20 participants

120 Smart Phones =
81 % (2016, UK)

cloudServices online

80 Tablet PCs =
71 % (2016, UK)

Cloud servers used

Google for Education

1 TB max. / person =

Microsoft Azure

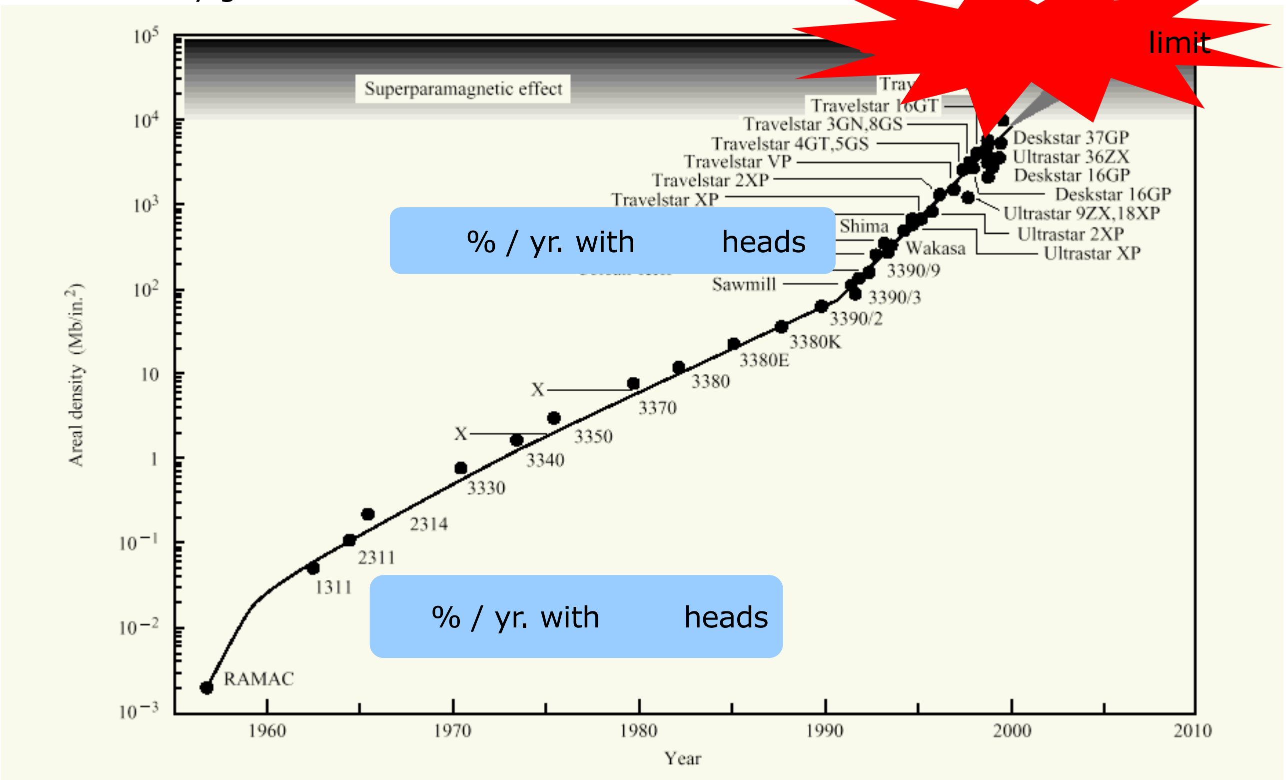
amazon web services

HDD Operation

* https://www.youtube.com/watch?v=NtPc0jl21i0

Aerial Density Increase by GMR Introduction

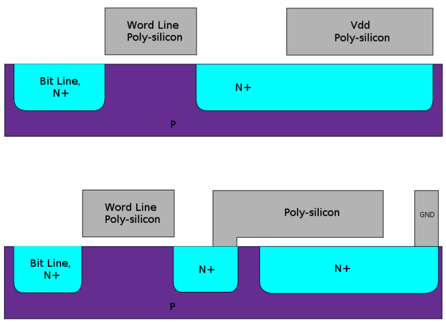
Aerial density growth of hard disk drives :

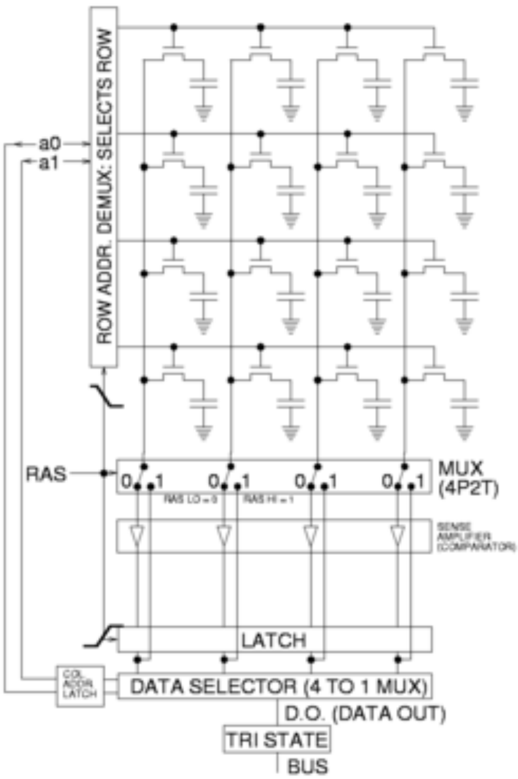


* D. A. Thompson *et al.*, *IBM J. Res. Develop* **44**, 311 (2000).

Random Access Memory

In a computer, data is transferred from HDD to a dynamic random access memory :





Data stored in a capacitor.

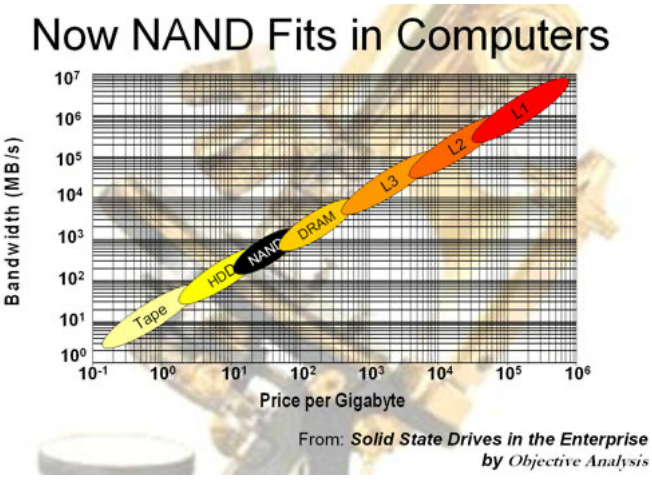
→ Electric charge needs to be refreshed.

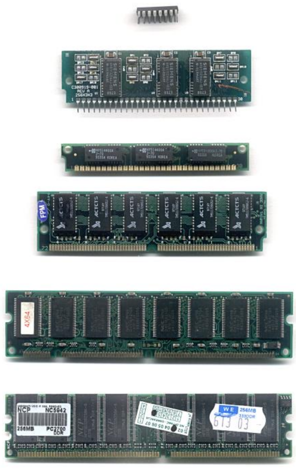
→ DRAM requires large power consumption.

* http://www.wikipedia.org/

Gap between HDD and DRAM

A gap between data storage and operation :

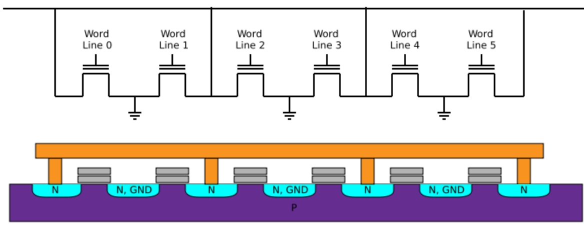


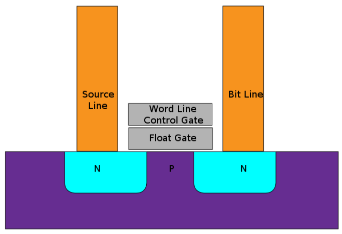


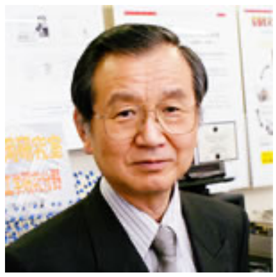
* http://agigatech.com/blog/page/2/

Flash Memory

In 1980, Fujio Masuoka invented a NOR-type flash memory :







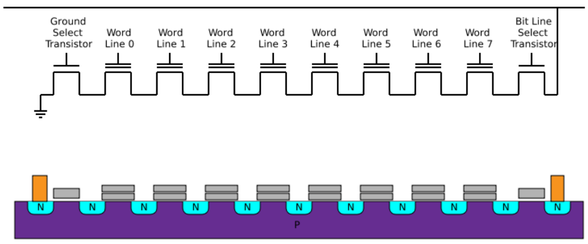
✓ byte high-speed read-out

× writing speed

× Difficult to

× Flash erase for a (kbyte) only !

In 1986, Fujio Masuoka invented a NAND-type flash memory :



× No byte high-speed read-out

✓ writing speed

✓ Ideal for

* http://rikunabi-next.yahoo.co.jp/tech/docs/ct_s03600.jsp?p=000500
* http://www.wikipedia.org/

Solid State Drive with Flash Memory

Solid state drive (SSD) started to replace HDD :

pureSi introduced 2.5” 1-TB SDD in 2009 :

✓ Data transfer speed at 300 MB/s

× Slow write speed

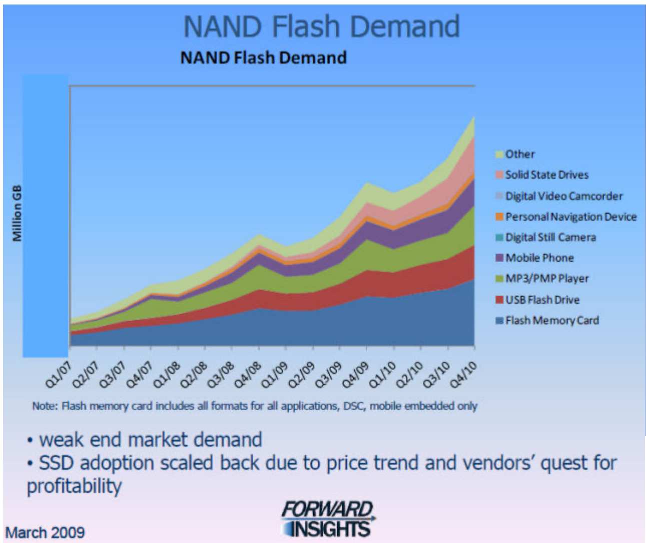
For example, a system with a units of 2kB for read / out and 256 kB for erase :

in order to write 1 bit, the worst case scenario is

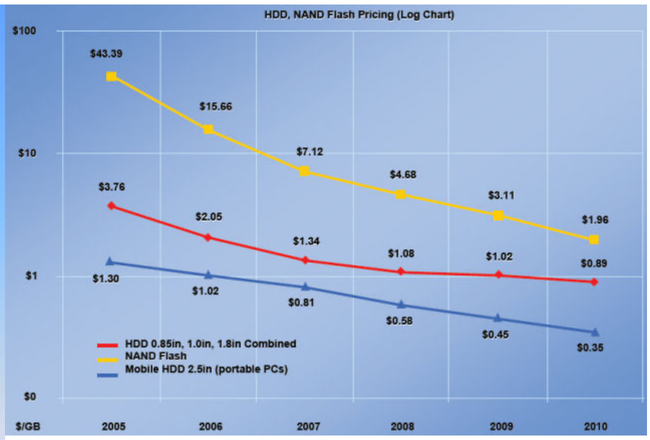
- times read-out
- time flash erase
- times re-write

HDD vs Flash Memory

Demand for flash memories :

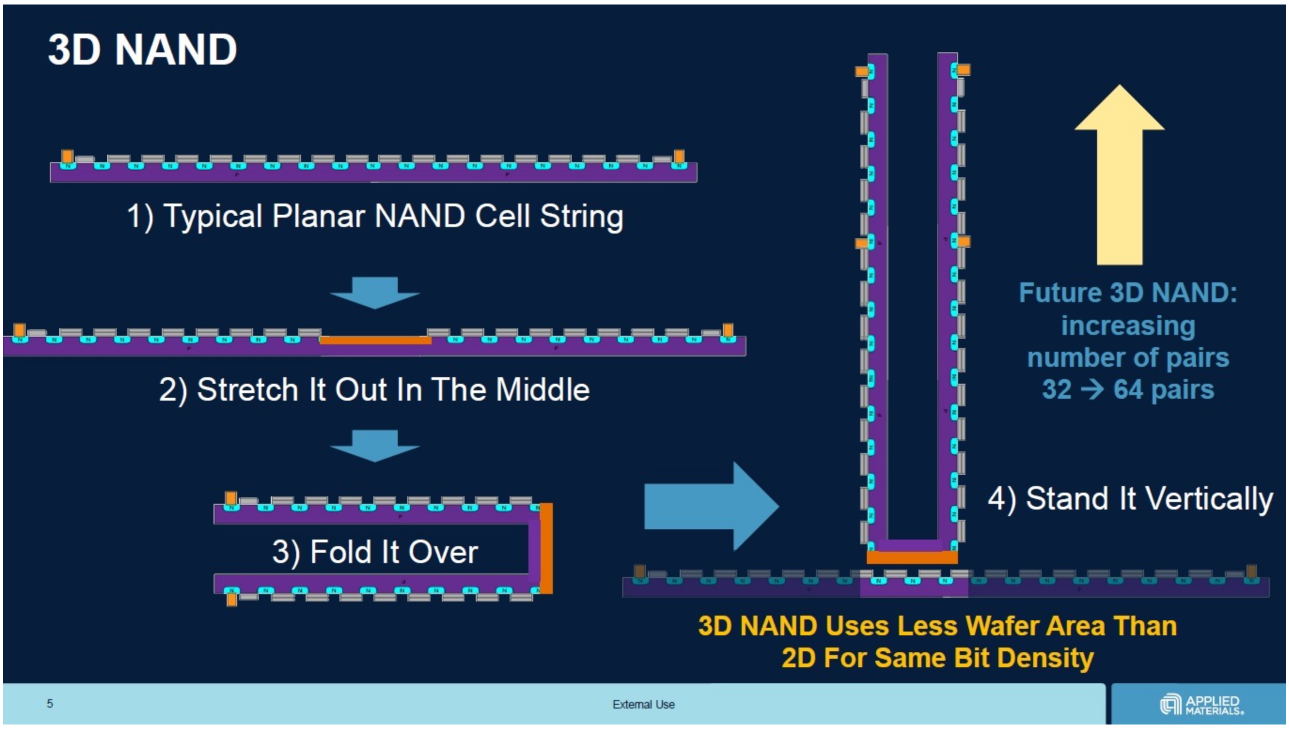


Price of flash memories :



* http://www.manifest-tech.com/ce_products/flash_revolution.htm

3D Flash Memory



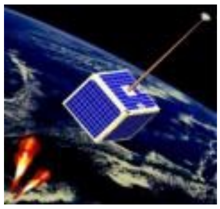
MRAM / Spin RAM as a Universal Memory

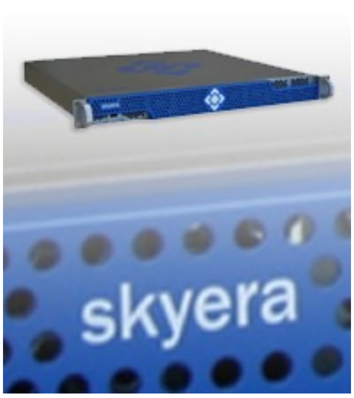
	Spin RAM	MRAM	FLASH		DRAM		FeRAM	SRAM
Rules	32 nm	90 nm	32 nm	90 nm	45 nm	90 nm		90 nm
Non-volatility	Y	Y	Y	Y	N	N	Y	N
Read time	~1 ns	300 ns (GMR) <60 ns (TMR)	10–50 ns	10–50 ns	10 ns	10 ns	100–200 ns	1.1 ns
Write time	~1 ns	<10 ns	0.1–100 ms	0.1–100 ms	10 ns	10 ns	~100 ns	1.1 ns
Repetition	$>10^{15}$	$>10^{15}$	$>10^{6}$	$>10^{6}$	$>10^{15}$	$>10^{15}$	10^{9}–10^{12}	$>10^{15}$
Cell size	0.01 μm^2 5 Gb cm^{-2}*	0.25 μm^2 256 Mb cm^{-2}	0.02 μm^2 2.5 Gb cm^{-2}*	0.1 μm^2 512 Mb cm^{-2}		0.25 μm^2 256 Mb cm^{-2}		1–1.3 μm^2 64 Mb cm^{-2}
Cell density	6 F^2	27 F^2		4 F^2	6 F^2	8 F^2	8 F^2	92 F^2
Chip capacity		>1 Gb		>1 Gb			<10 Mb	
Program energy per bit		120 pJ	10 nJ	30–120 nJ		5 pJ + refresh		5 pJ
Soft error hardness		Y		Y		Y	Y	N
Process cost		RT process		Lower bit cost			HT process	

Note: * represents target values.

* A. Hirohata and K. Takanashi, *J. Phys. D: Appl. Phys.* **47**, 1930001 (2014).

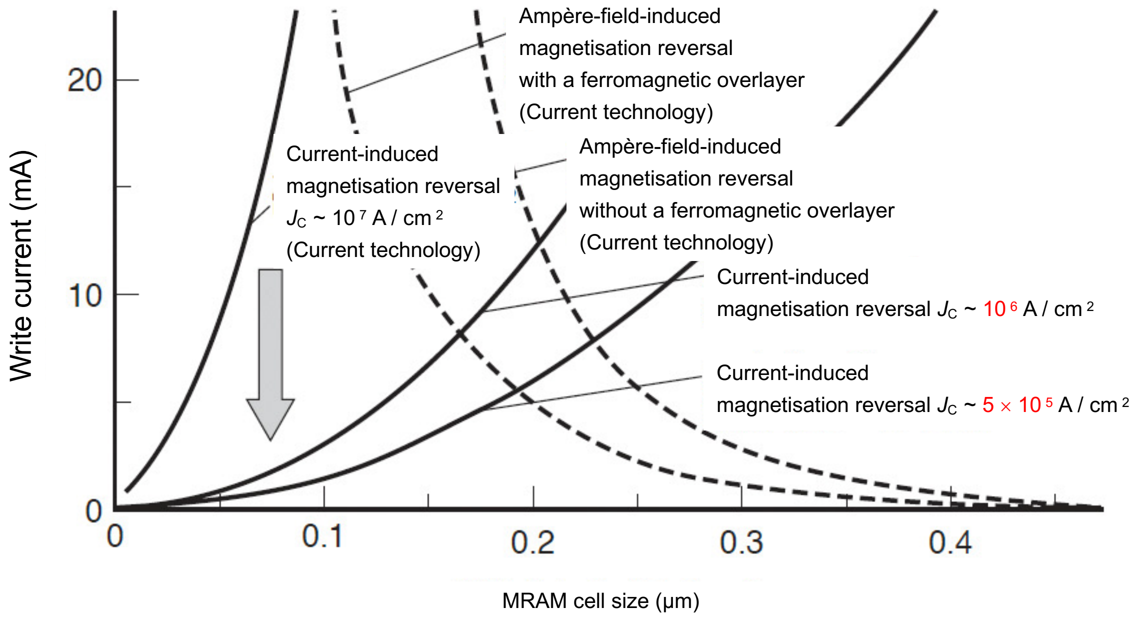
MRAM Applications





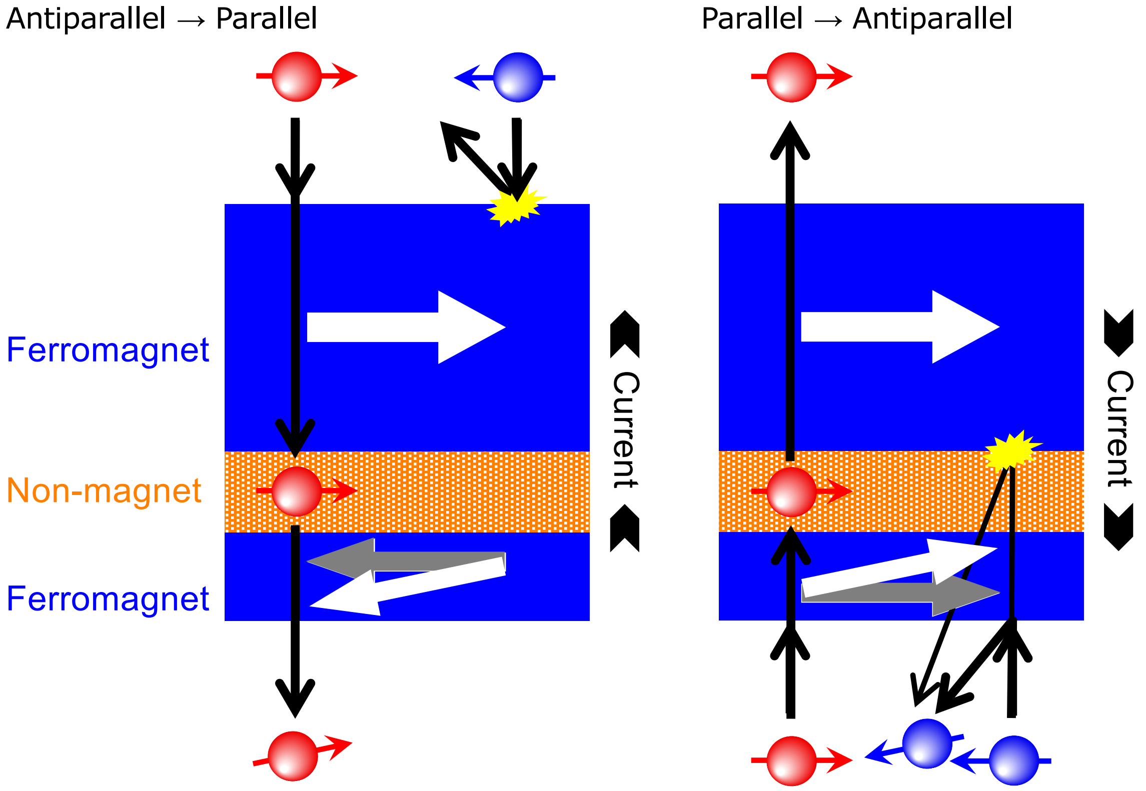
Improved MRAM Operation

Required writing currents for several techniques dependent upon cell size :

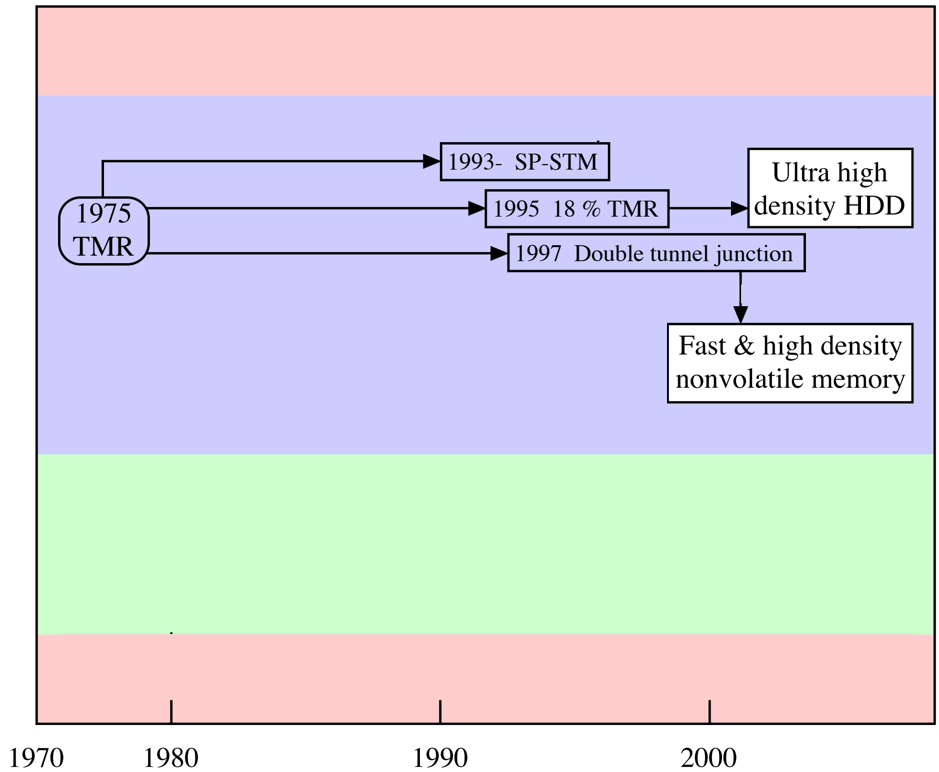


* S. Nakamura, Y. Saito and H. Morise, *Toshiba Rev.* **61**, 40 (2006).

Current-Induced Magnetisation Switching



Recent Progress in Magnetoelectronics II - *Tunnel Magnetoresistance*

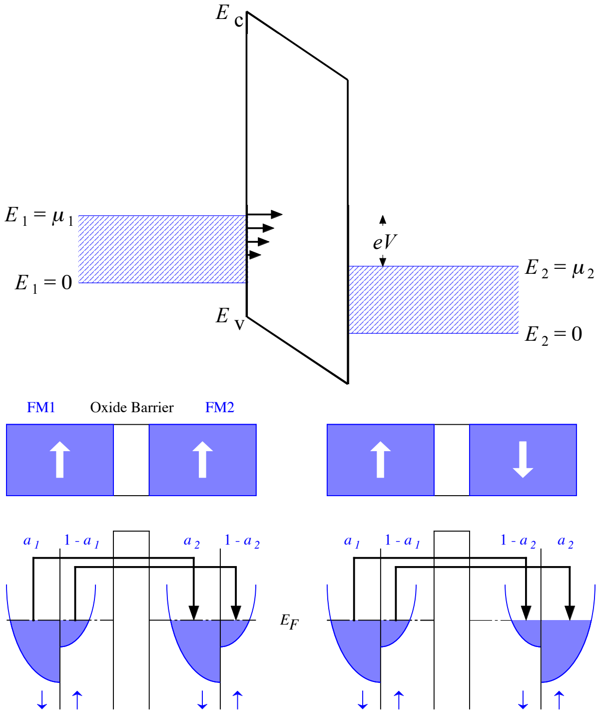


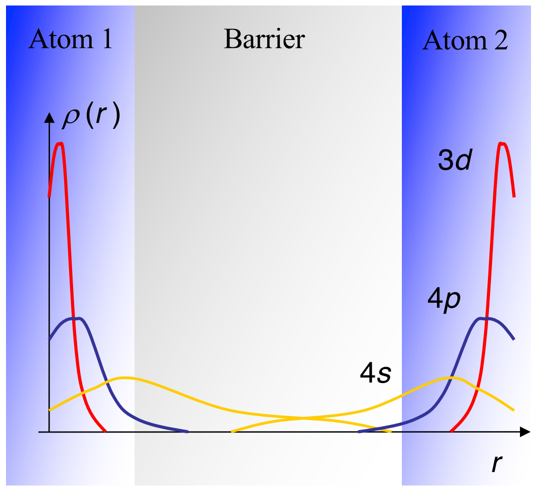
* *After* K. Inomata, *J. Magn. Soc. Jpn.* **23**, 1826 (1999).

Spin-Dependent Electron Tunneling

Jullière's model :

FM / insulator / FM junctions *

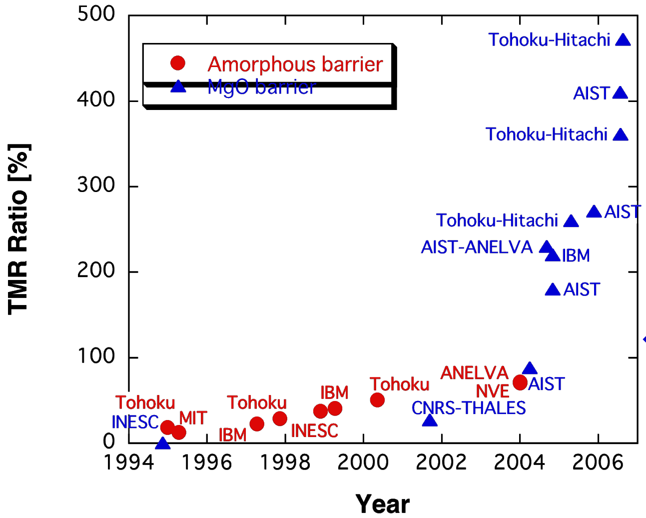




* M. Jullière., *Phys. Rep.* **54A**, 225 (1975).

TMR for Device Applications

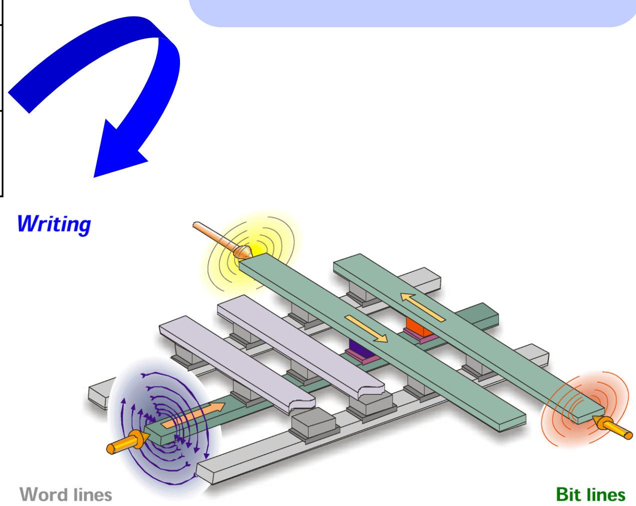
Recent progress in TMR ratios :



> 400 % *TMR ratio* has been achieved !

↓

> Gbit MRAM can be realised.



NOT following Jullière's model : **

TMR = $2P_1P_2$ / (1 - P_1P_2)

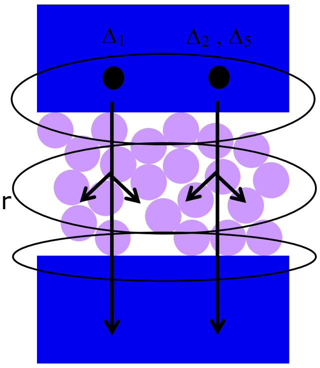
* M. Jullière., *Phys. Rep.* **54A**, 225 (1975).

** S. S. P. Parkin, *1st Int'l Sch. on Spintronics and Quantum Info. Tech.*, May 13-15, 2001 (Maui, HI, USA).

Improved Tunnel Barriers

Conventional amorphous barriers : *

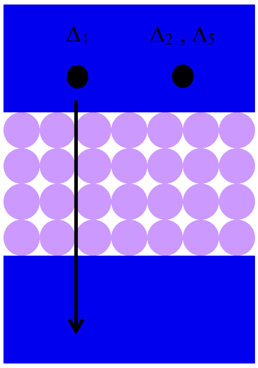
Defects in
the barrier



Disorder at the interface :
- FM over-oxidation
- lattice defects

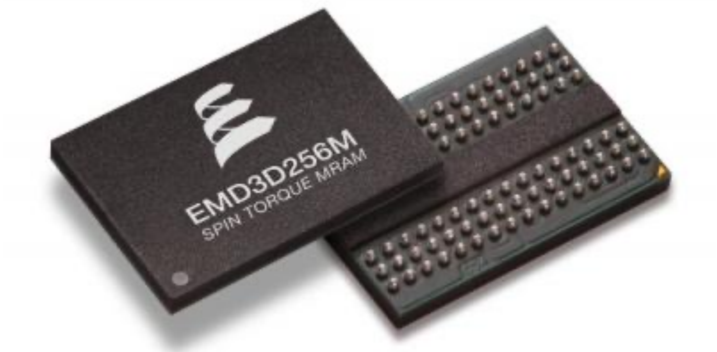
Disorder at the interface :
- FM over-oxidation
- lattice defects
- island growth of the barrier

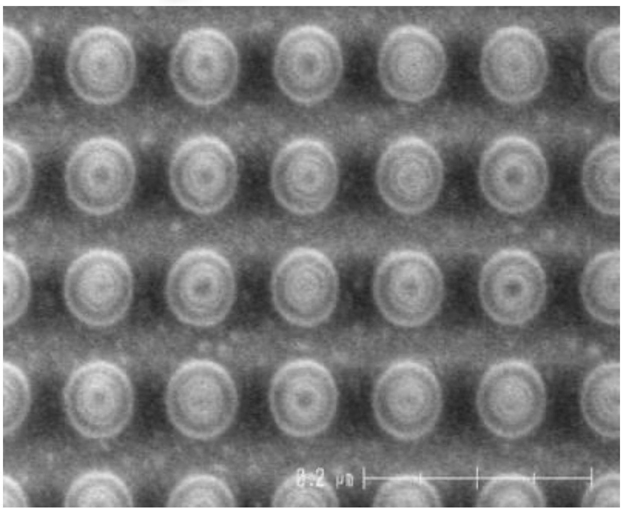
Epitaxial (oriented) barriers : *

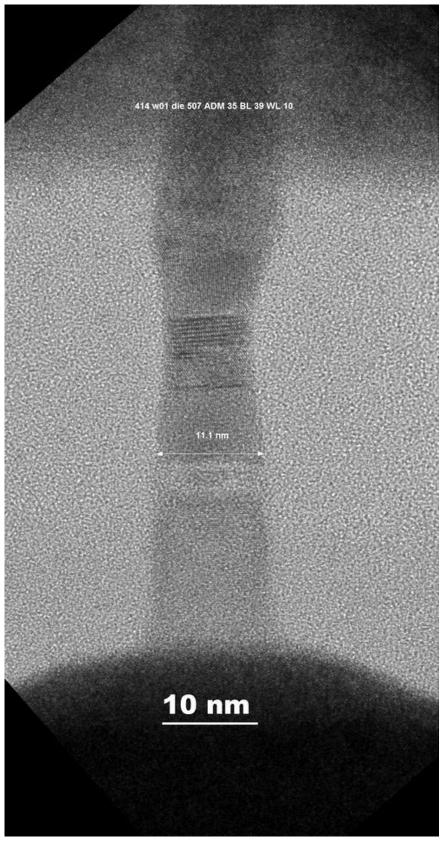


* *After* S. Yuasa *et al.*, *28th Annual Conference on Magnetics*, Sep. 21-24, 2004 (Okinawa, Japan).

Latest MRAM

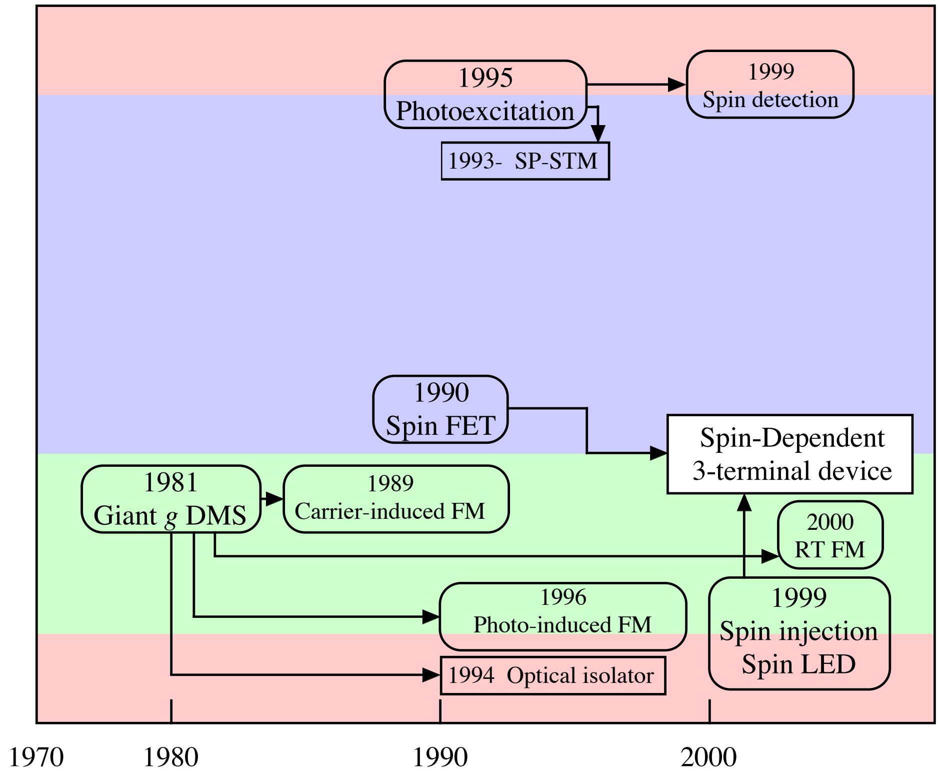






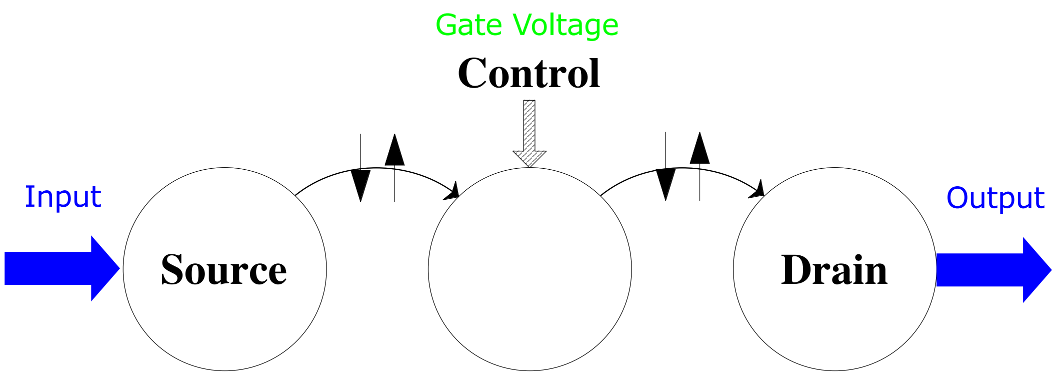
* News from EverSpin, IBM and Toshiba.

Recent Progress in Spintronics



* *After* K. Inomata, *J. Magn. Soc. Jpn.* **23**, 1826 (1999).

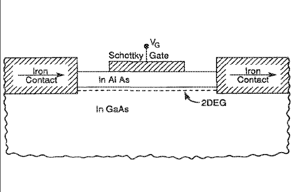
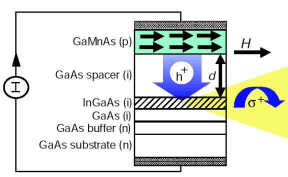
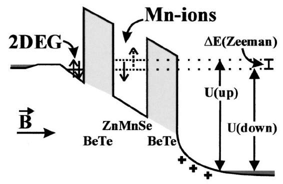
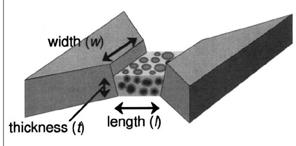
Spin-Polarised Three-Terminal Devices



	FM / SC hybrid Structures	Magnetic tunnel junctions (MTJ)	All metal and spin valve structures
Interface			
Spin carriers			
Device applications	FM / 2DEG Schottky diodes Spin FET Spin LED Spin RTD	MOS junctions Coulomb blockade structures SP-STM Supercond. point contacts Spin RTD	Johnson transistors Spin valve transistors

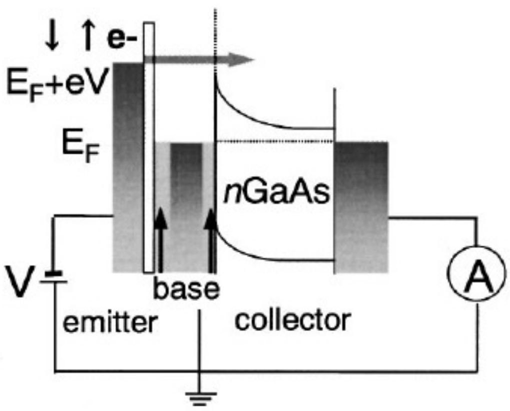
* *After* M. Johnson, *IEEE Spectrum* **37**, 33 (2000).

Major Spin-Polarised Three-Terminal Devices

	Spin FET	Spin LED	Spin RTD	Coulomb blockade
				
Input	Spin-polarised electrons / holes	Spin-polarised electrons / holes	Spin-polarised electrons / holes	Spin-polarised electrons
Source				
Gate	Bias voltage	Bias voltage	Bias voltage	Bias voltage
Drain				
Output	Electrical signals - Spin-polarised electrons / holes	Circularly polarised electroluminescence (EL)	Circularly polarised electroluminescence (EL)	Electrical signals
Notes		• Low temperature • High magnetic field	• Low temperature	• Low temperature
Refs.	S. Datta and B. Das, *Appl. Phys. Lett.* **56**, 665 (1990).	Y. Ohno *et al.*, *Nature* **402**, 790 (1999).	T. Gruber *et al.*, *Appl. Phys. Lett.* **78**, 1101 (2001).	K. Yakushiji *et al.*, *Appl. Phys. Lett.* **78**, 515 (2001).

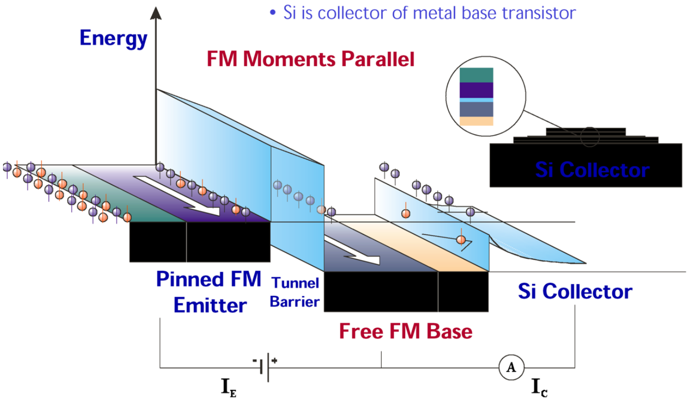
Spin Valve / Magnetic Tunnel Transistors

Spin valve transistor : *



Magnetic tunnel transistor : †

- MTJ prepared on H-terminated n doped Si
- MTJ forms emitter and base of metal base transistor
- Si is collector of metal base transistor



Combining semiconductor with GMR / TMR devices :

→ First step towards all metal devices

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† S. S. P. Parkin, *1st Int'l Sch. on Spintronics and Quantum Info. Tech.*, May 13-15, 2001 (Maui, HI, USA).