2234-18

Meeting of Modern Science and School Physics: College for School Teachers of Physics in ICTP

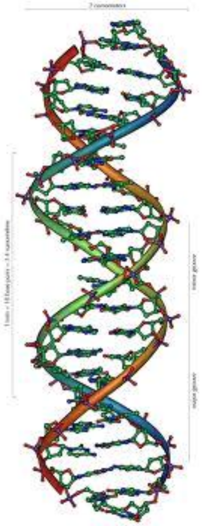
27 April - 3 May, 2011

Information storage

Igor Lukyanchuk
University of Picardie
Amiens
France

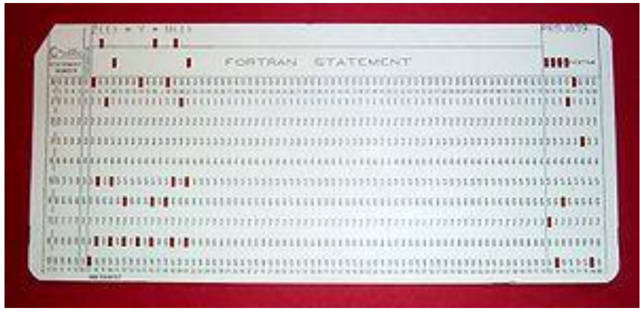
Igor Lukyanchuk

Information Storage



For computers

40-70s: Mechanical…



50-90s electronic

2000… Materials…

Tendencies in technology

“Macro”
1m-1cm-1mm
Mecanical devices

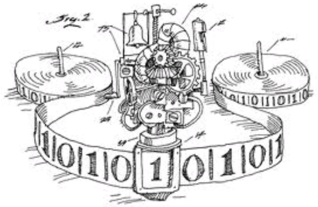
“Micro”
1μm–1mm
Electronic devices

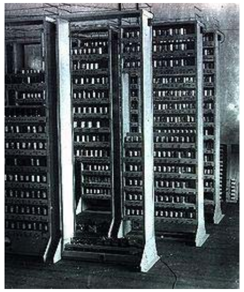
“Nano*”
10nm–1μm
Functional materials

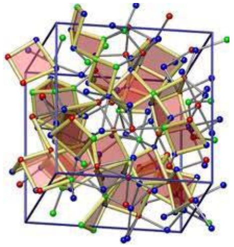
bc… 50s

40s-2000

90s-…





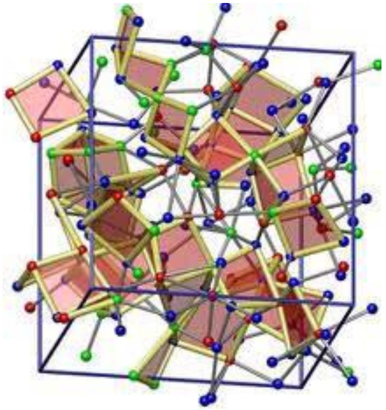


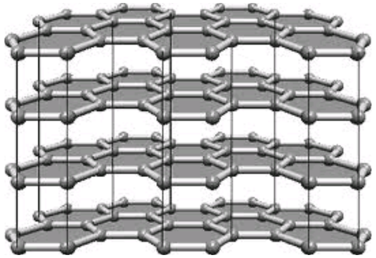
Technology: structural material and molecular level

*See also: **Wednesday, April, 27**
10.00-11.00 **Yuri GALPERIN**
Introduction to nano-physics

Objective: what « smart » properties of material can be used for memory storrage?

What ! Physical Principle is beoyond?





See also: Thursday, April, 28
8.30-9.30 **Giuseppe BALESTRINO**
Tailoring of new materials

History:

First computers:

The German Z3 (1941) was the first general-purpose digital **electromechanical**, computer, It used relays for all functions.

Destroyed in a bombing raid on Berlin in December 1943.

Power Consumption: Around 4000 watts

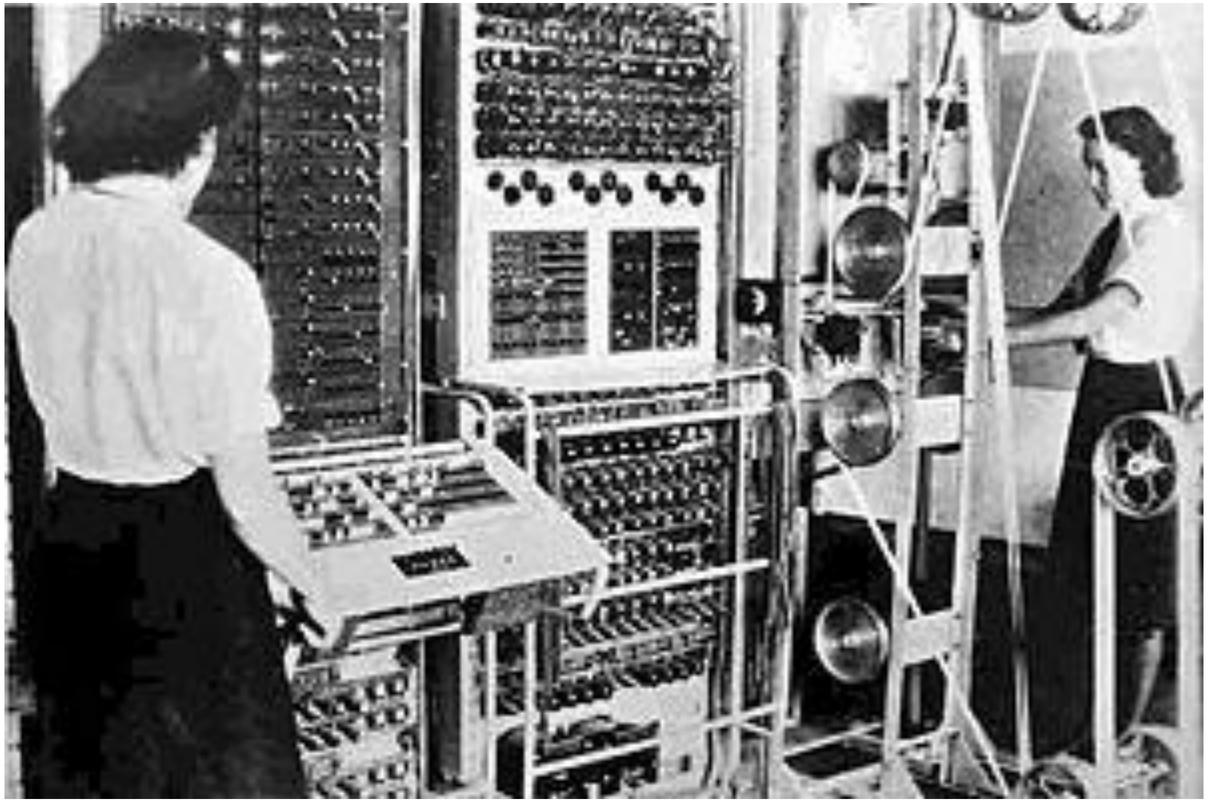
Average calculation Speed: Addition 0.8 seconds Multiplication 3 seconds

Elements: Around 2,000 relays (1,400 for the memory)

Frequency: 5.3 Hertz
Data memory: 64 words with a length of 22 bits

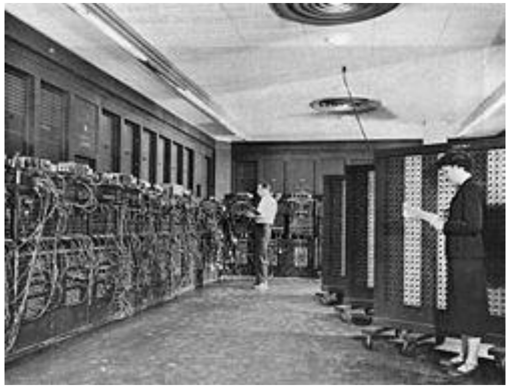
Relays memory

The ten British Colossus computers (used for cryptanalysis starting in 1943) were designed by Tommy Flowers. The Colossus computers were digital, electronic, and were programmed by plugboard and switches, but they were dedicated to code breaking and not general purpose.[24]



ENIAC Electronic Numerical Integrator And Computer) was the first general-purpose digital programming electronic computer.

ENIAC was designed to calculate artillery firing tables for the United States Army's Ballistic Research Laboratory. When ENIAC was announced in 1946 it was heralded in the press as a "Giant Brain"



July 29, 1947, - October 2, 1955

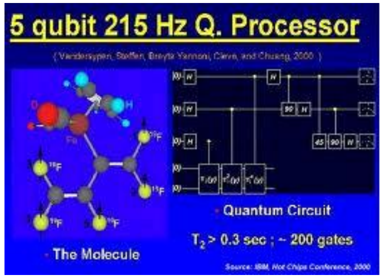
17,468 vacuum tubes, 7,200 crystal diodes, 1,500 relays, 70,000 resistors, 10,000 capacitors
weighed more than 30 tons,
took up 167 m^2, and consumed 150 kW of power

Vacuum tube memory

From Computer Desktop Encyclopedia
Reproduced with permission.
© 1998 IBM Corporation

« Our days »

Future ….



5 qubit 215 Hz Q. Processor

(Vandersypen, Steffen, Breyta, Yannoni, Cleve, and Chuang, 2000)

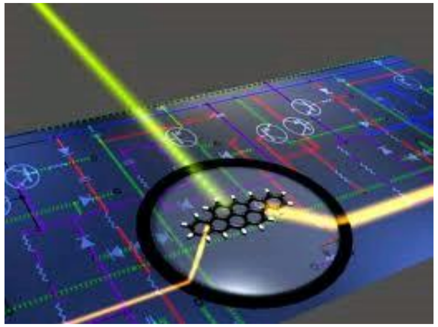
- The Molecule

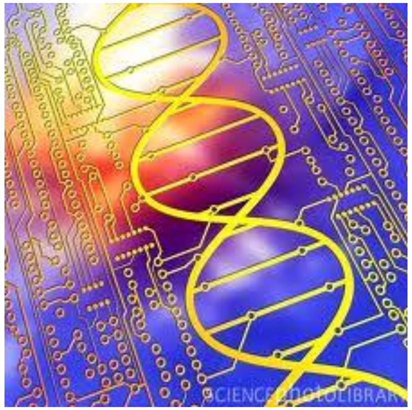
- Quantum Circuit

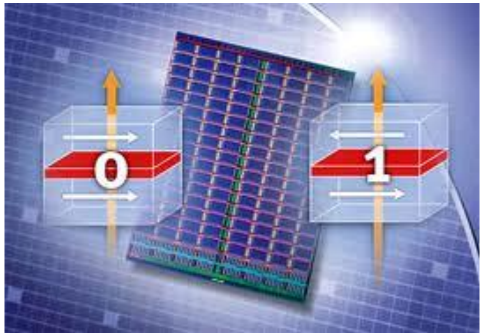
$T_2 > 0.3$ sec ; ~ 200 gates

Source: IBM, Hot Chips Conference, 2000

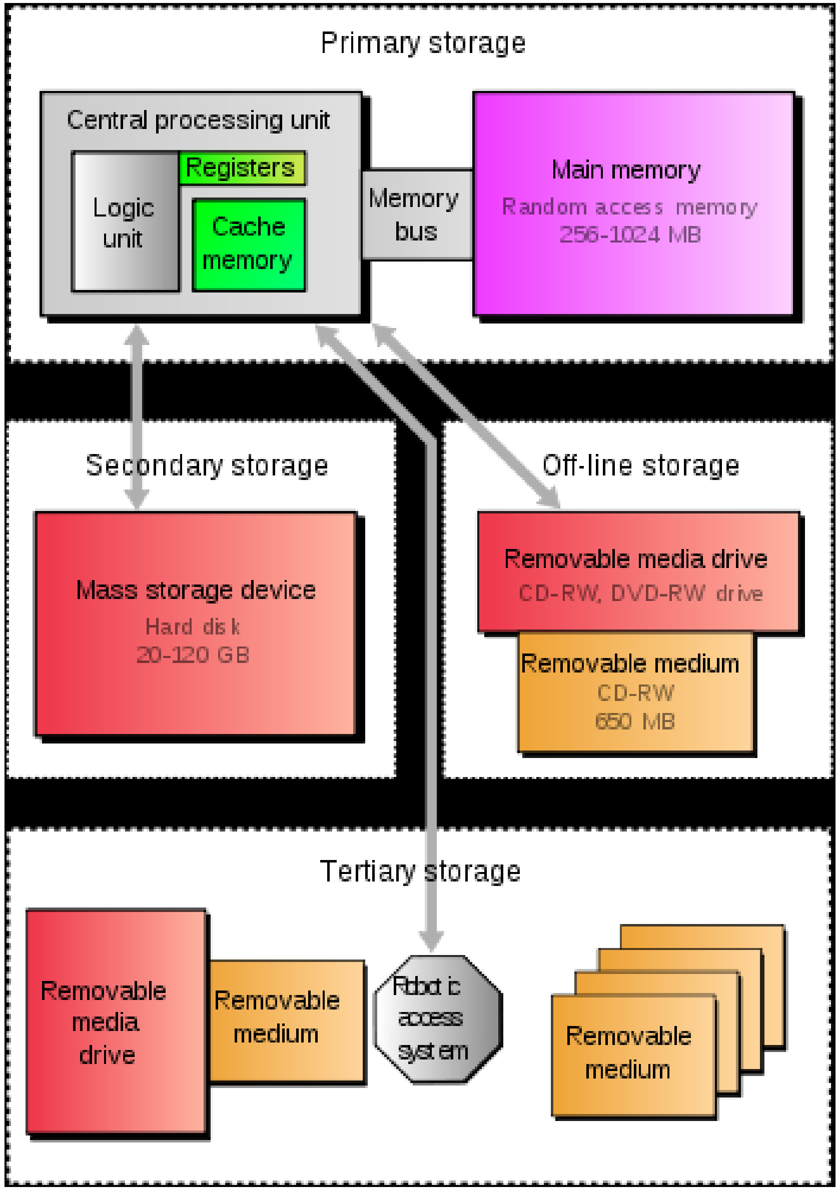
Quantum computer*
Chemical computer,
DNA computing,
Optical computer,
Spintronics based computer







* See also: Friday, April, 29
8.30-9.30 **Boris ALTSULLER**
Towards Quantum Computer



Computer data storage

Hierarchy of storage

Volatile Memory (temporary)

Dynamic RAM and Static RAM in computer

requires power to maintain the stored information

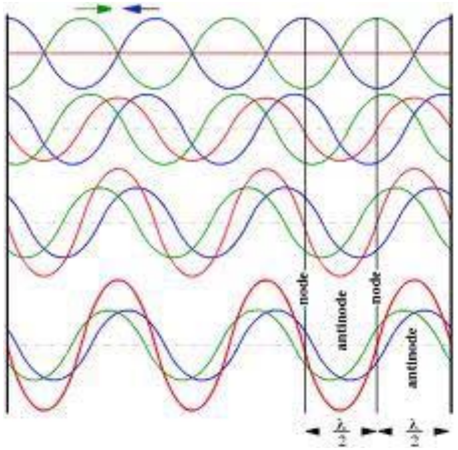
History…

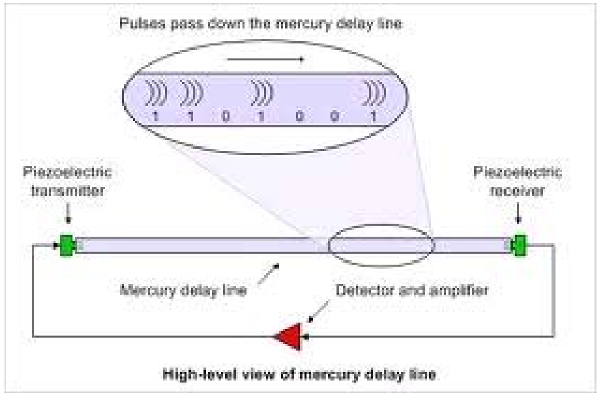
Delay line memory serial-access

invented by J. Presper Eckert in the mid-1940s for use in computers such as the EDVAC and the UNIVAC I

Mercury memory of UNIVAC I (1951)

Physical Principle: Wave propagation in Hg

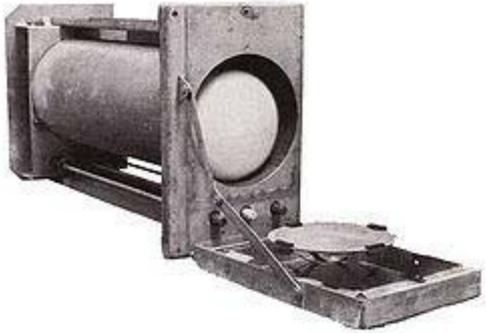




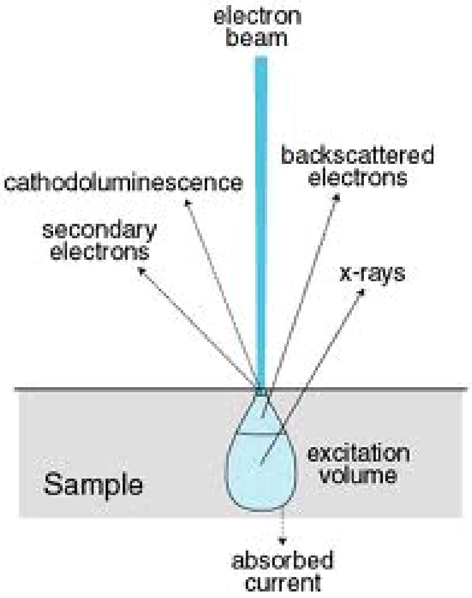
Modification: Electric and Piezoelectric delay lines, THz

Williams tube

developed in about 1946 or 1947, was a cathode ray tube used to electronically store binary data.
It was the first random-access digital storage device



Physical Principle: Cathod Luminiscence



Electronic memory…

ENIAC, vacuum tubes memory 40-50s

Mainfraim semiconducting memory: 60-70

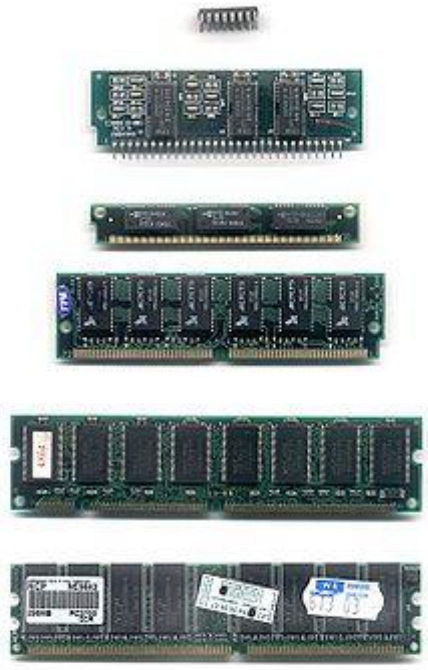
Dynamic random-access memory (**DRAM**) stores each bit of data in a separate capacitor within an integrated circuit.

DRAM is volatile memory

Refresh logic is provided in a DRAM controller which automates the periodic refresh with rate 64 ms -> slowning

The transistors and capacitors are extremely small;
Hundreds of billions can fit on a single memory chip

DRAM is much cheaper per storage cell and because each storage cell is very simple



Common DRAM packages. From top to bottom: DIP, SIPP, SIMM (30-pin), SIMM (72-pin), DIMM (168-pin), DDR DIMM (184-pin).

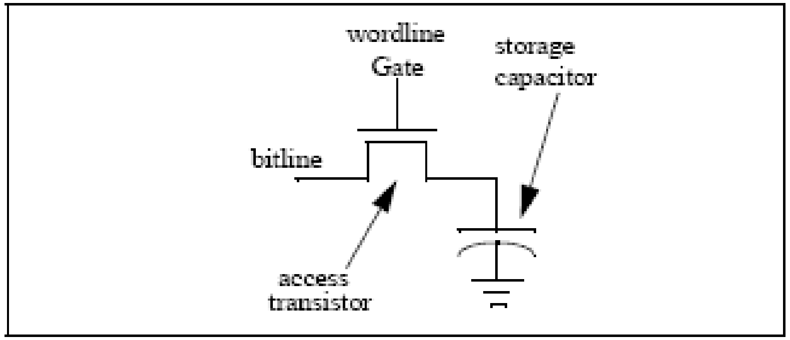
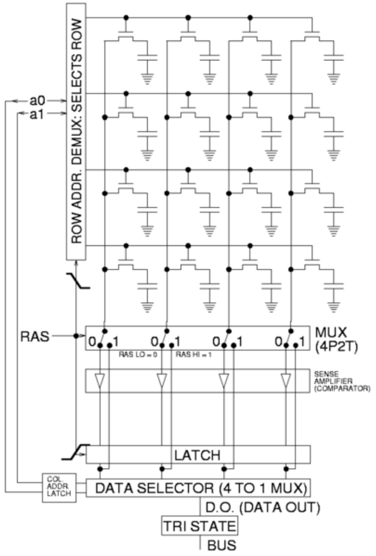
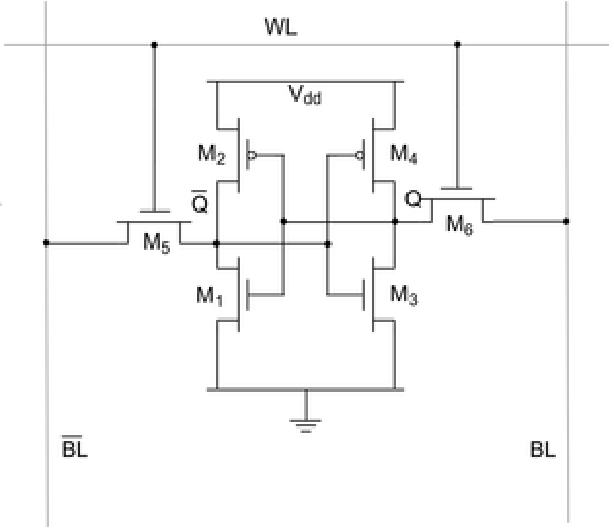


Figure 2.2: Basic 1T1C DRAM Cell Structure.



Static random-access memory (SRAM) does not need to be periodically refreshed, as SRAM uses bistable latching circuitry to store each bit. SRAM exhibits data remanence,[1] but is still *volatile* in the conventional sense that data is eventually lost when the memory is not powered.



Tendency:

Volatile DRAM, SRAM -> Nonvolatile RAM

Use the smart funtional material properties:
Magnetism, ferroelectricity….

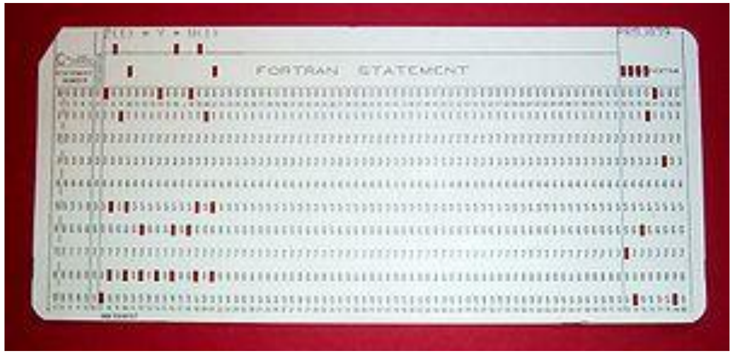
Non-Volatile Memory

Non-volatile memory, in the most basic sense, is computer memory that can retain the stored information even when not powered.

Typically, non-volatile memory either costs more or performs worse than volatile random access memory.

Mecanical recording

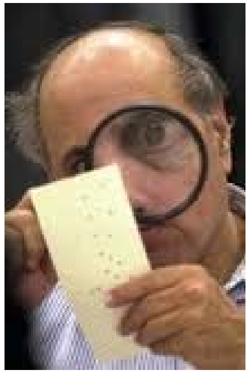
Read only



punched tape

Read only ???

Bunch card, « error corrections »

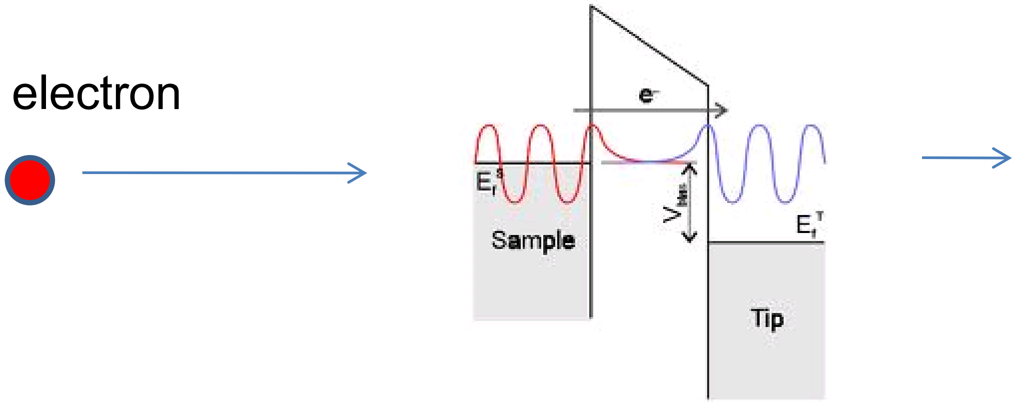


Flash memory

is a non-volatile computer storage chip that can be electrically erased and reprogrammed

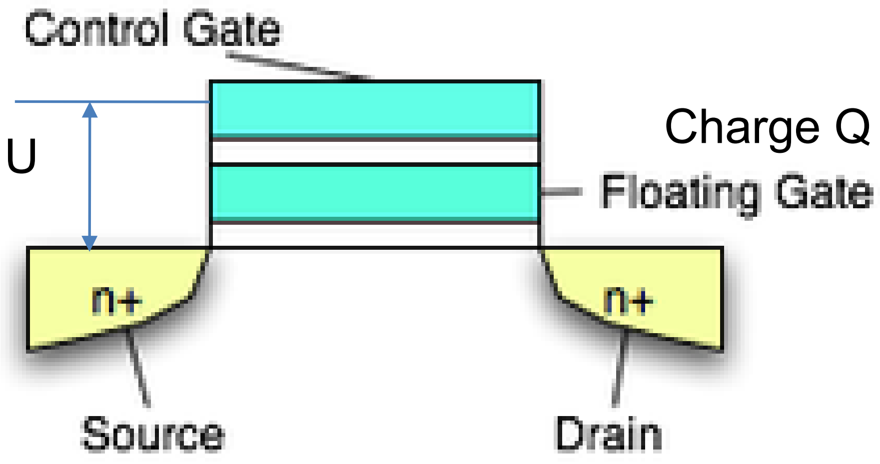
Life-time of read: 10 years

Physical Principle: Electron Tunneling



quantum mechanical phenomenon where a particle **tunnels** through a barrier that it classically could not surmount because its total kinetic energy is lower than the potential energy of the barrier.

Realization floating-gate transistor

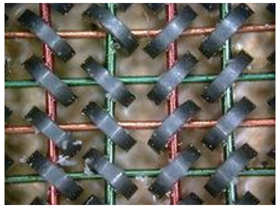


Read: resistence change R(Q) of floating gate

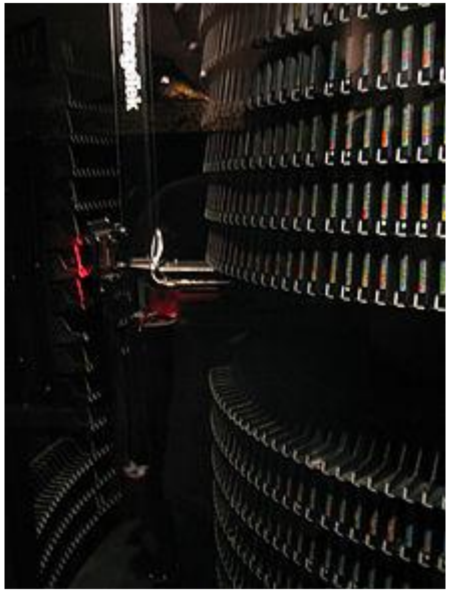
10 years « read » but

endurance is 10,000 to 1,000,000 erase cycles

Magnetic recording



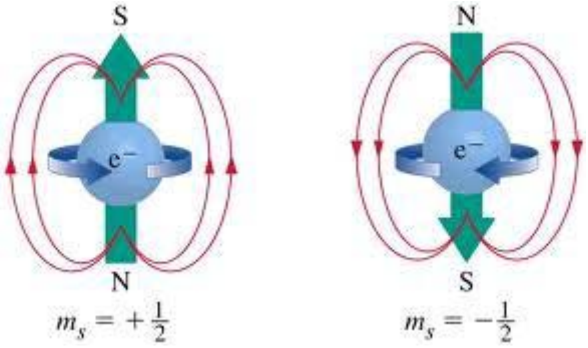
Core RAM memory
50s…, nonolatile !!!



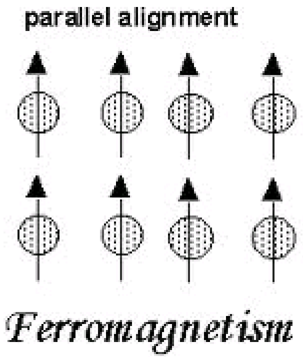
Tertiary storage

Physical Principle: Ferromagnetism

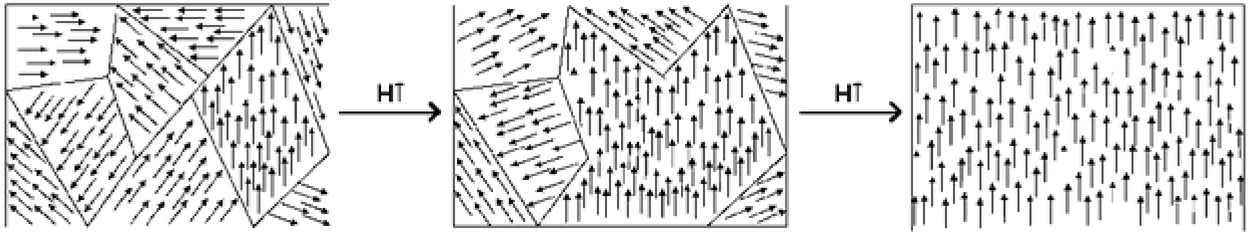
The spin of an electron, combined with its electric charge, results in a magnetic dipole moment and creates a small magnetic field,



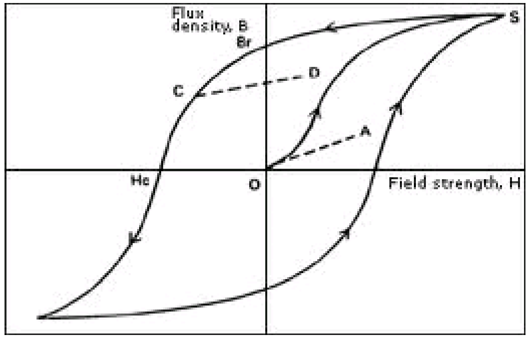
When these tiny magnetic dipoles are aligned in the same direction, their individual magnetic fields add together to create a measurable macroscopic field



Physical Principle: Domains

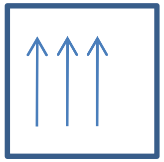


Hysteresis

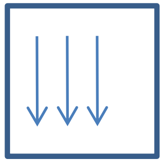


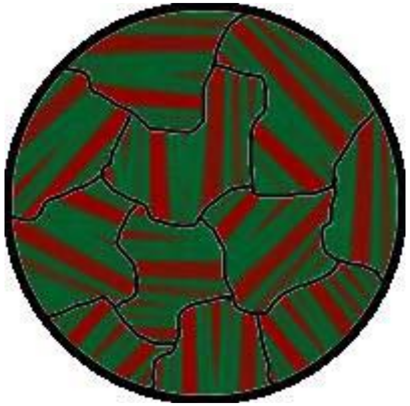
Information storrage:

« up » +1



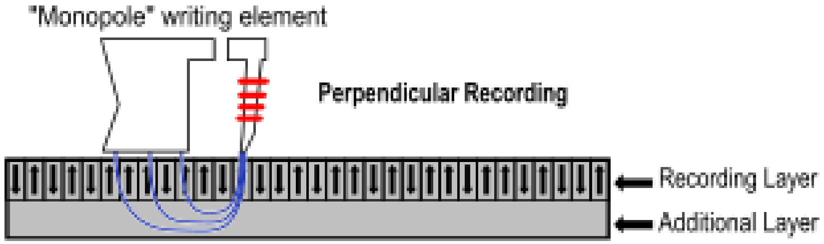
« down » 0





Weiss domains
Microstructure in NdFeB

PRINCIPLE OF MAGNETIC RECORDING



perpendicular recording, first shipped in 2005,[10] and as of 2007 the technology was used in many HDDs.

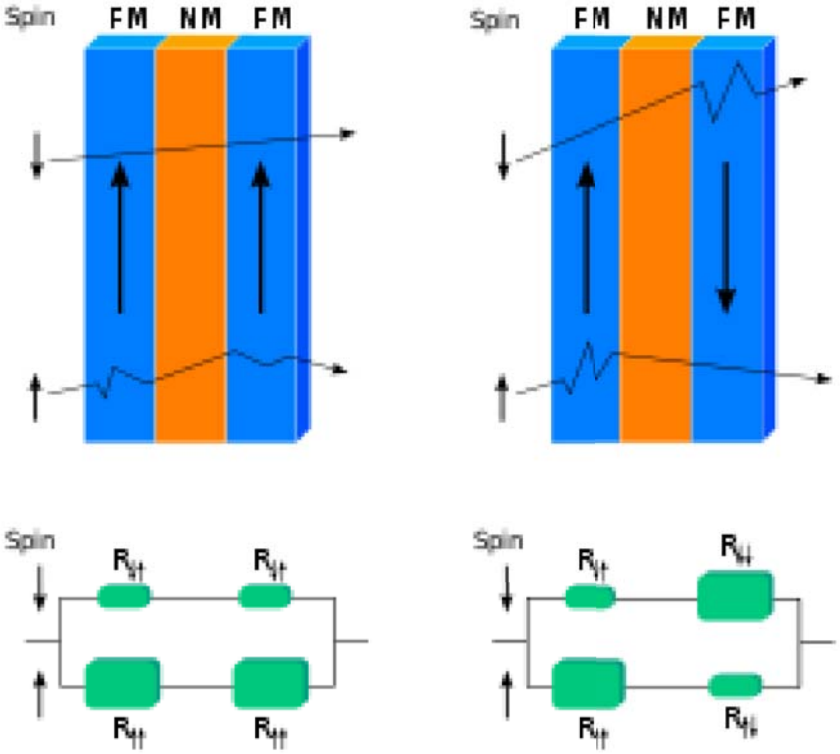
write heads using the electromagnet

read heads using magnetoresistance : the electrical resistance of the head changed according to the strength of the magnetism from the platter.

Physical Principle: (giant) magnetorestence

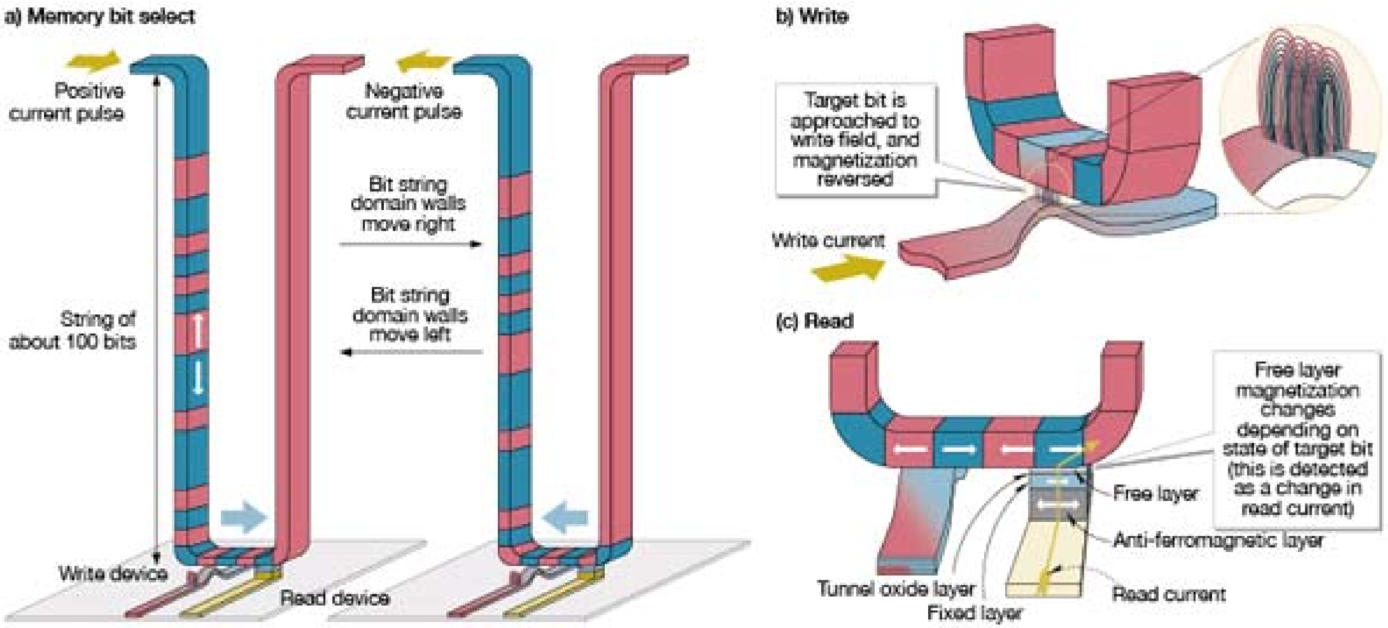
Nobel Prize 2007
Albert Fert and Peter Grünberg

Giant magnetoresistance is a quantum mechanical effect: significant change in the electrical resistance depending on whether the magnetization of adjacent ferromagnetic layers are in a parallel or an antiparallel alignment. The overall resistance is relatively low for parallel alignment and relatively high for antiparallel alignment.

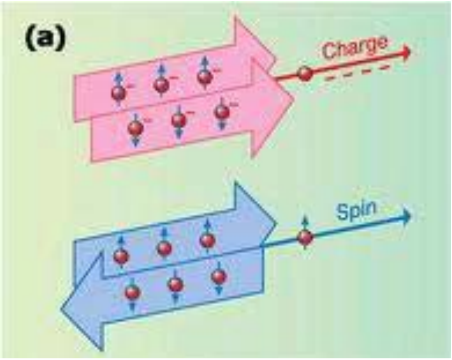


Domain motion (300m/s) - Magnetic Race-Track Memory (IBM 2005))

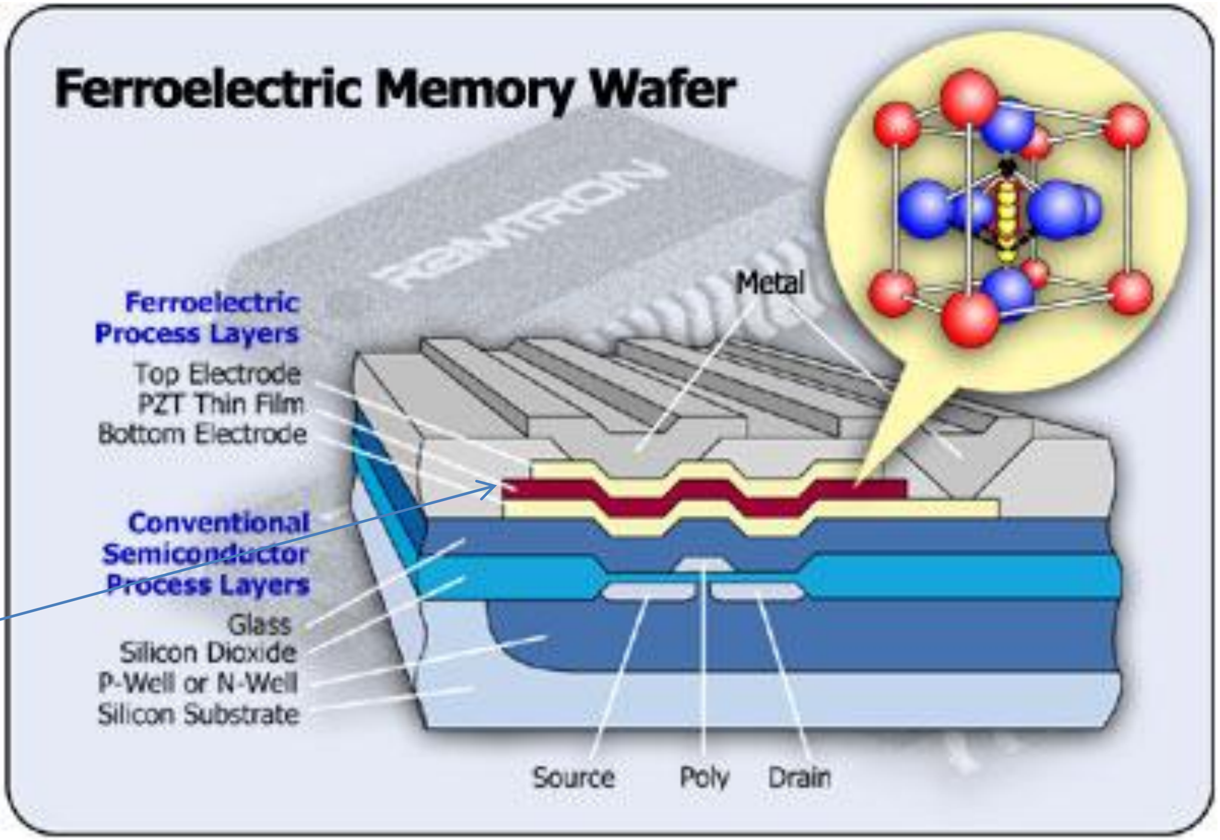
« Read », 1ns



Physical Principle: Spintronics



Ferroelectric Random-Access Memory- **FeRAM**



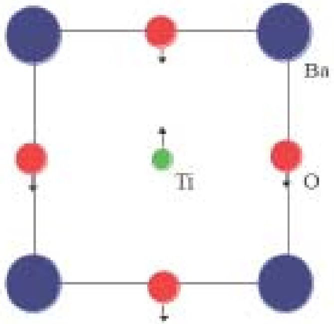
$Pb(Zr,Ti)O3$ (PZT)

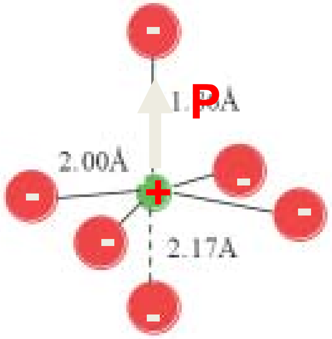
© Ramtron

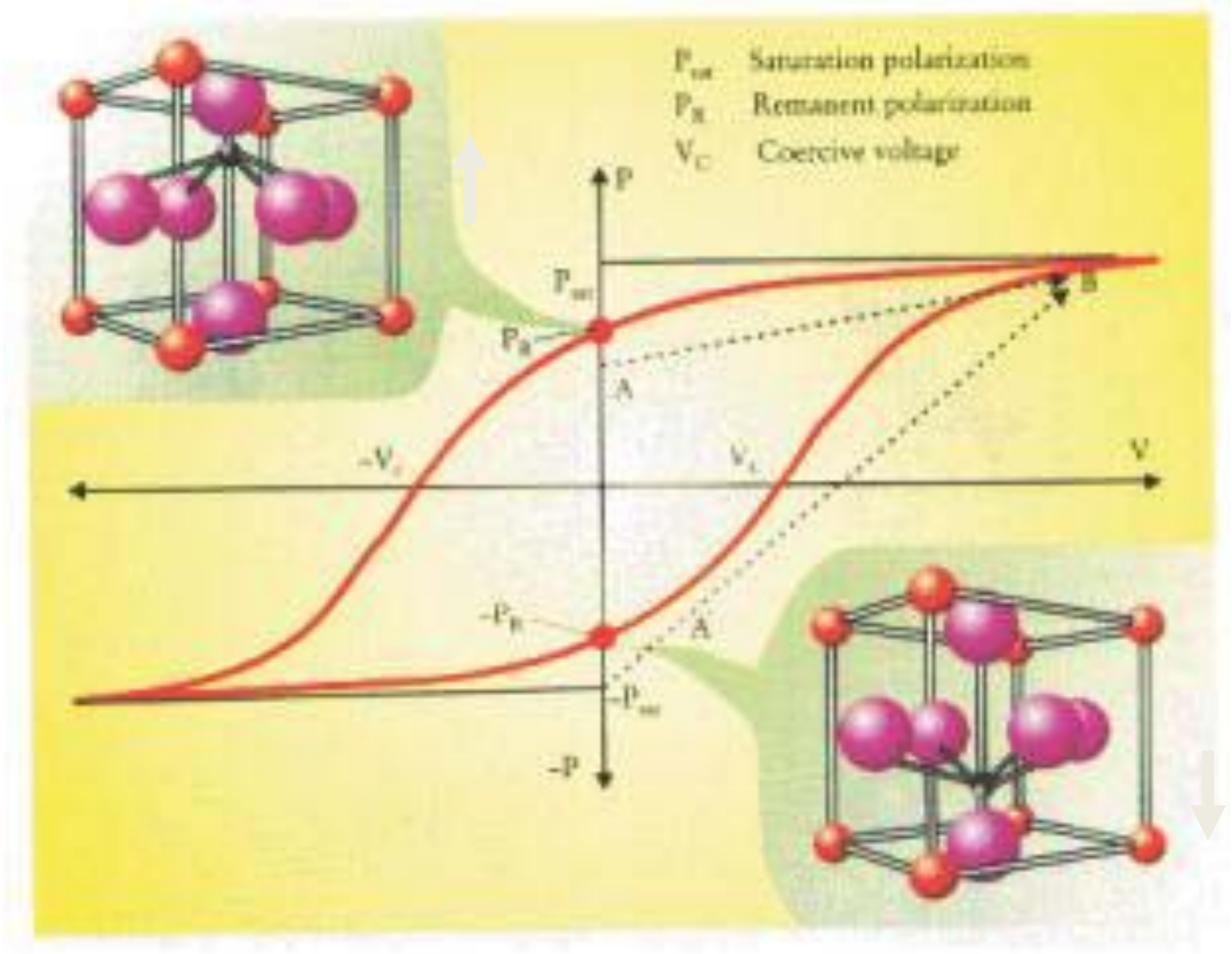
Physical Principle: Ferroelectricity

What is Ferroelectric ?

Crystal with dipolar moment **P**



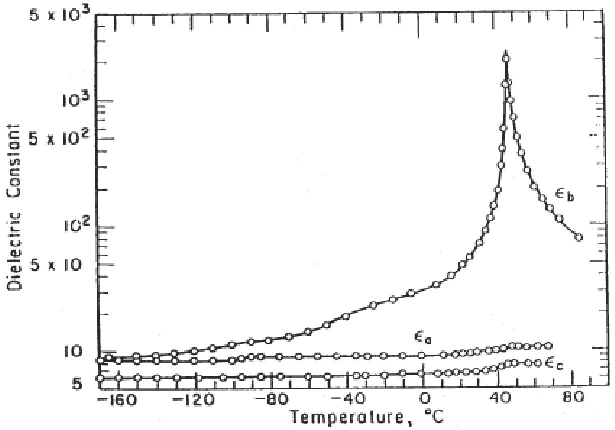




Ferroelectrics: Basic properties

- High – ε

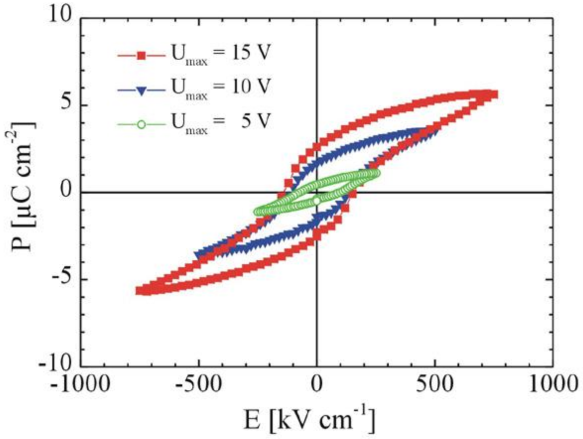
  (Curie behavior)



I-2. Dielectric constant of tri-glycine sulfate as a function of temperature

- Spontaneous polarization,

  Hysteresis



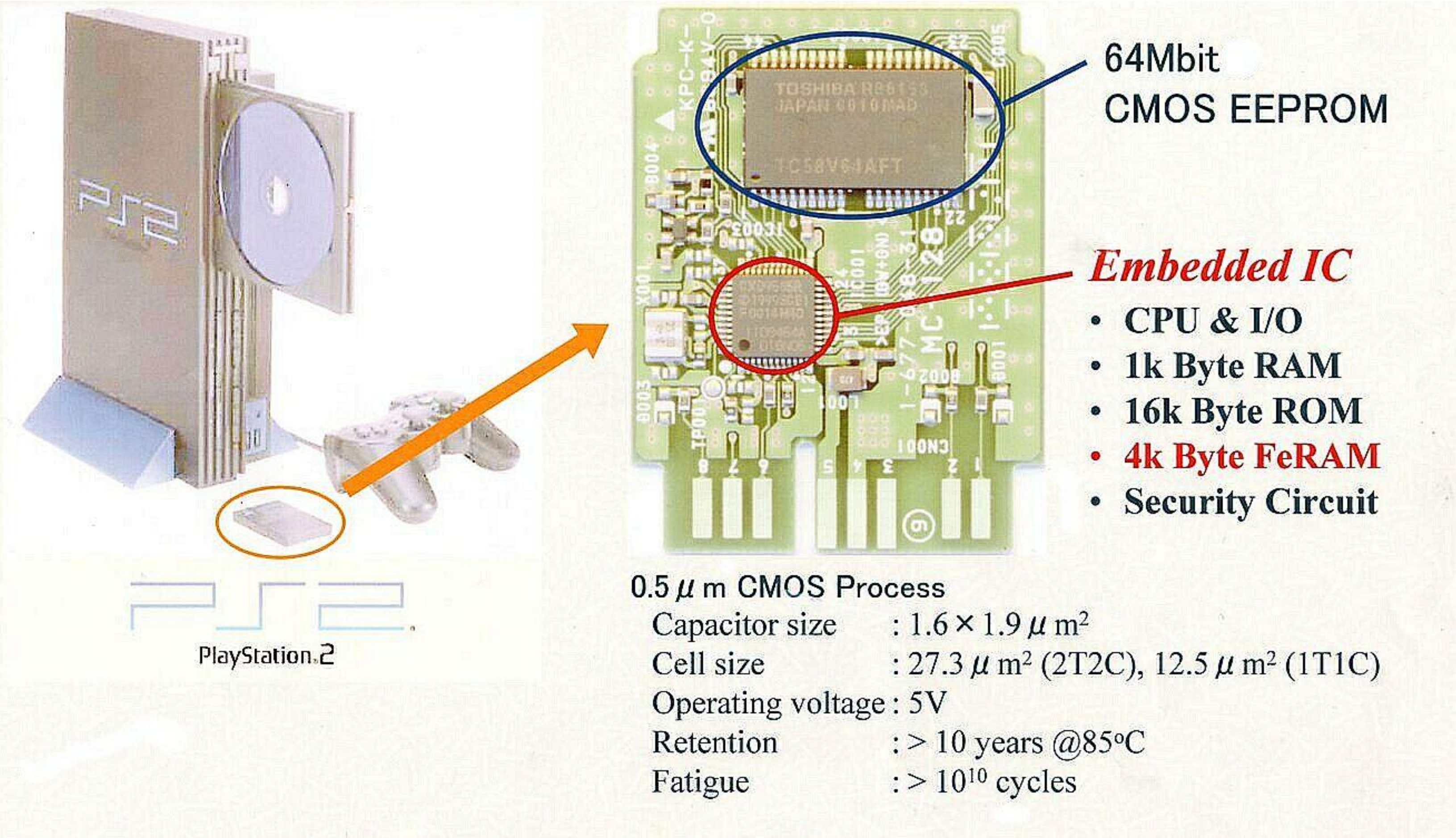
- Various structural transition

- Strong ferro-elastic coupling

Optimization for applications

- High-ε~10.000 (easy polarizability)
- Low hysteresis: <3V (domains, nano-films)
- High-k ~92% (Piezo-response, Relaxors)
- Optical nonlinearity ($LiNbO_3$, TTB)
- Lead-Free composition

Application: Commercial Fujitsu FeRAM



64Mbit
CMOS EEPROM

Embedded IC

- **CPU & I/O**
- **1k Byte RAM**
- **16k Byte ROM**
- **4k Byte FeRAM**
- **Security Circuit**

0.5 μm CMOS Process

Capacitor size	: 1.6 × 1.9 μm²
Cell size	: 27.3 μm² (2T2C), 12.5 μm² (1T1C)
Operating voltage	: 5V
Retention	: > 10 years @85°C
Fatigue	: > 10^{10} cycles

On 24th, January 2008, Japan Railroad announced that all across Japan, the standard JR E-Ticket, E-Purse and credit card are the Panasonic FeRAM card.

C: J. Scott

The future of FeRAMs

International Technology Roadmap for Semiconductors, 2005

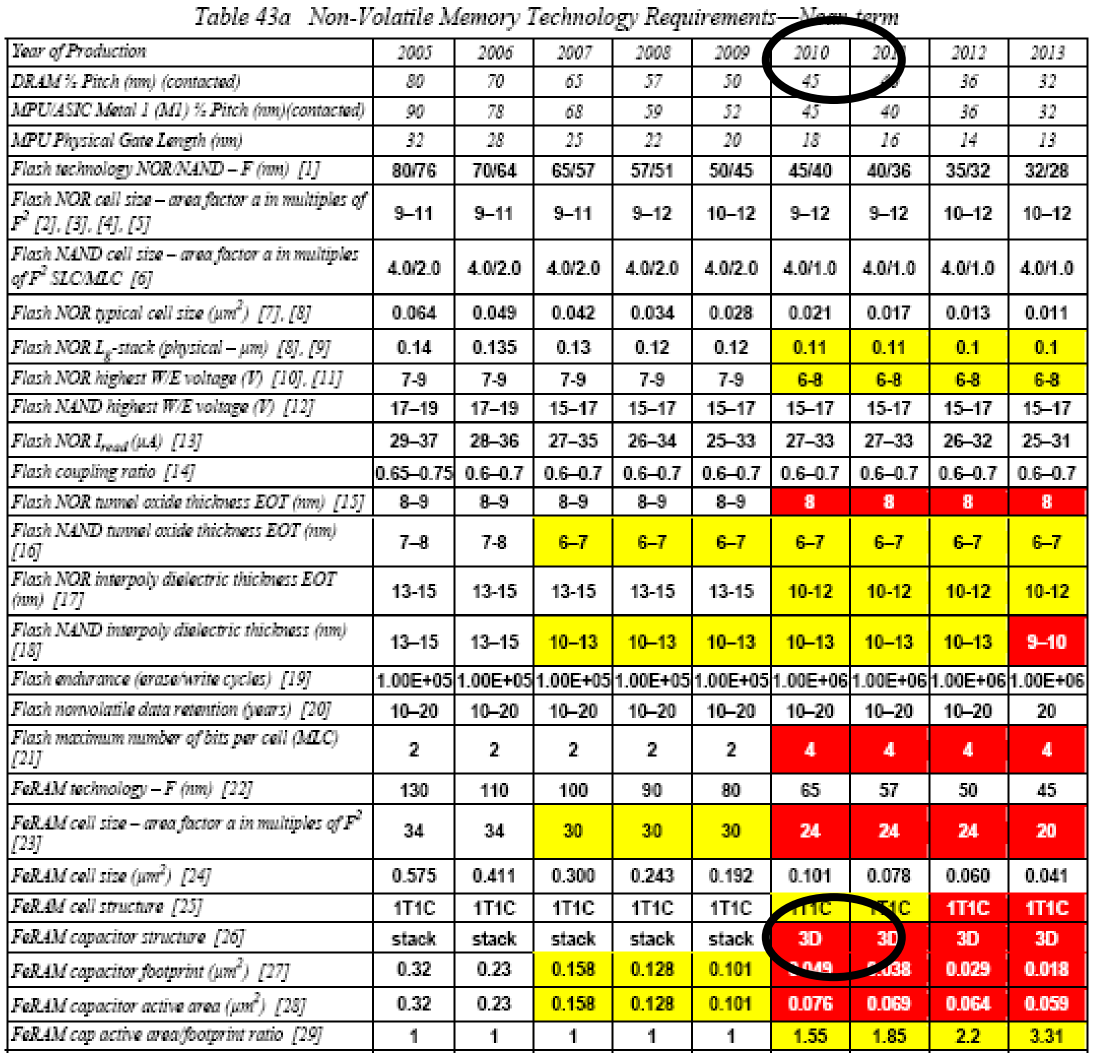
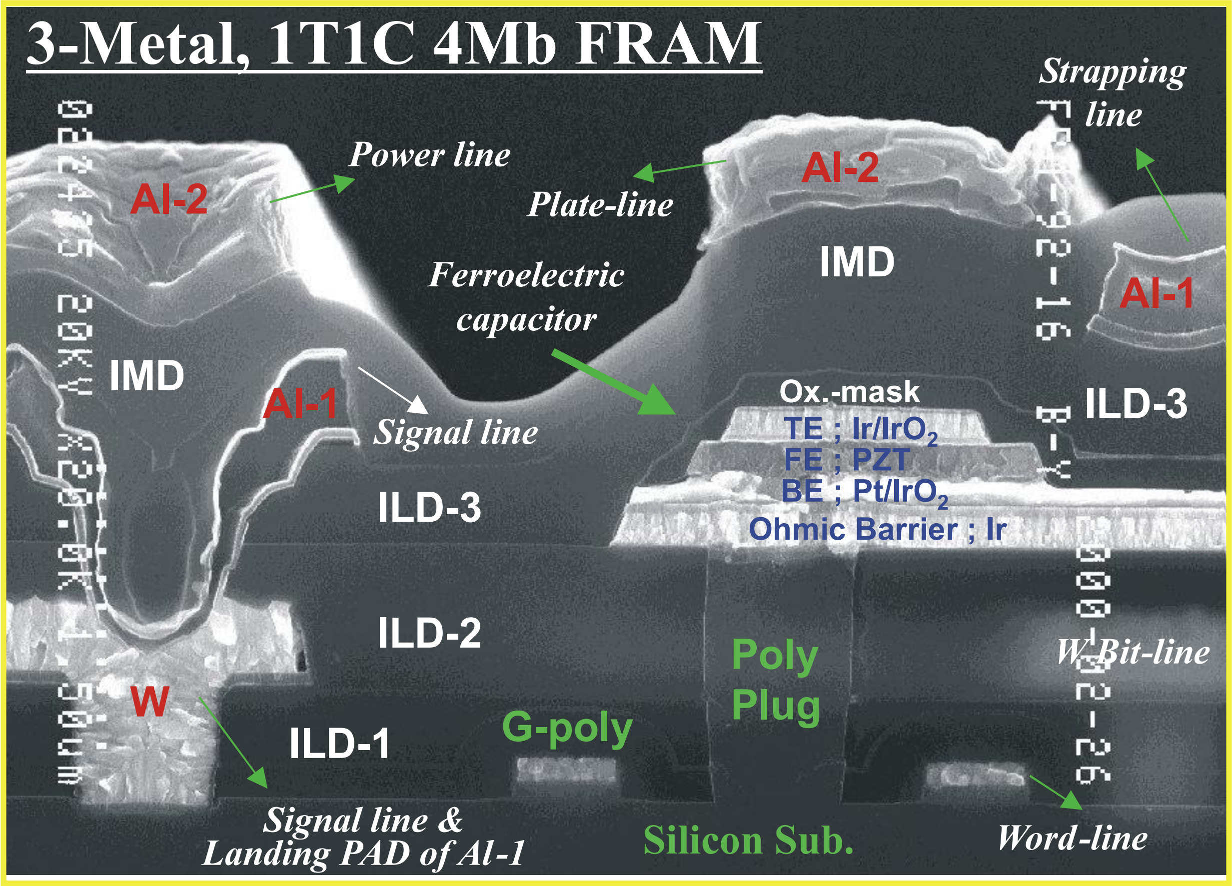


Table 43a Non-Volatile Memory Technology Requirements—Near-term

Year of Production	2005	2006	2007	2008	2009	2010	2011	2012	2013
DRAM ½ Pitch (nm) (contacted)	80	70	65	57	50	45	40	36	32
MPU/ASIC Metal 1 (M1) ½ Pitch (nm)(contacted)	90	78	68	59	52	45	40	36	32
MPU Physical Gate Length (nm)	32	28	25	22	20	18	16	14	13
Flash technology NOR/NAND – F (nm) [1]	80/76	70/64	65/57	57/51	50/45	45/40	40/36	35/32	32/28
Flash NOR cell size – area factor a in multiples of F^2 [2], [3], [4], [5]	9–11	9–11	9–11	9–12	10–12	9–12	9–12	10–12	10–12
Flash NAND cell size – area factor a in multiples of F^2 SLC/MLC [6]	4.0/2.0	4.0/2.0	4.0/2.0	4.0/2.0	4.0/2.0	4.0/1.0	4.0/1.0	4.0/1.0	4.0/1.0
Flash NOR typical cell size (μm^2) [7], [8]	0.064	0.049	0.042	0.034	0.028	0.021	0.017	0.013	0.011
Flash NOR L_g-stack (physical – μm) [8], [9]	0.14	0.135	0.13	0.12	0.12	0.11	0.11	0.1	0.1
Flash NOR highest W/E voltage (V) [10], [11]	7-9	7-9	7-9	7-9	7-9	6-8	6-8	6-8	6-8
Flash NAND highest W/E voltage (V) [12]	17–19	17–19	15–17	15–17	15–17	15–17	15-17	15–17	15–17
Flash NOR I_{read} (μA) [13]	29–37	28–36	27–35	26–34	25–33	27–33	27–33	26–32	25–31
Flash coupling ratio [14]	0.65–0.75	0.6–0.7	0.6–0.7	0.6–0.7	0.6–0.7	0.6–0.7	0.6–0.7	0.6–0.7	0.6–0.7
Flash NOR tunnel oxide thickness EOT (nm) [15]	8–9	8–9	8–9	8–9	8–9	8	8	8	8
Flash NAND tunnel oxide thickness EOT (nm) [16]	7–8	7-8	6–7	6–7	6–7	6–7	6–7	6–7	6–7
Flash NOR interpoly dielectric thickness EOT (nm) [17]	13-15	13-15	13-15	13-15	13-15	10-12	10-12	10-12	10-12
Flash NAND interpoly dielectric thickness (nm) [18]	13–15	13–15	10–13	10–13	10–13	10–13	10–13	10–13	9–10
Flash endurance (erase/write cycles) [19]	1.00E+05	1.00E+05	1.00E+05	1.00E+05	1.00E+05	1.00E+06	1.00E+06	1.00E+06	1.00E+06
Flash nonvolatile data retention (years) [20]	10–20	10–20	10–20	10–20	10–20	10–20	10–20	10–20	20
Flash maximum number of bits per cell (MLC) [21]	2	2	2	2	2	4	4	4	4
FeRAM technology – F (nm) [22]	130	110	100	90	80	65	57	50	45
FeRAM cell size – area factor a in multiples of F^2 [23]	34	34	30	30	30	24	24	24	20
FeRAM cell size (μm^2) [24]	0.575	0.411	0.300	0.243	0.192	0.101	0.078	0.060	0.041
FeRAM cell structure [25]	1T1C	1T1C	1T1C	1T1C	1T1C	1T1C	1T1C	1T1C	1T1C
FeRAM capacitor structure [26]	stack	stack	stack	stack	stack	3D	3D	3D	3D
FeRAM capacitor footprint (μm^2) [27]	0.32	0.23	0.158	0.128	0.101	0.049	0.038	0.029	0.018
FeRAM capacitor active area (μm^2) [28]	0.32	0.23	0.158	0.128	0.101	0.076	0.069	0.064	0.059
FeRAM cap active area/footprint ratio [29]	1	1	1	1	1	1.55	1.85	2.2	3.31

C: J. Scott

Samsung 4Mb PZT FeRAM

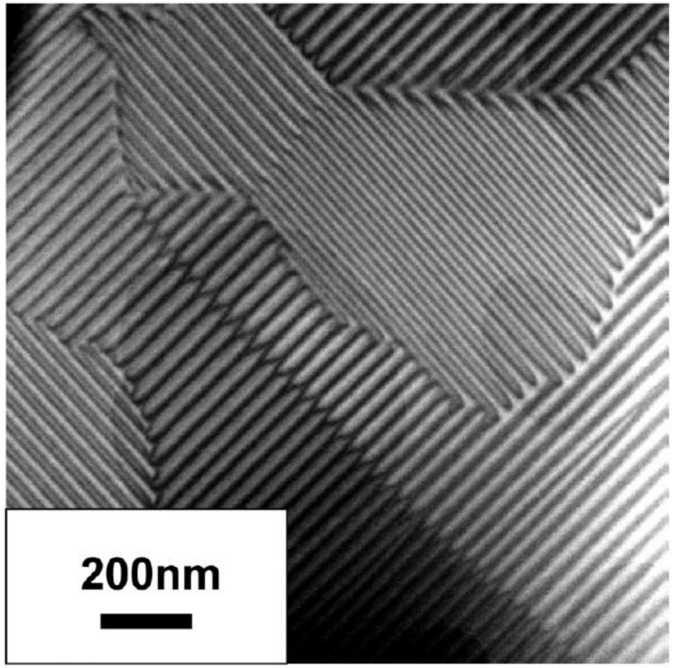


C: J. Scott

Ferroelectric domains as the information storage units

Nanoscale $BaTiO_3$

STEM micrograph of domains in sub 100 nm thick $BaTiO_3$ single crystal



Centre for Ferroics

UNIVERSITY OF CAMBRIDGE

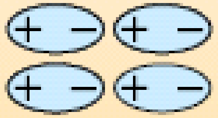
Functional Materials

Ferromagnetism

spontaneous
magnetization

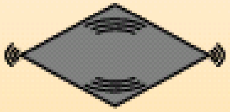
Ferroelectricity

spontaneous
polarization



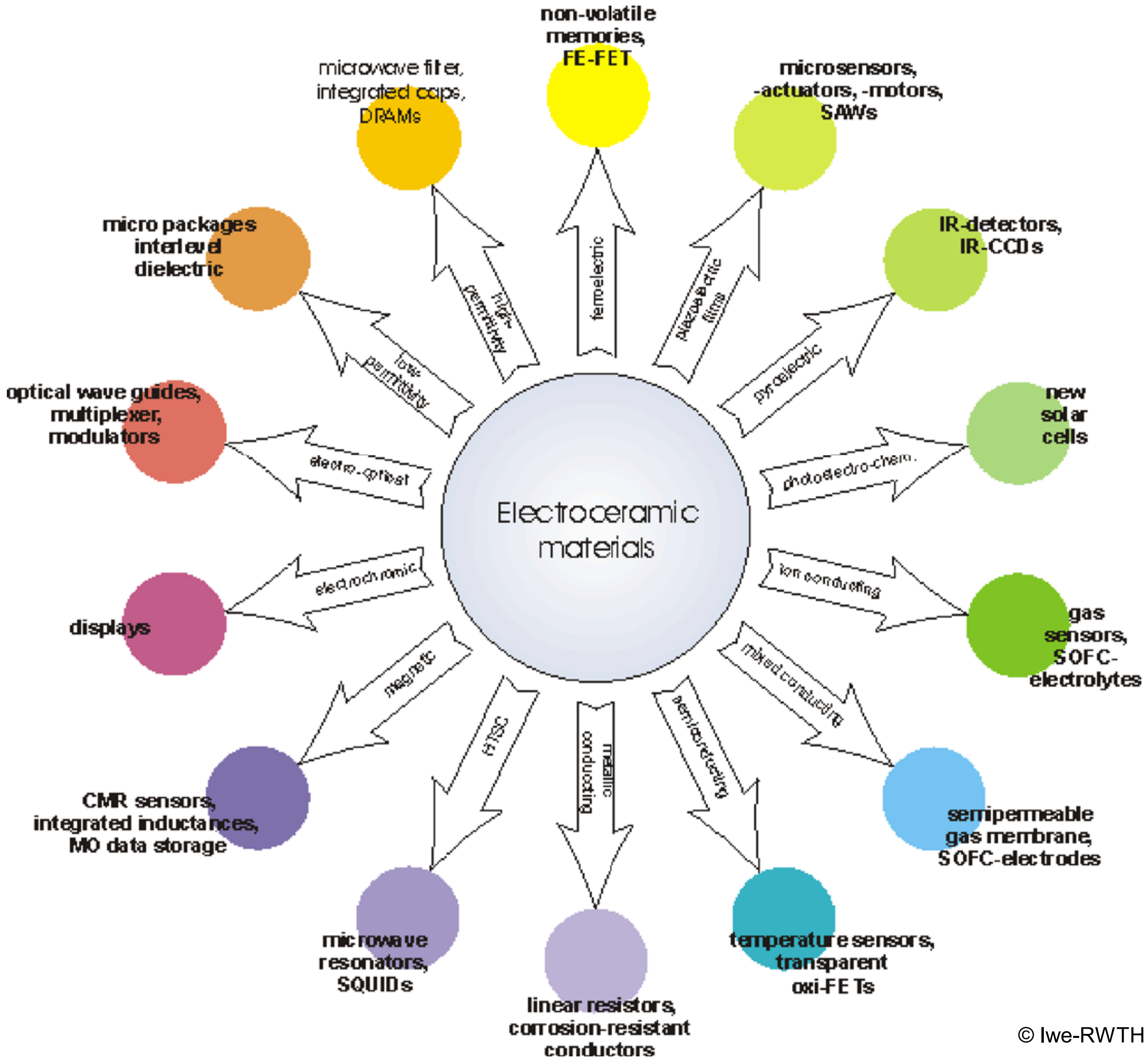
Ferroelasticity

spontaneous
strain



+ Superconductivity ….

APPLICATIONS



Electroceramic materials

non-volatile memories, FE-FET

microsensors, -actuators, -motors, SAWs

IR-detectors, IR-CCDs

new solar cells

gas sensors, SOFC-electrolytes

semipermeable gas membrane, SOFC-electrodes

temperature sensors, transparent oxi-FETs

linear resistors, corrosion-resistant conductors

microwave resonators, SQUIDs

CMR sensors, integrated inductances, MO data storage

displays

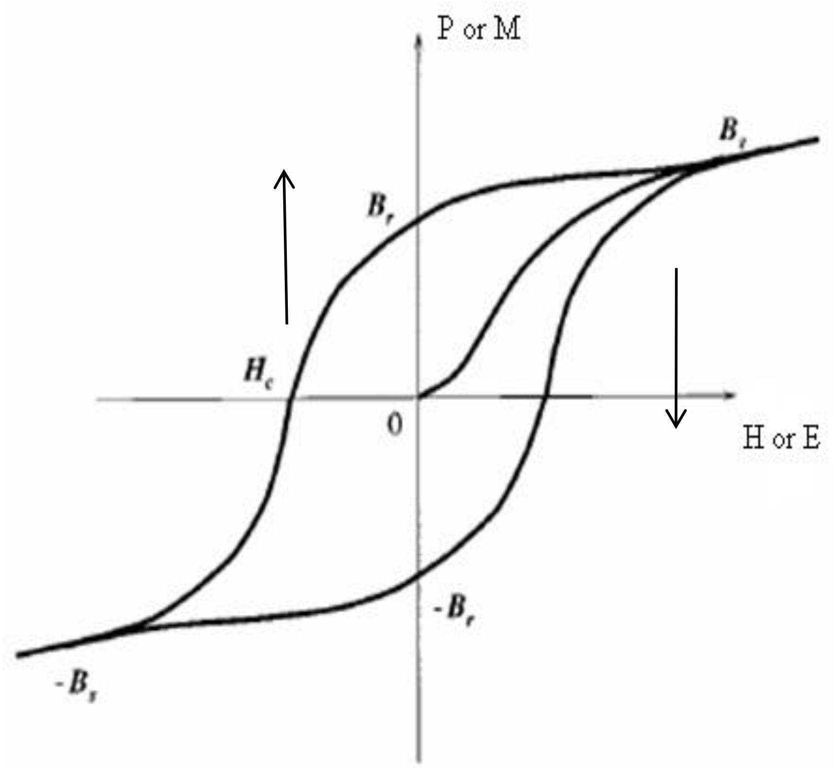
optical wave guides, multiplexer, modulators

micro packages interlevel dielectric

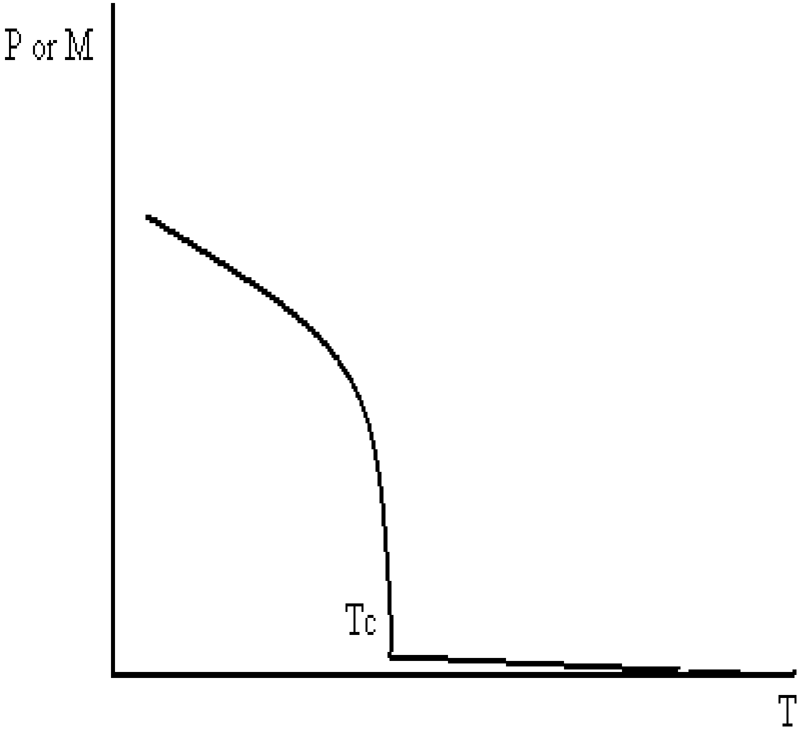
microwave filter, integrated caps, DRAMs

Functional properties of ordered state

Hysterisis Loop



Temperature Dependence



Ferromagnetism.

- Display spontaneous magnetization.
- Produce Hysterisis Loop.
- Can be found mainly in metals.

Ferroelectricity.

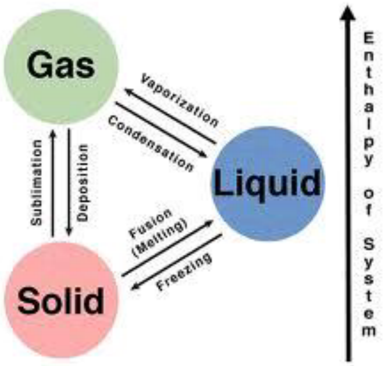
- Display spontaneous polarization.
- Produce Hysterisis Loop.
- Ferroelectrics are insulators

Physical Principle: Phase transition

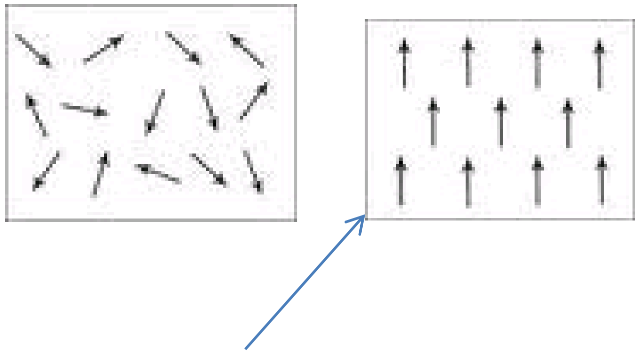
A **phase transition** is the transformation of a thermodynamic system from one phase or state of matter to another.

properties of the medium change, often discontinuously …

Gas-Liquid-Solid



Paramagnet - Ferromagnet



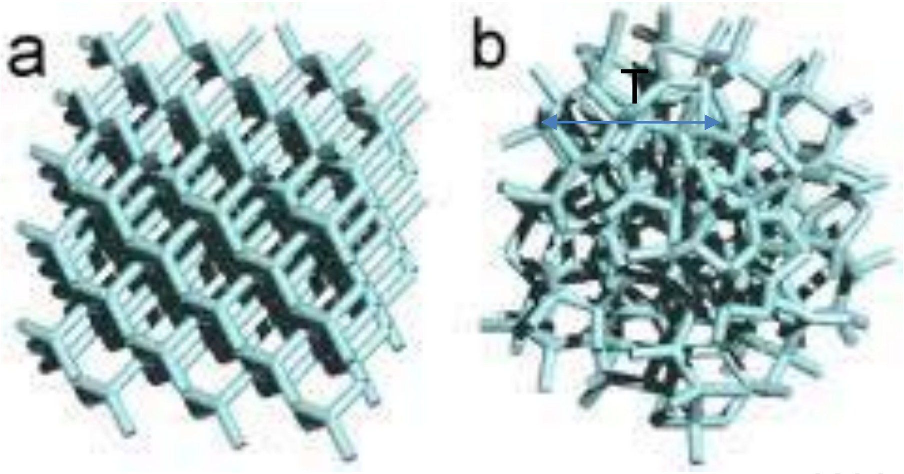
New quality – magnetisation M _ order parameter

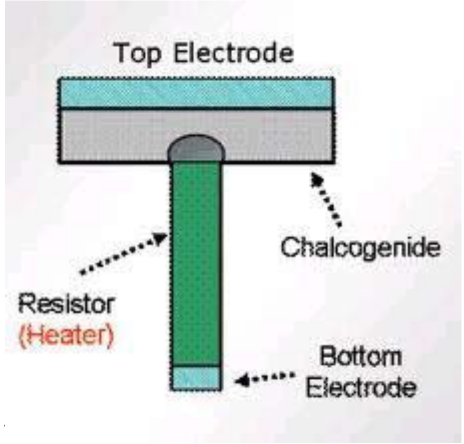
Phase-change non-volatile memory

exploit the unique behavior of chalcogenide glass. With the application of heat produced by the passage of an electric current, this material can be "switched" between two states, crystalline and amorphous.

PRAM vs. Flash

Working material: phase transition in chalcogenide glass





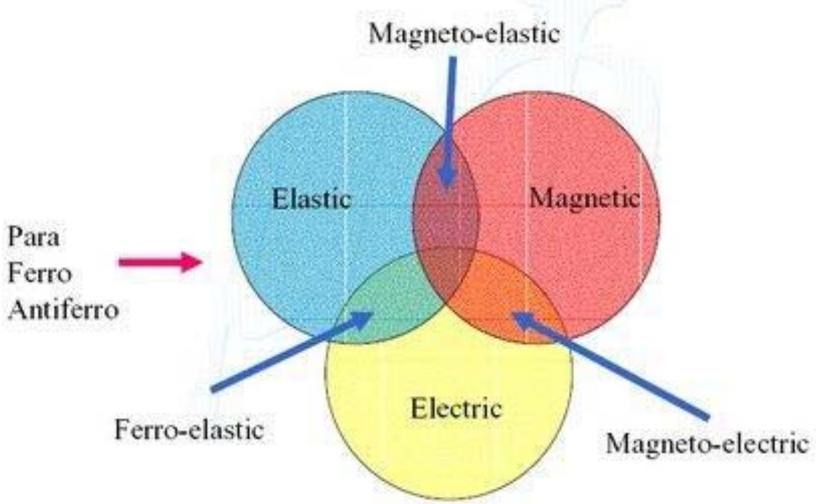
Write: heat pul
Read: R change

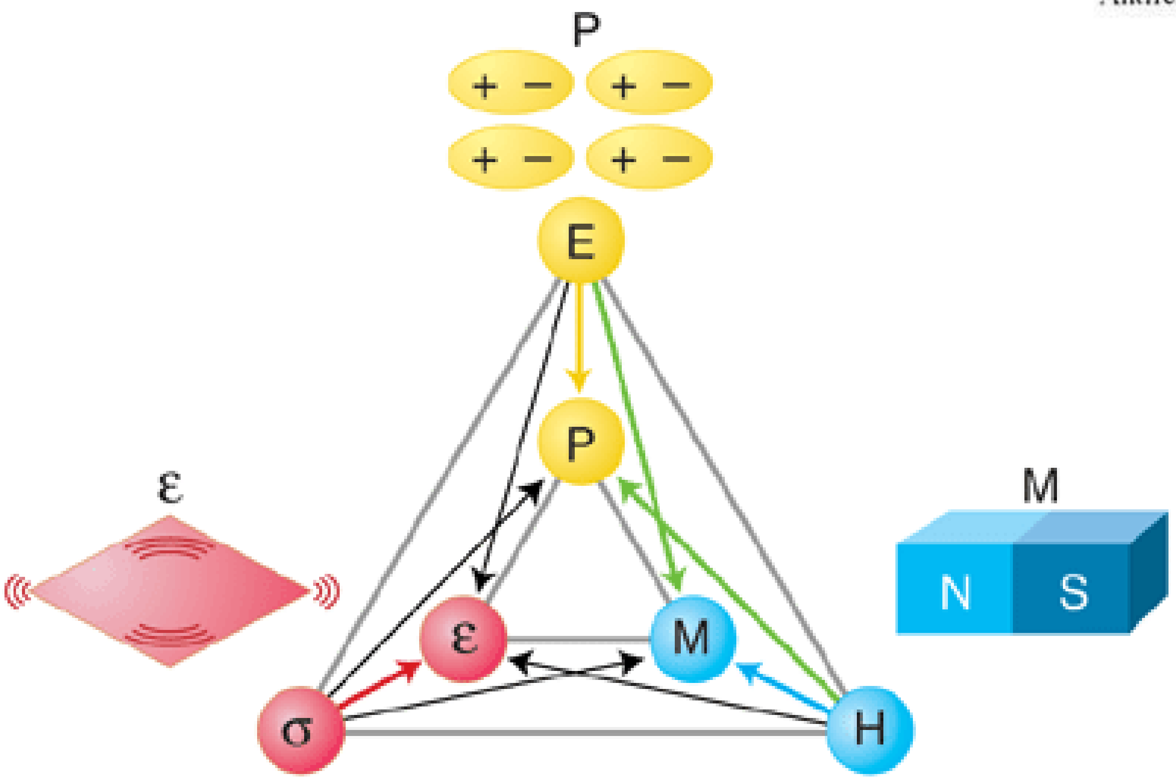
April 2010

Physical Principle: Electron localization

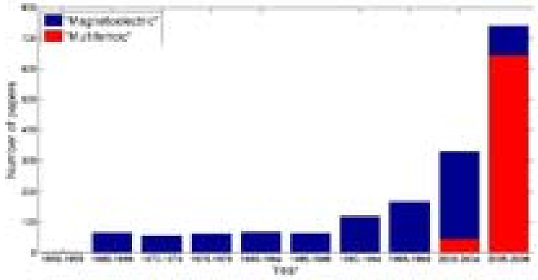
Resistivity of disordered (amorphous)
Material is much higer then of crystal

Tendency: **Multiferroics**



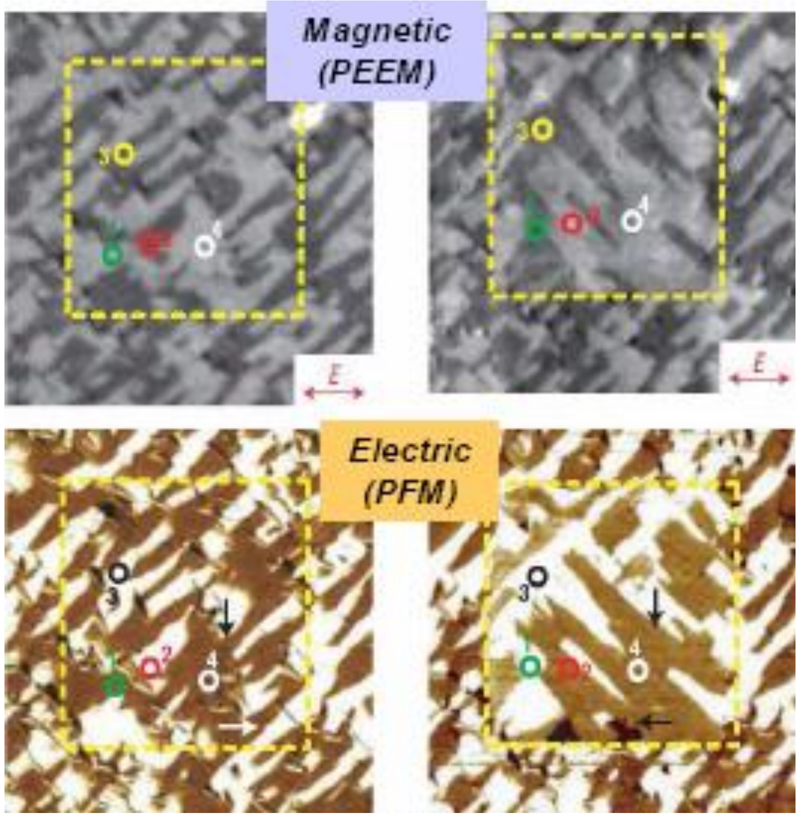


publications



Spalding et. al., *Science*, Vol 309, 391-392 (2005)

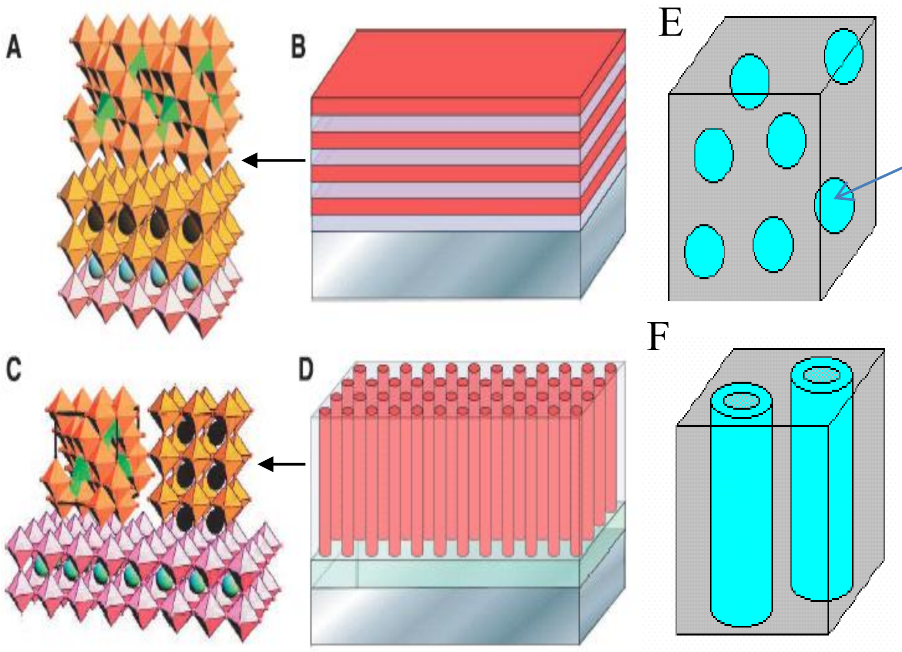
$BiFeO_3$



T. Zhao et al., Nature Mat. 5 (06)

Tendency: composite nanostructures – artificial multiferroics

(Nano-islands, Nano-pillars, nano-wires, Nano-tubes, and nano-thick layers)



Ferroelectric
Inside
Ferromagnet …

Zheng et al., Science 303,661 (2004)

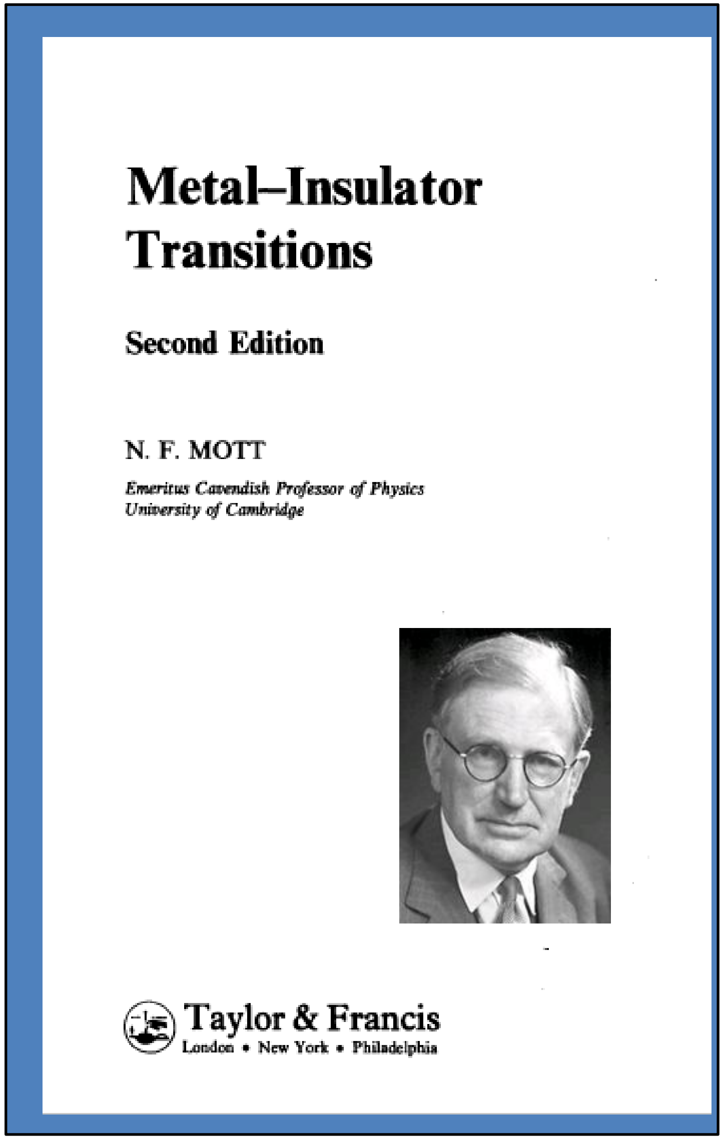
Towards 3D

Optical storage

Tendency: 3D optical data storage

Terabyte …, Petabyte

Physical Principle: Nonlinear Optics

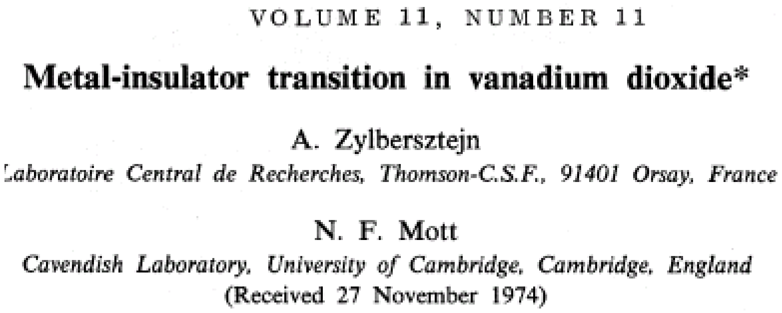


Metal–Insulator Transitions

Second Edition

N. F. MOTT
Emeritus Cavendish Professor of Physics
University of Cambridge

Taylor & Francis
London • New York • Philadelphia



VOLUME 11, NUMBER 11

Metal-insulator transition in vanadium dioxide*

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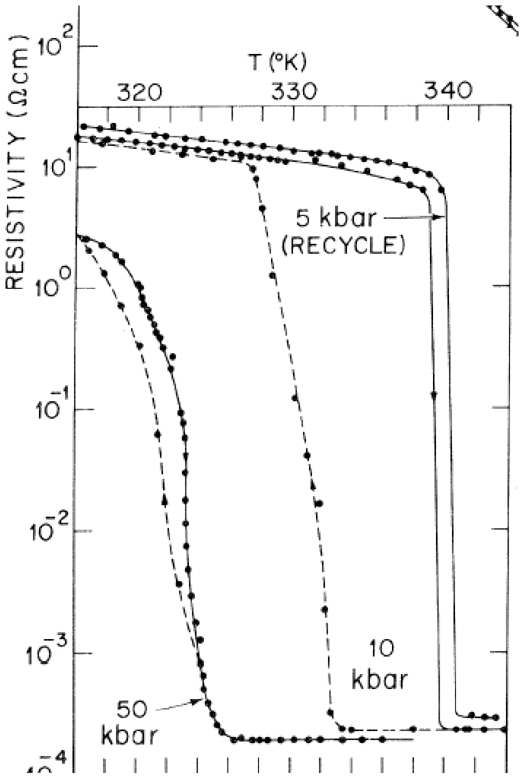
Laboratoire Central de Recherches, Thomson-C.S.F., 91401 Orsay, France

N. F. Mott
Cavendish Laboratory, University of Cambridge, Cambridge, England

(Received 27 November 1974)

VO2



$\Delta R \sim 10^5$,

1st order transition

Monoclinic - Tetragonal
(Insulator) (Metal)

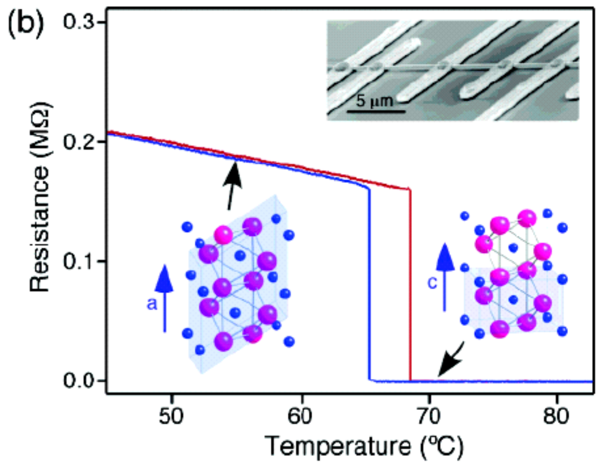
Tc=68°C

Eg=0.6eV

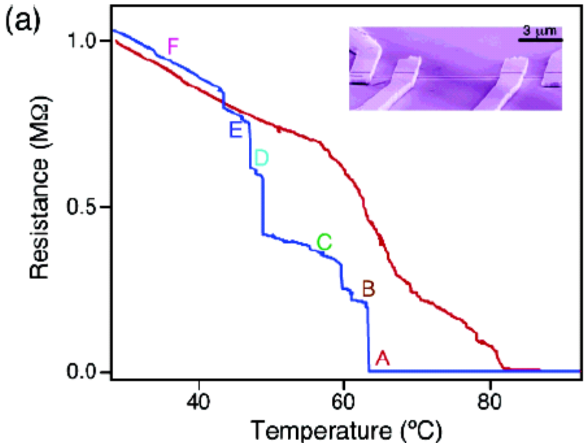
$\Delta c/c = +1\%$, $\Delta a/a = -0.5\%$, $\Delta V/V = 0.44\%$
$\Delta a/a \sim \Delta b/b$

Mott field-effect transistor ?

Suspended VO2 nanobeam



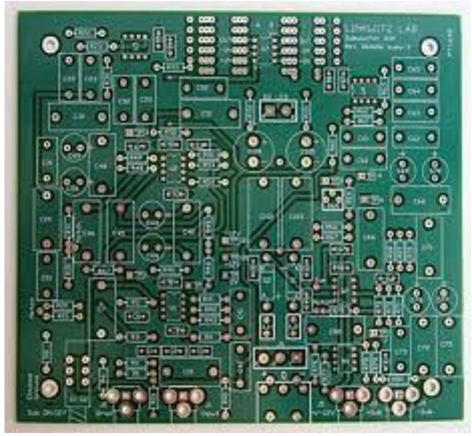
On-substrate VO2 Nanobeam



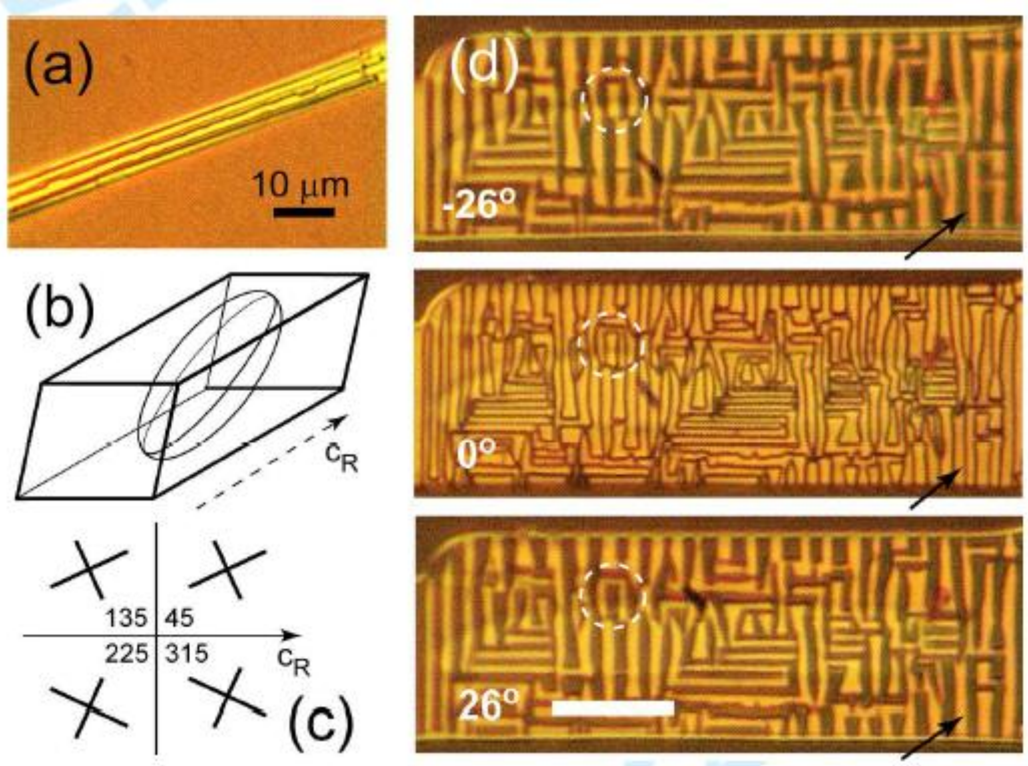
domains between HT and LT Phases

Idea: nano-interconect

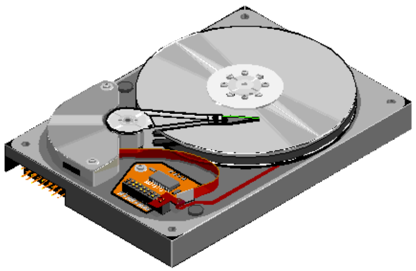
Micro-level



nano-level



CONCLUSION: state of art



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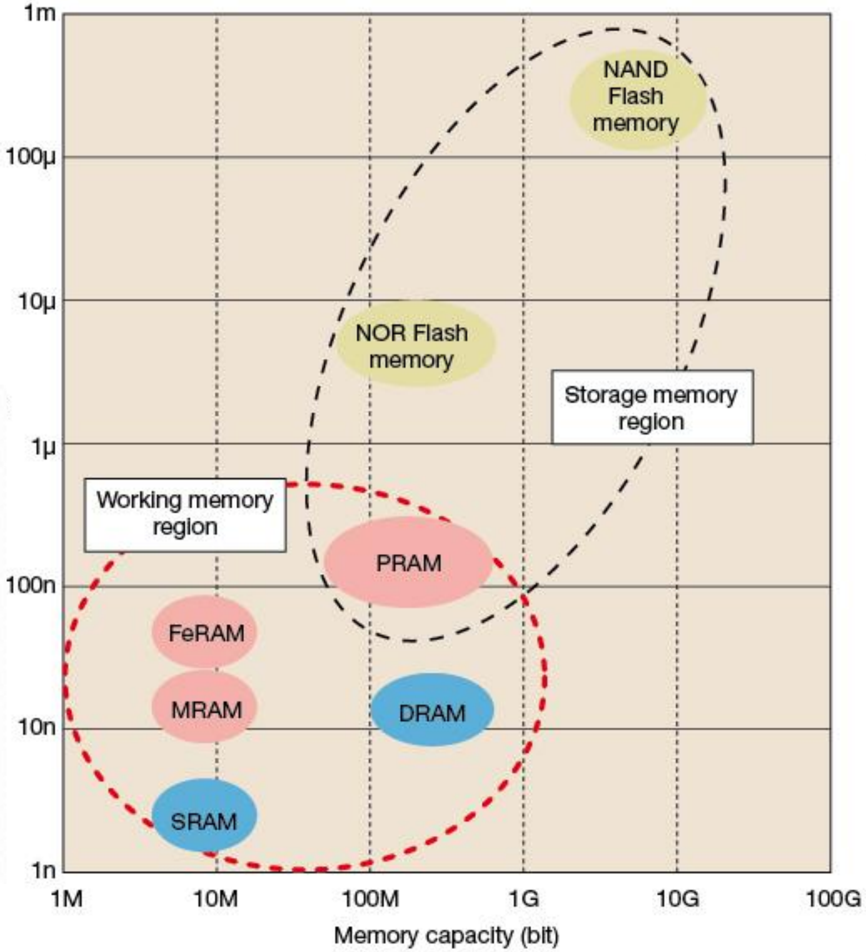


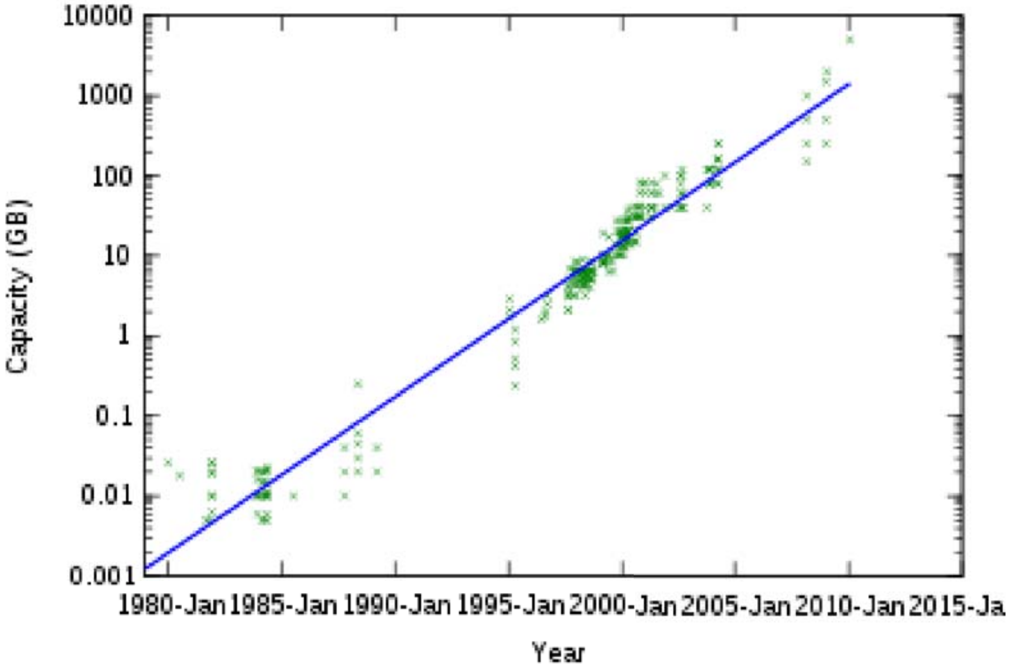
● : Volatile RAM

● : NV-RAM not requiring erase before write

● : Flash memory requiring erase before write

Fig 1 Host of New Non-Volatile RAMs Offer Fast Write, No Data Loss Diagram shows a comparison by write time and memory capacity. NOR Flash memory write time is per-byte, and NAND Flash memory per-page.

Moore's law (DR ROM)



Atomic level is achieved, Whats the next ??????

Saturday, April, 30, 17.30 -18.30 **Giovanni FILOCAMO**

"No fear! Physics helps you"