Spintronics
An Overview

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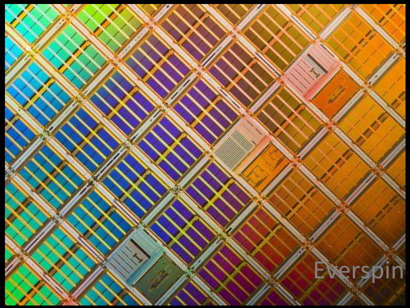

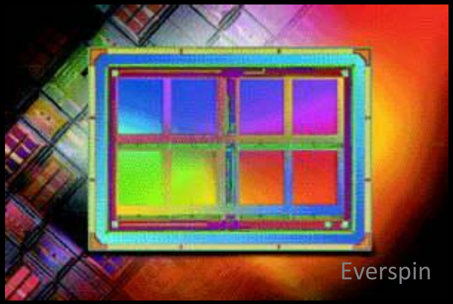

1st NANOTEC Workshop
Granada
January 21th, 2011

CIN2

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Spintronics

An overview

Spintronics. Brief introduction

Current spintronic technologies

- GMR/TMR
- MRAM

Emerging topics:

- RF components
- Spin Logics
- Qubits and Quantum Computing
- Spin Hall effects, Topological Insulators
- Multiferroics
- Spin Thermoelectronics

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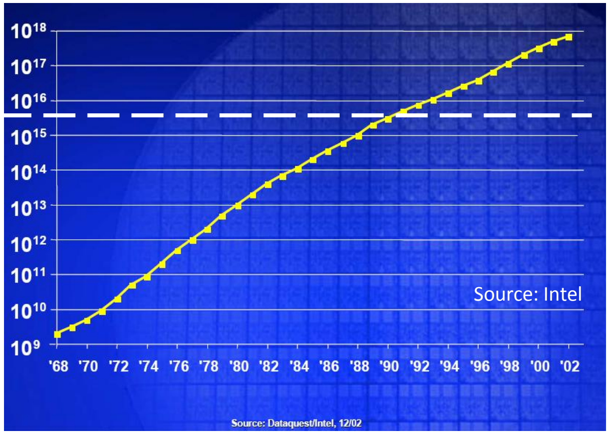
Why spintronics?

The end of Moore s law

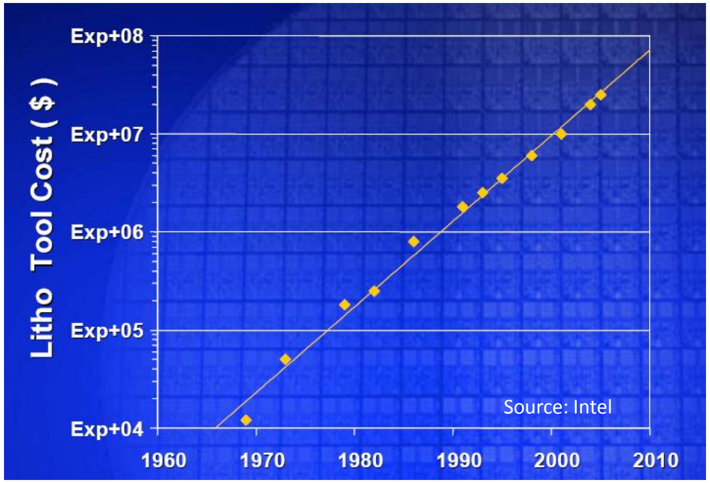
Instructions per second (in millions)

Number of transistors per year

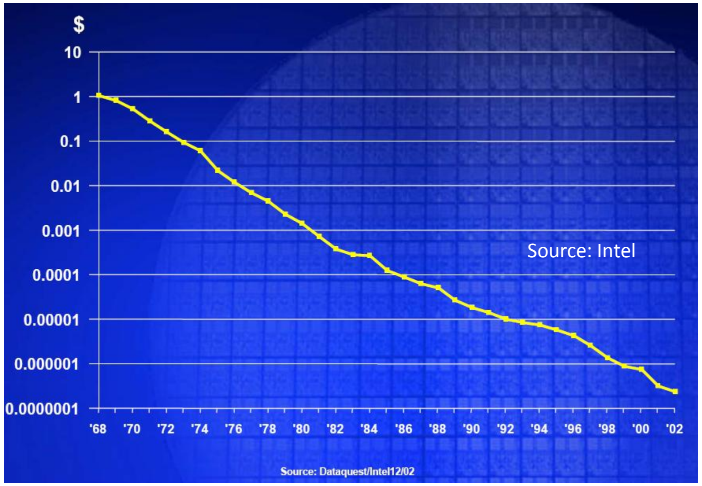


World ant population
Number of raindrops in california per year

Lithography tool cost



Transistor cost



Equivalent to printing one letter in a Newspaper

Dissipation in microprocessor ~100 W (>50% wasted in transistor leakage in the 45 nm node)
Computers approaching 10% use of worlwide electricity

Spin currents vs. charge currents

Non-volatility, transport of information without dissipation

Charge

$$\vec{j}_e = \frac{d}{dt}(q\vec{r}) \qquad \vec{j}_e = q\vec{v}$$

Moving charge, kinetic energy and dissipation

Spín

$$\vec{j}_s = \frac{d}{dt}(\sigma\vec{r}) \qquad \vec{j}_s = \sigma\vec{v} + \dot{\sigma}\vec{r}$$

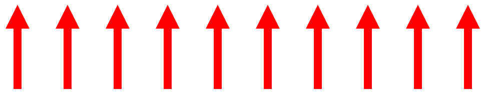
Spin currents are even under time reversal

Electrons do not need to move

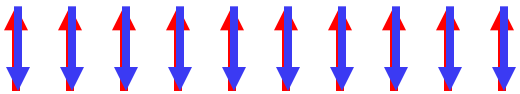
Nonvolatile memory

Possibility to reduce dissipation

Spins in motion



Spin dynamics



J. Shi, *et al.*, Phys. Rev. Lett. **96**, 076604 (2006).

Spintronics

Fundamental physics and applications

Moore's Law

"Beyond" CMOS

SPIN

2010

2015

SPIN

CHARGE

CHARGE

Magnetic memories and magnetic data storage

Spin-based logic

Integrated circuits

Control based on magnetic fields

HDD, MRAM

Spin-polarized charge currents

STT, MRAM, DW

Electric field controlled spin orientation

Spin and magnetization manipulation with electric fields

Pure spin currents

Spin logics and spin transfer with pure spin currents (no charge transport)

Quantum computing

Quantum manipulation and Coupling of spin states

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Multiferroics

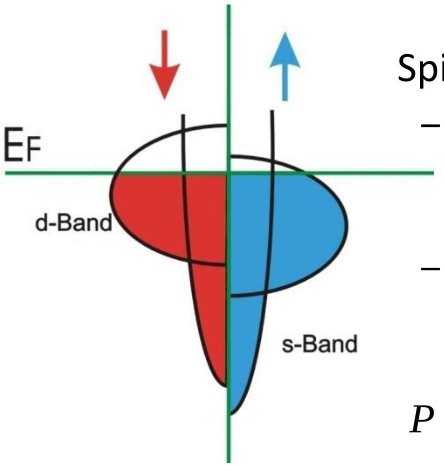
Spin Thermoelectronics

Spin valves (Overview)

Giant magnetoresistance (GMR), tunnel magnetoresistance (TMR)

Two spin channel model (Mott 1930)

Metallic ferromagnets. Spin-up and spin-down are two independent families of carriers

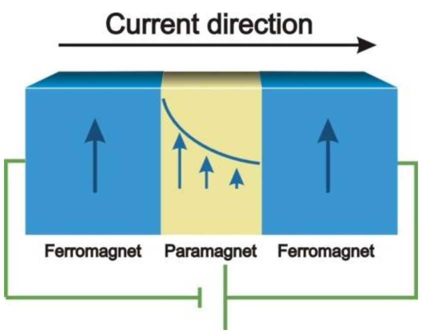


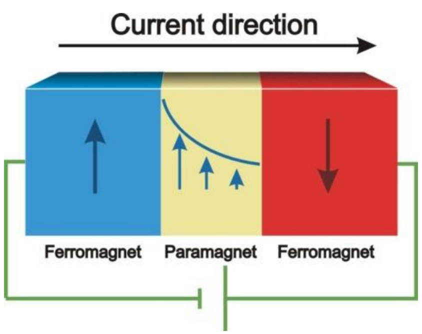
Spin splitting

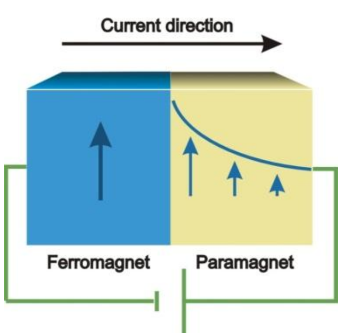
- Different density of states at the Fermi level for spin up and down carriers
- Different mobility for spin up and down carriers

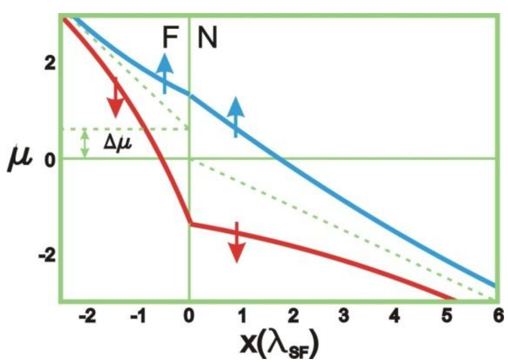
$$P = \frac{N_M - N_m}{N_M + N_m} \qquad -1 \leq P \leq 1$$

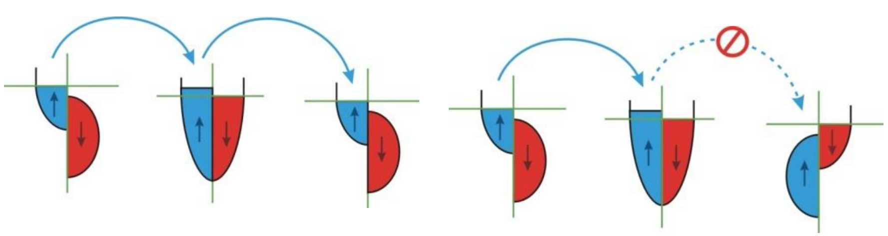
Fert, Grünberg. Nobel Prize 2007











Parallel Magnetization, ↑↑

High conductance

Antiparallel Magnetization, ↑↓

Low conductance

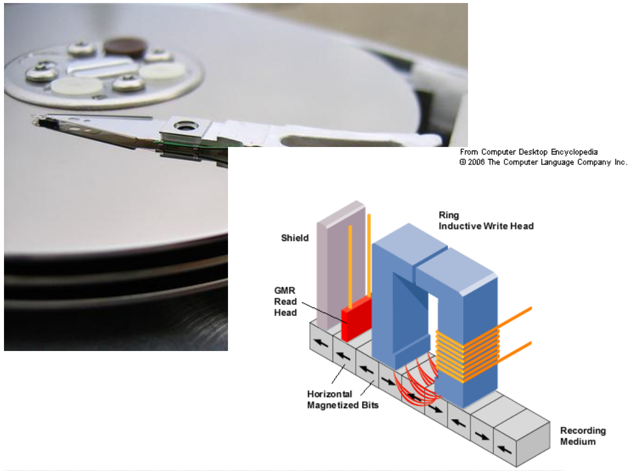
Johnson and Silsbee PRB **35**, 4959 (1987)

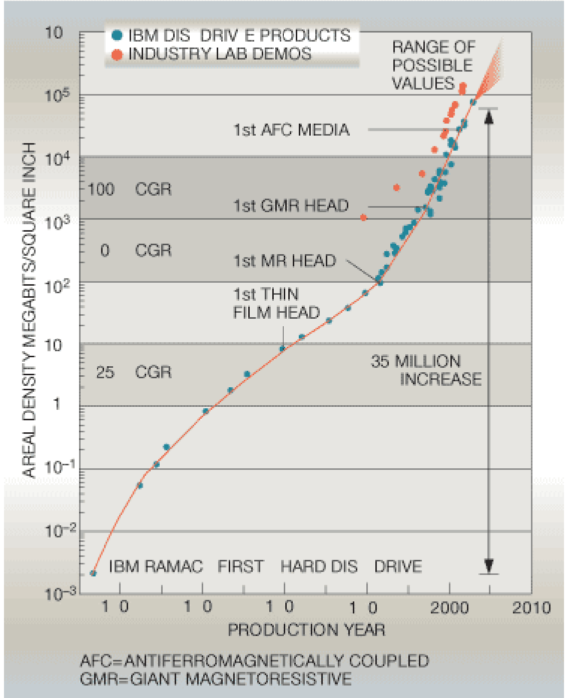
van Son et al., PRL **58**, 2271 (1987)

Spin valves (Current technology)

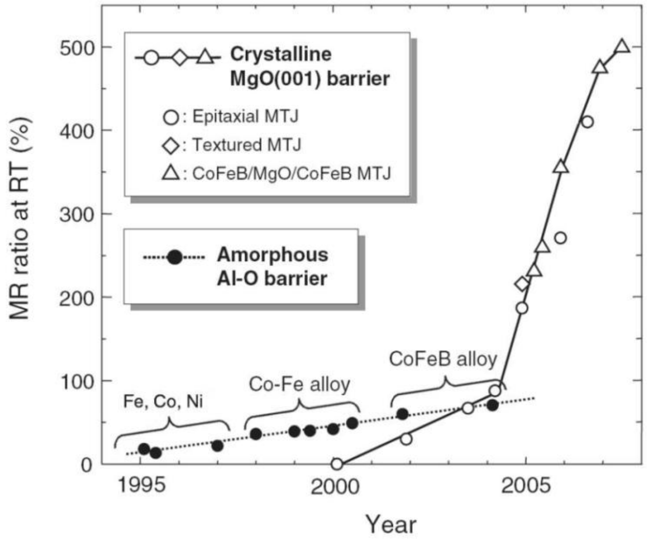
Giant magnetoresistance (GMR), tunnel magnetoresistance (TMR)

Magnetic field sensors/data storage

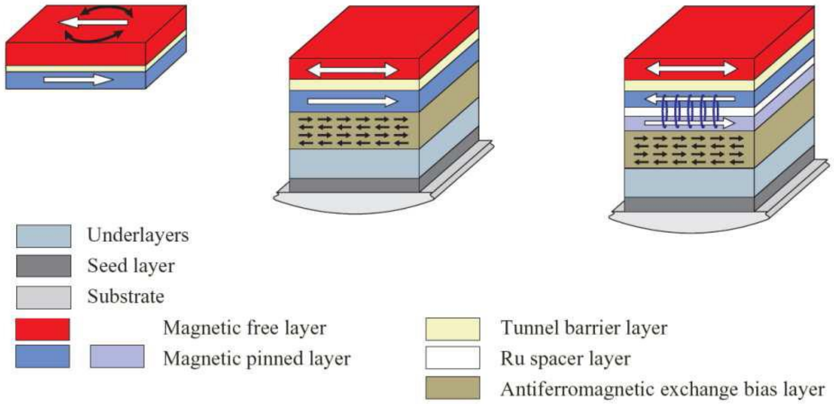




Tunneling magnetoresistance

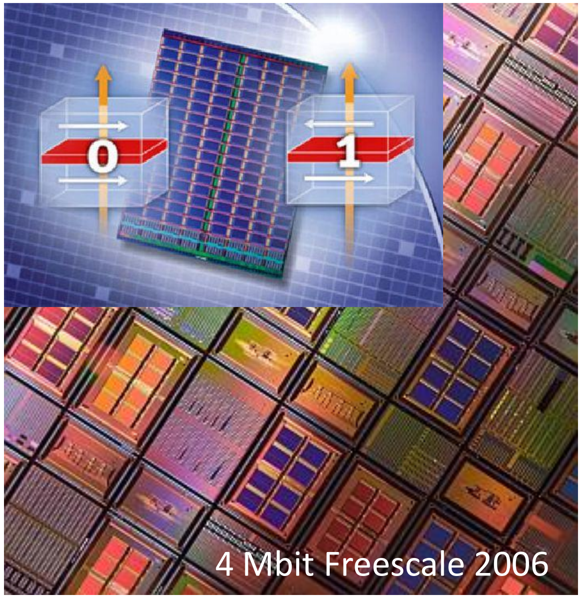


Physical mechanism for TMR not fully understood (necessary for further process)



Spin valves (current)

Magnetic Access Random Memory (MRAM)



No need to constantly refresh the information through the periodic application of an electrical charge. Less leakage.

Start-up routines go faster

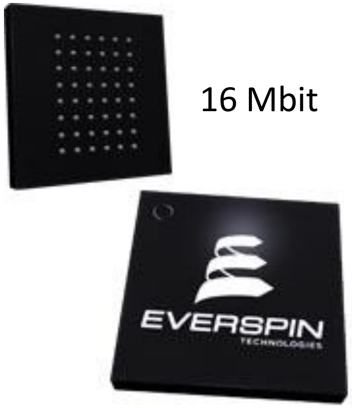
Reduced risk of data loss from unexpected power outages

Reduced dissipation

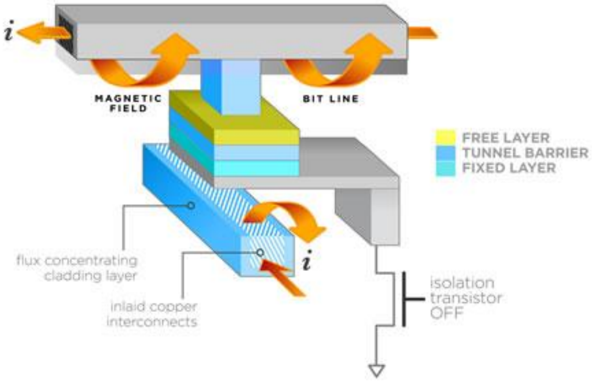
Fast writing/reading

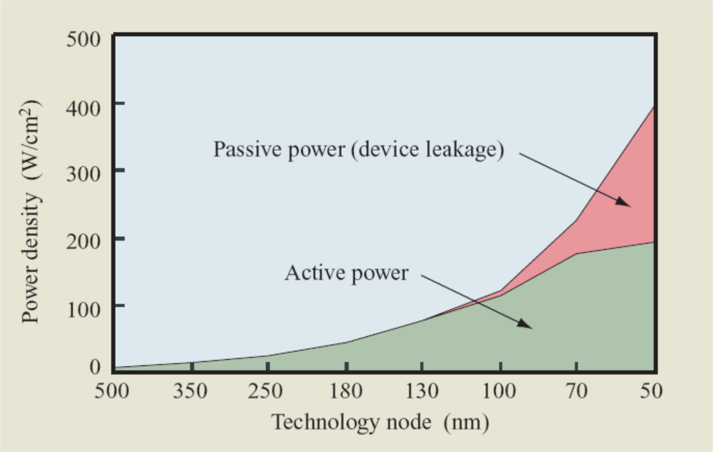
Larger power requirement for writing

Larger memory cell size



16 Mbit

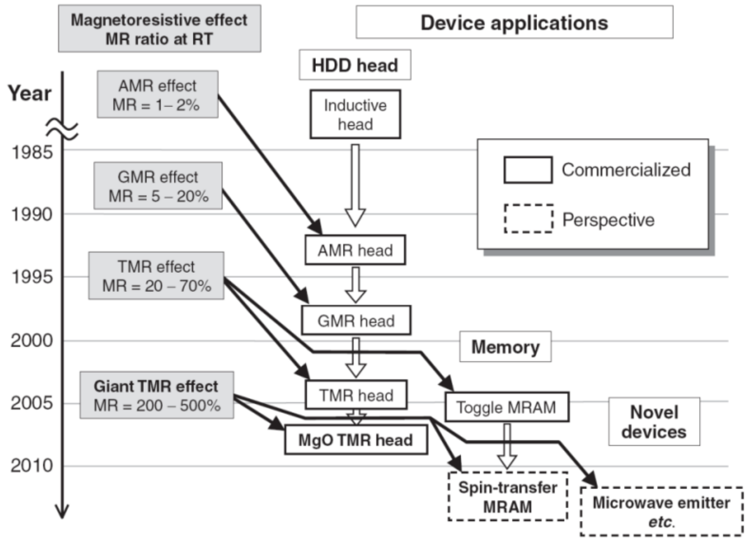


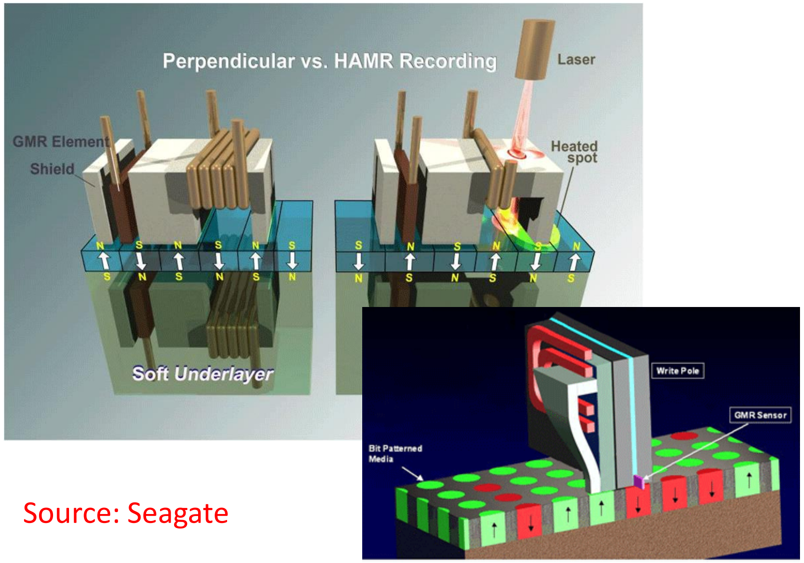


Industrial computing/automation (Siemens), aeronautics (Airbus), aerospace. Competes with SRAM (size, consumption)

Spin valves (< 5 years)

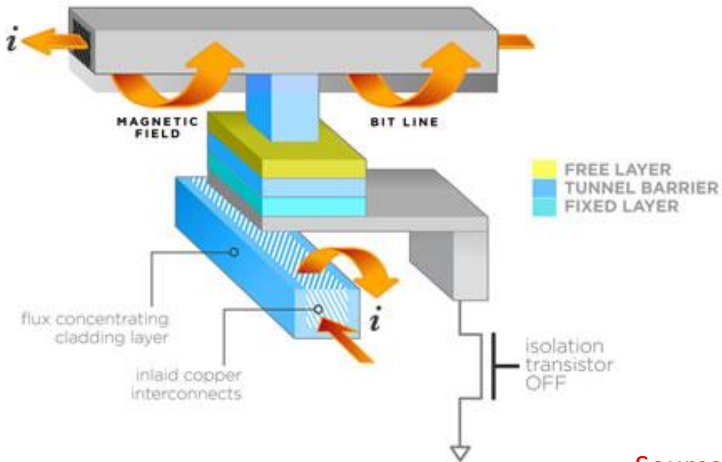
Magnetic Access Random Memory (MRAM) Current developments



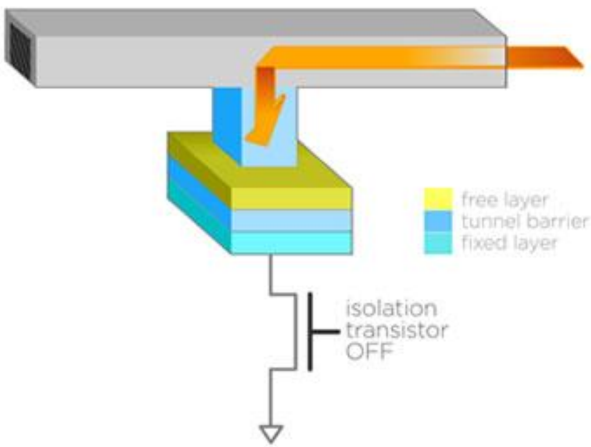


Source: Seagate

Toggle RAM (commercialized)



Spin Transfer Torque RAM (under development)



Source: Everspin

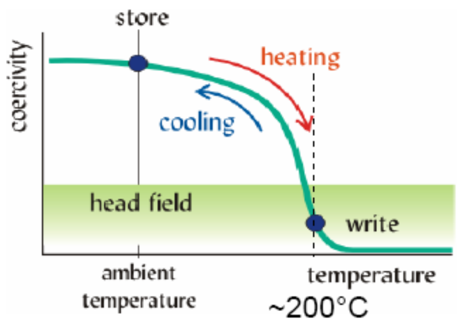
Spin valves (< 5 years)

Magnetic Access Random Memory (MRAM) Current developments

spintec — SPIN IN ELECTRONICS

Thermally Assisted Switching (TAS) MRAM

CROCUS Technology — Blossoming future



- Use temperature-dependence of switching field
  - ➢ **Write at elevated temperature**
  - ➢ **Store / read at room temperature**
- Same basic concept as in Heat Assisted Magnetic Recording.
- Here heating produced by Joule dissipation around tunnel barrier.

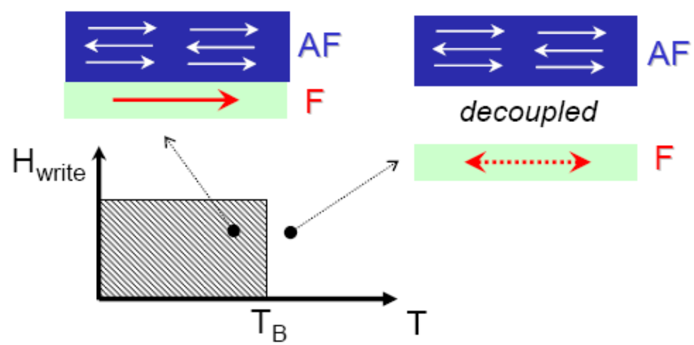
❖ Use **exchange biased storage bilayer** to “lock” the stored data:

→ **high stability**

❖ Locally **heat the magnetic cell** above its “blocking temperature” to “unlock” the storage layer :

→ **selectivity**

reduced write power



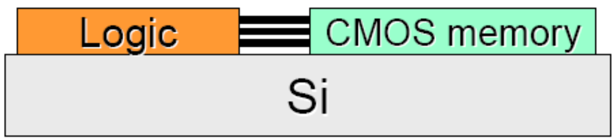
Bernard Dieny (SPINTEC/CROCUS)

Spin valves (< 5 years)

Magnetic Access Random Memory (MRAM) Current developments

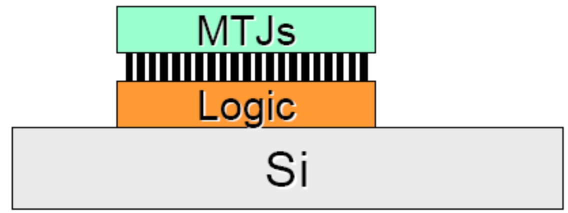
Benefit from "Above IC" technology

With CMOS technology only:

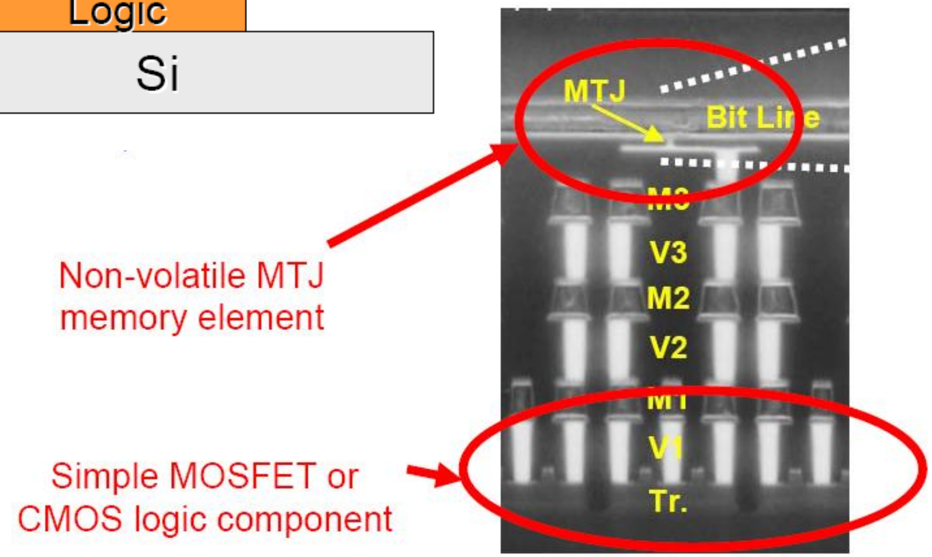


With hybrid CMOS/magnetic:

B. Dieny (SPINTEC/CROCUS)



- -Non-volatility in logic
- -Large energy saving
- -Fast communication between logic and memory
- -Numerous short vias
- -Simpler interconnection paths
- -Smaller occupancy on wafer



Study other torque/switching mechanisms (e.g. via electric fields, Rashba field, multiferroics, DW, etc) Nature Materials, Vol. 6 Iss. 1 (2007), Miron Nature Materials (2010), etc.

Other companies: Everspin, STT Grandis, Hynix, Toshiba-NEC (DW), Samsung, NVE, Hitachi, Avalanche, Fujitsu, Spin Transfer Technologies, …, research labs in Japan, US, etc.

Racetrack memory (5-10 years)

Domain wall motion. Related to twistor/bubble memory

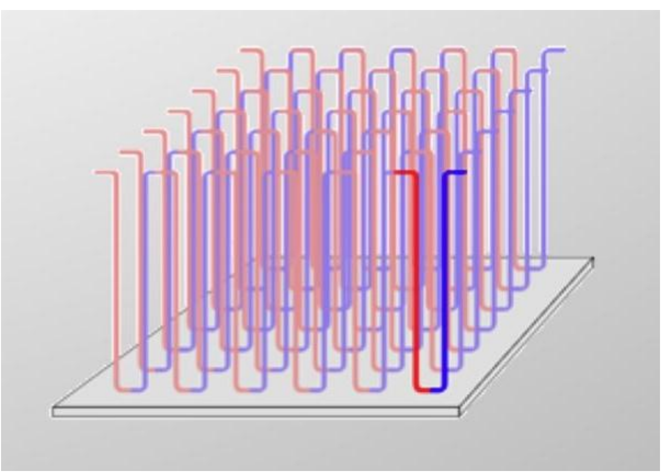
Racetrack memory is an experimental non-volatile memory device under development at IBM

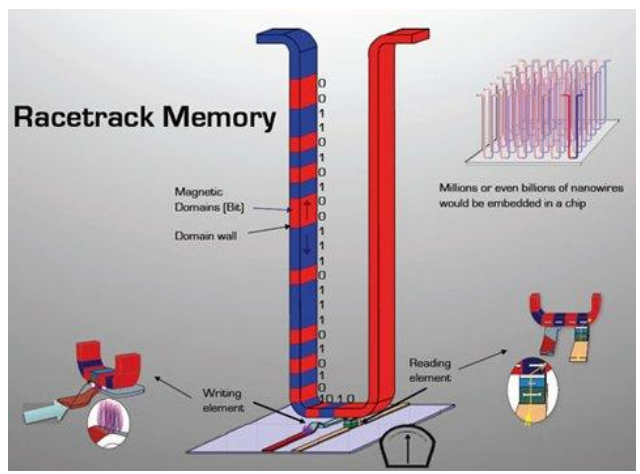
It promises higher density than Lash (similar to HDD) and higher write/read speeds

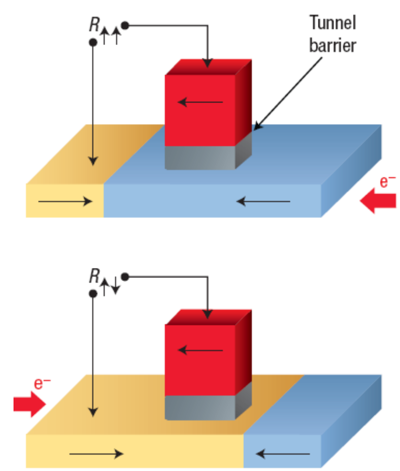
The "track" is moved at fixed rate (~100 m/s) past the read/write sensor. Bits at different positions on the "track" would take different times (10 ns/bit) to be accessed by the read/write sensor.

Need for high current density (>108 A/cm^2). It appears not to be able to compete with STT-MRAM

Domain walls move slowly through the wires. Microscopic imperfections along the wire slows pin domain walls







See, e.g. Chauppert Nat. Mater. (2006)

Patent WO 2006/064022

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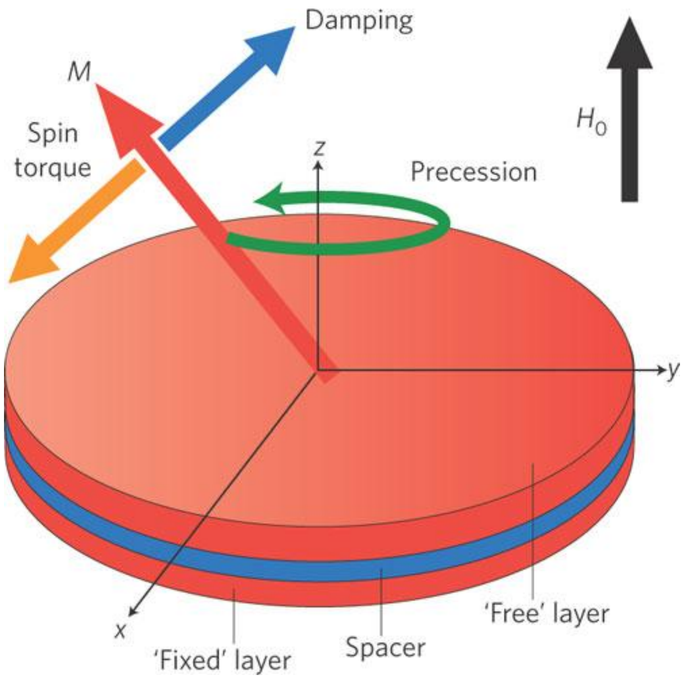
- **Qubits and Quantum Computing**
- **Spin Hall effects, Topological Insulators**
- **Multiferroics**
- **Spin Thermoelectronics**

RF applications (5-10 years)

Magnetization oscillations driven by spin polarized currents (Katine PRL 2000, Kiselev Nature2003)



Source: Slavin, Nat. Nanotech. (2009)

Promising microwave generators. Radar an telecommunications

Compatible with existing planar technology

Radiation hard

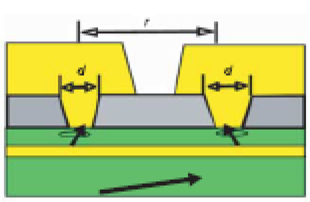
Tunable via a bias magnetic field or a bias electric current

Low output power (500 nW or less) relatively large linewidth

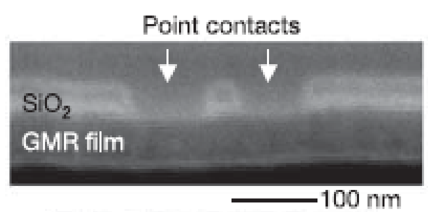
Poor understanding of high bias torque

Effects of nonlinearity of the oscillators on coupling and phase locking

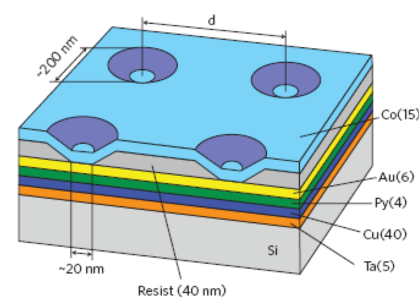
Coupling possible, reduces linewidth and increases power (N^2)



Kaka et al. Nature (2005)



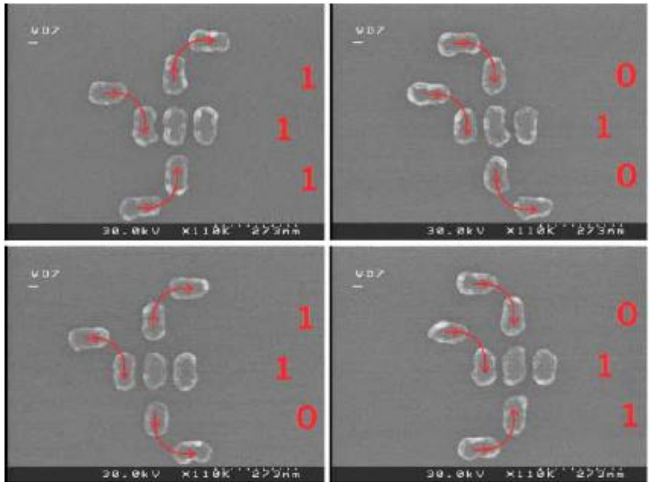
Mancoff et al. Nature (2005)



Ruotolo, Nat. Nanotech. (2009)

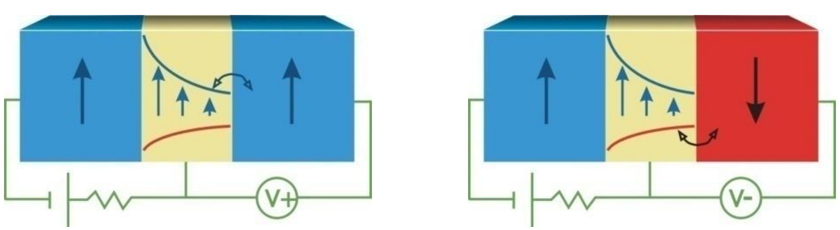
Spin/Magnetic logics (>5-10 years)

Quantum dot cellular automata



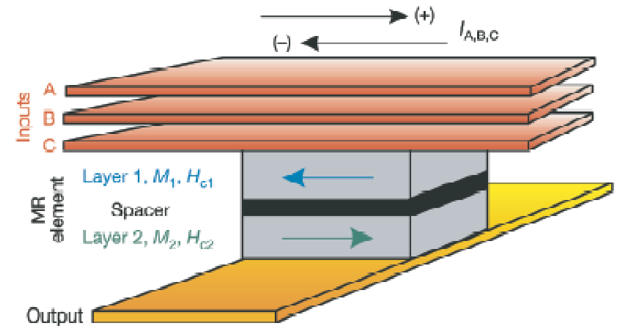
Cowburn Science (2000) Imre, Science (2006)

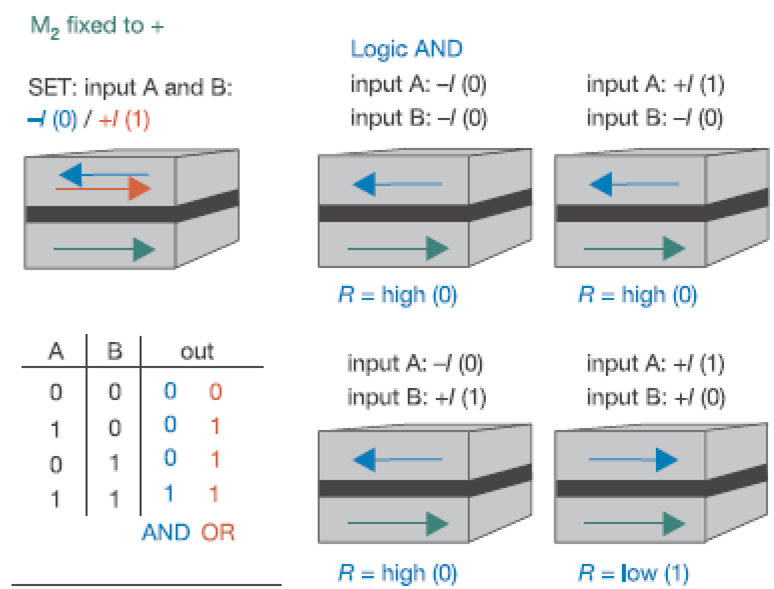
Nonlocal devices



Johnson and Silsbee, PRL **55**, 1790 (1985); Johnson, Science **260**, 320 (1993)

Logic based on MTJ



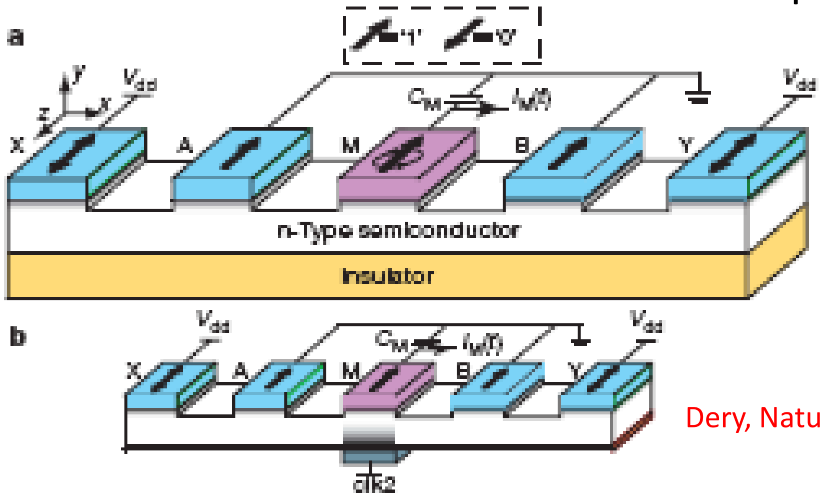


Black, JAP (2000) ; Ney, Nature (2003)

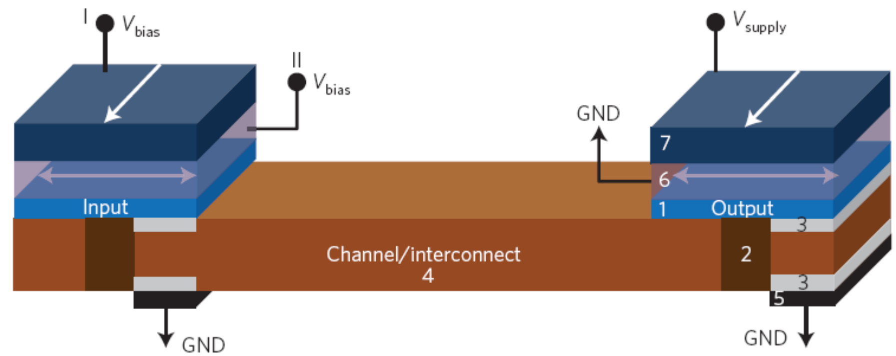
Spin logics (>5-10 years)

Spin logics with spin currents

Nonlocal spin logics proposals

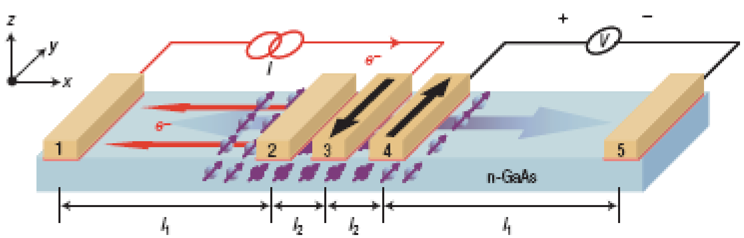


Dery, Nature (2007)



Behin-Aein, Nature Nanotech. (2010)

Encouraging experimental results

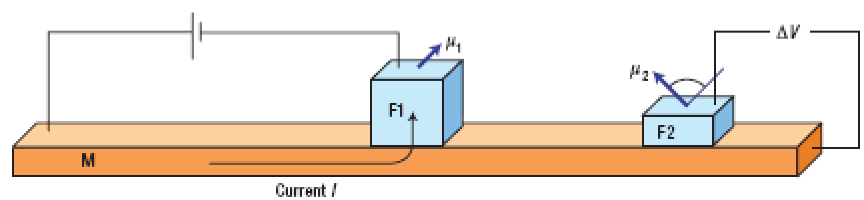


Long spin lifetimes in GaAs, Si and graphene

All electrical experiments at high temperature

Lu, Nature Phys. (2007), Appelbaum Nature (2007), Tombros Nature (2008)

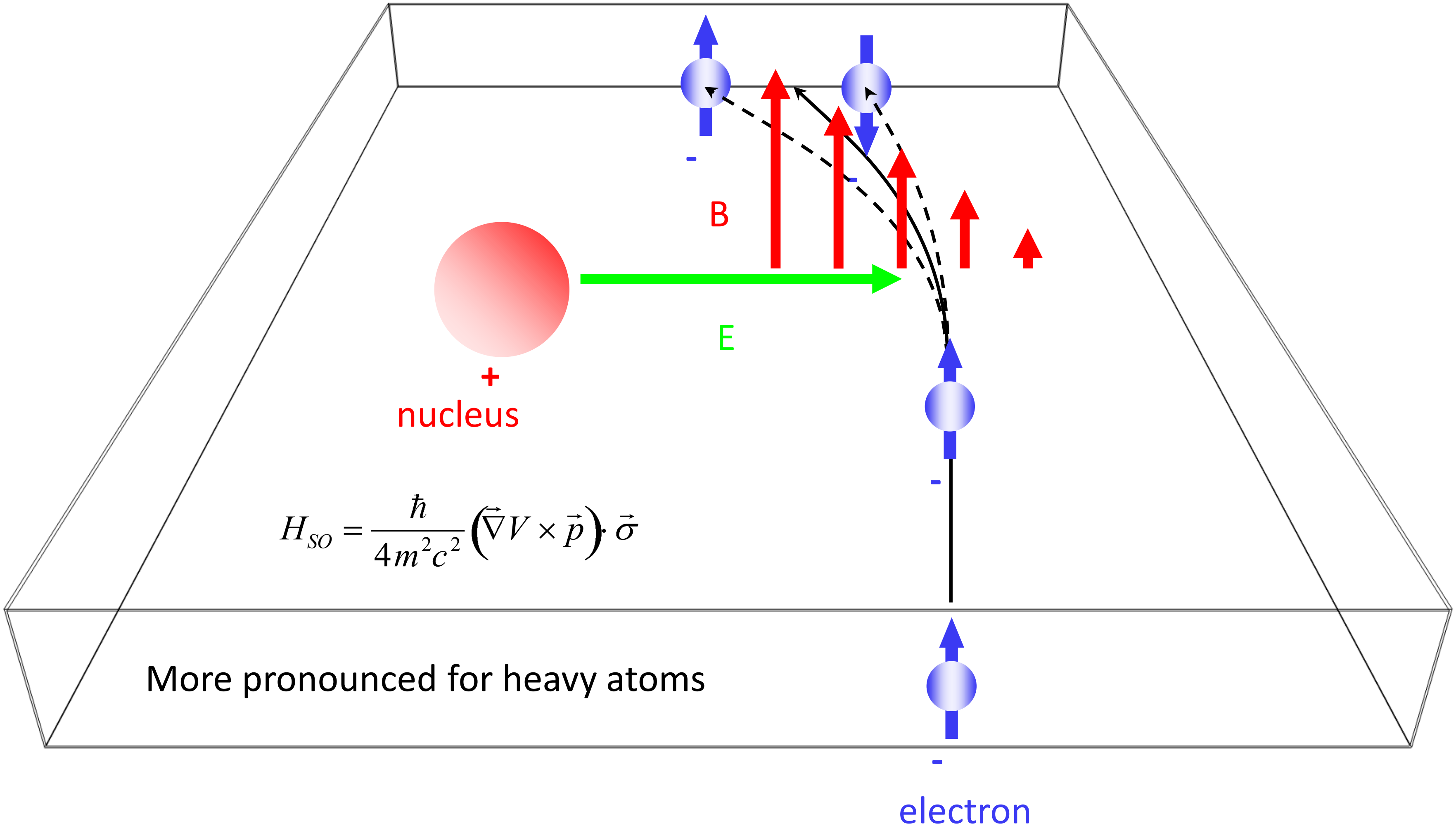
Reversible witching of ferromagnets demonstrated



Yang, Nature Phys. (2008)

Spin Hall Effects and Topological Insulators(>5-10 years)

Pure spin currents



$$H_{SO} = \frac{\hbar}{4m^2c^2}\left(\vec{\nabla}V \times \vec{p}\right)\cdot \vec{\sigma}$$

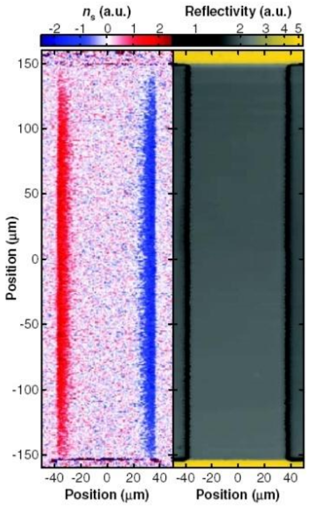
More pronounced for heavy atoms

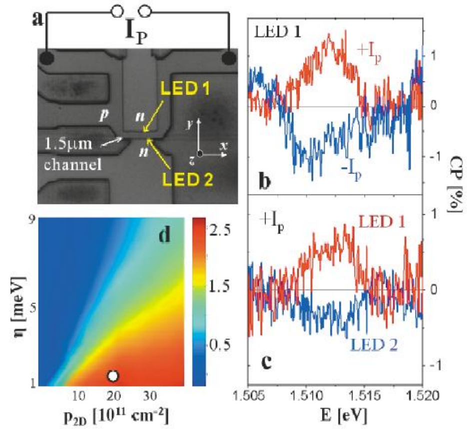
Axel Hoffmann, Argonne National Laboratory, US.

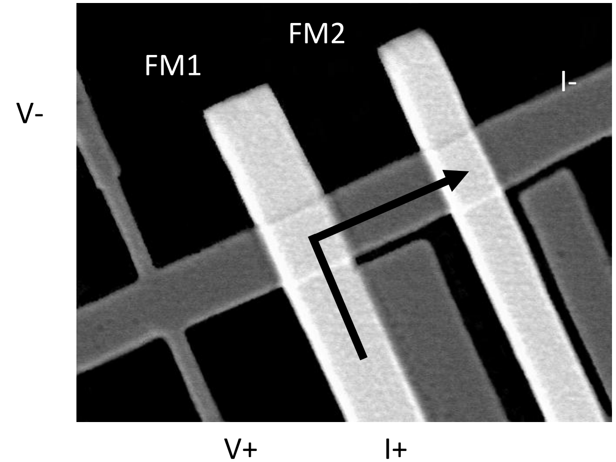
Spin Hall Effects and Topological Insulators (> 10 years)

Pure spin currents

Spin Hall effect







Y.K. Kato *et al.* Science (2004); J. Wunderlich, (2005).

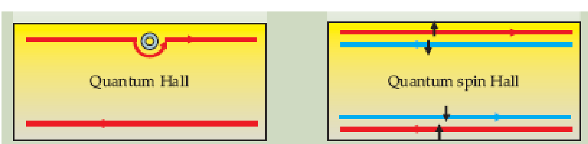
V. Sih *et al.* Nature Physics (2005).

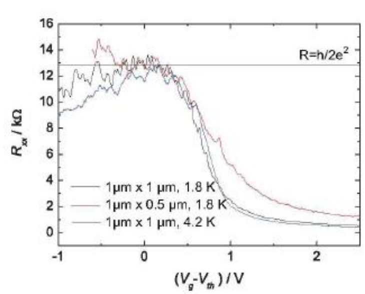
SOV *et al.* Nature (2006)

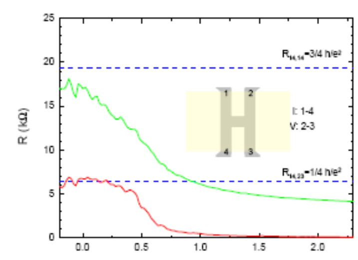
Quantum spin Hall effect and Topological Insulators. Nondissipative spin currents

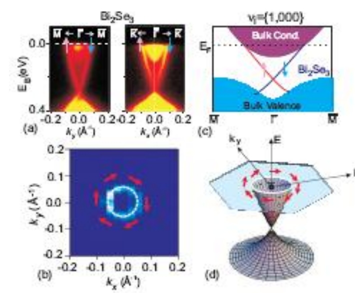
Similar to quantum Hall effect
No magnetic fields applied
Large spin-orbit

Observed experimentally, more than 50 compounds predicted









Kane, Mele, Zhang (2003-2010)

Konig, Science (2008)

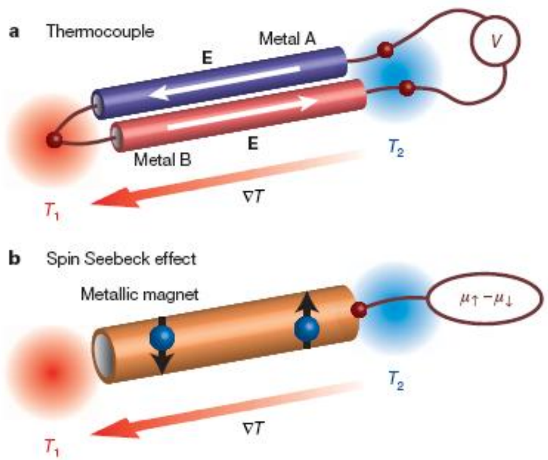
Roth, Science (2009)

Hsieh, Nature (2009)

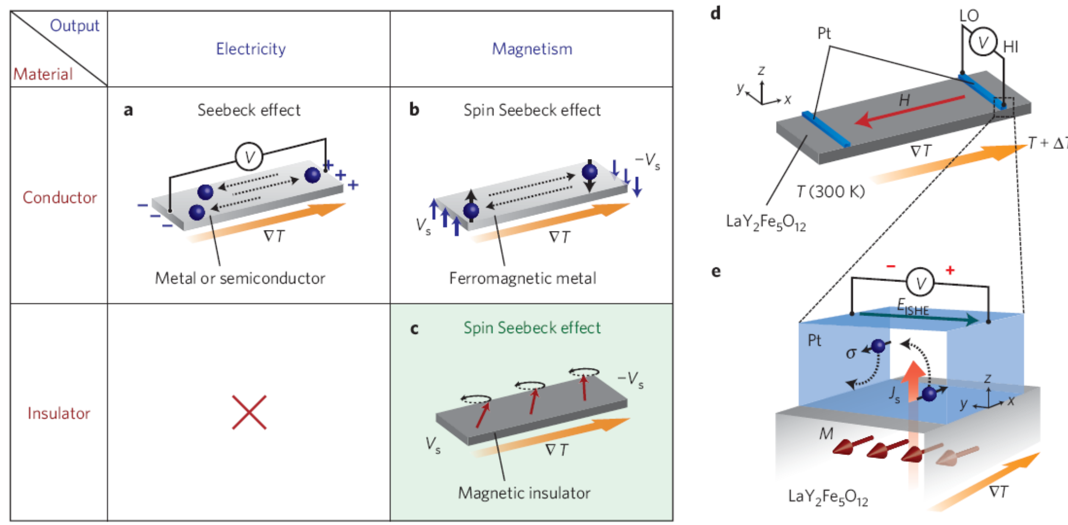
Spin thermoelectronics or spin caloritronics (> 5-10 years)

Pure spin currents

Spin Seebeck effect and magnon dynamics



Saitoh, Nature (2008)

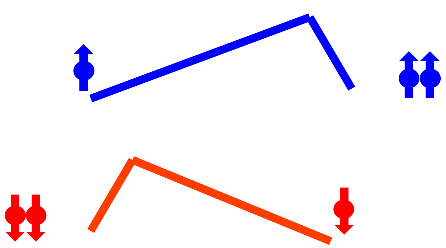


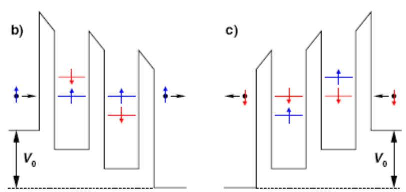
Uchida, Nature Materials (2010)

Information transfer via magnons along insulators

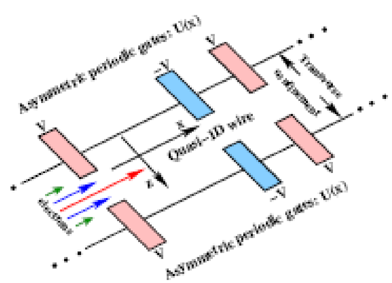
Ando, Nature (2010)

Pure spin currents from fluctuations, harvesting

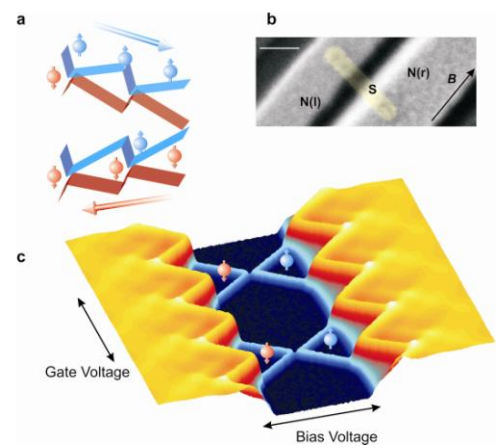




Scheid EPL (2009)



Smirnov, PRL (2008)



Costache and SOV, Science (2010)

Classical computing

Irreversible logic

Boole logic is irreversible

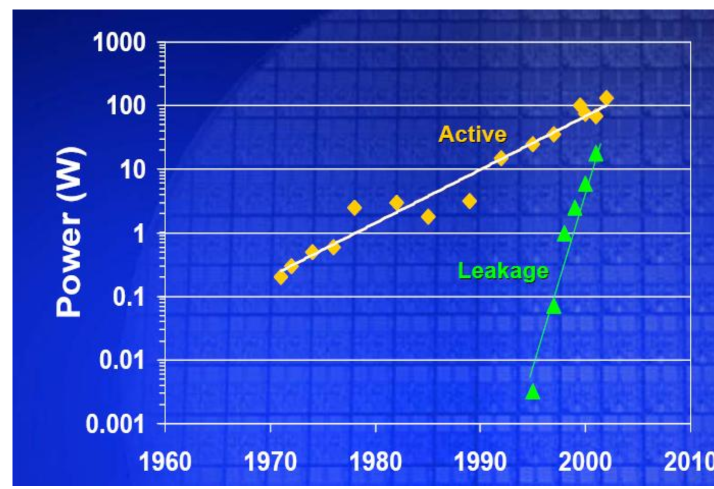
NOR

A	B	$\overline{(A + B)}$
0	0	1
0	1	0
1	0	0
1	1	0

In any Boole operation there is loss of information

Landauer principle:

"any logically irreversible manipulation of information, such as the erasure of a bit or the merging of two computation paths, must be accompanied by a corresponding entropy increase. … Each bit of lost information will lead to the release of an amount kT ln 2 of heat, where k is the Boltzmann constant and T is the absolute temperature of the circuit"

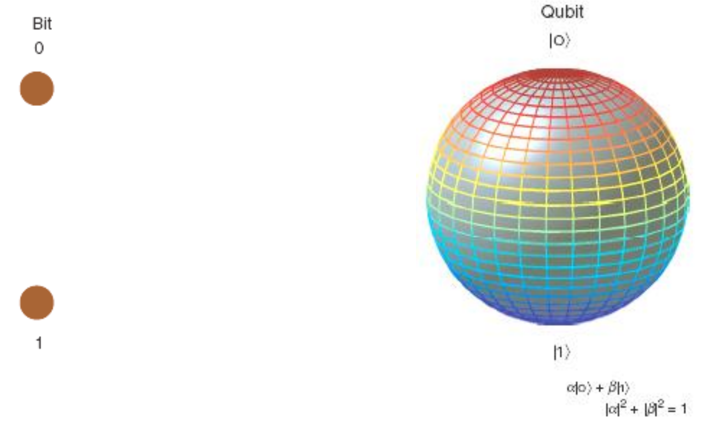


Quantum computing (> 10-15 years)

Bits and Qubits

A *qubit* is the analogue to a *bit*
in a quantum computer

A qubit is described by a vector in a space of continue variables b



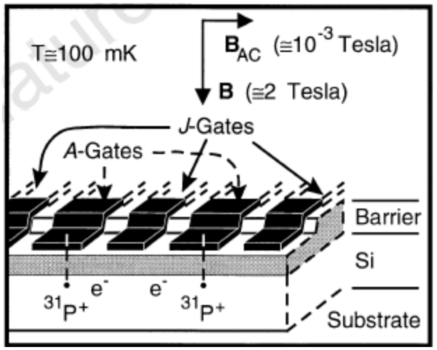
A spin qubit can be represented by the two states of a spin ½ particle

A quantum computer is a system formed by many interacting qubits whose evolution can be controlled

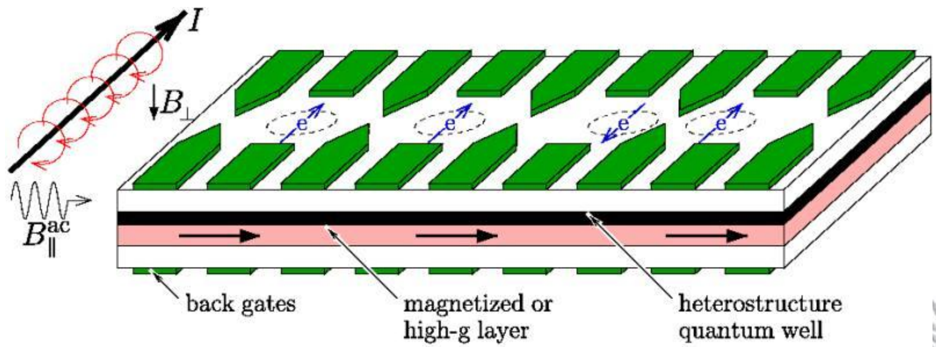
Computation involves time evolution of the quantum circuit, thus reversible unitary operations: No dissipation.

Quantum computing (> 10-15 years)

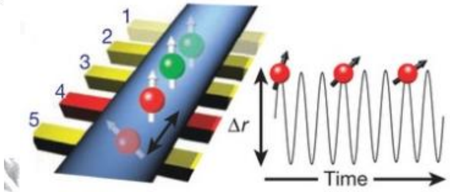
Bits and Qubits

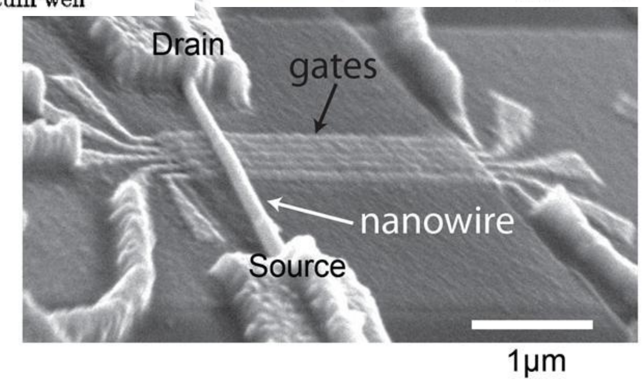


Kane, Nature (1998)

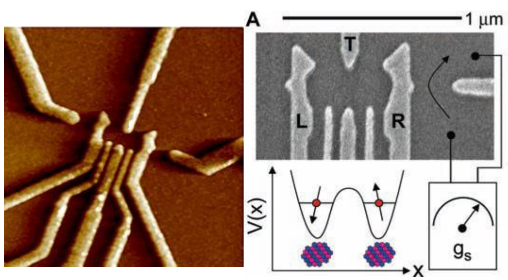


Loss, DiVincenzo, (1998)

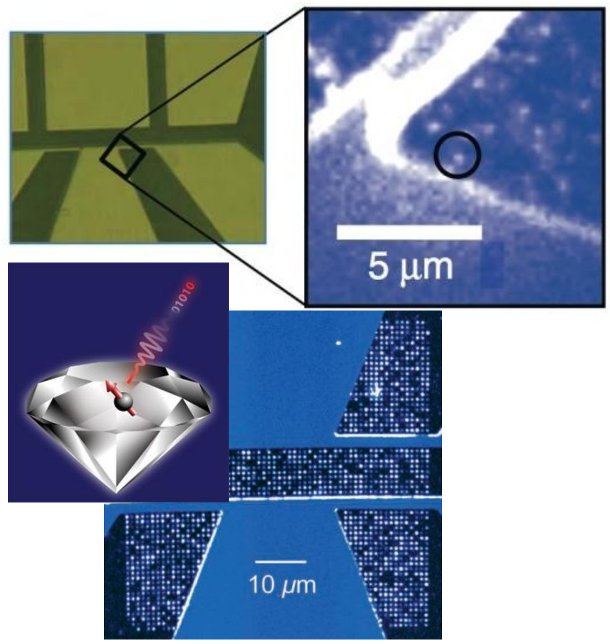




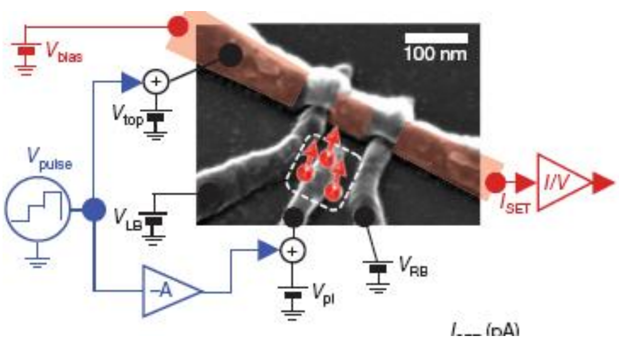
Nadj-Perge, Nature (2010)



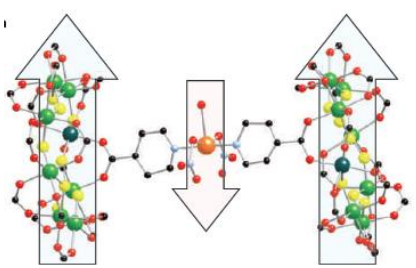
Marcus (Harvard) and
Kouwenhoven (Delft) groups…



Lukin (Harvard) , Awschalom (UCSB)
Yacoby (Harvard) groups…



Morello, Nature (2010)



Molecular Magnets, Wernsdorfer

Summary

1- Current spintronic technologies

GMR/TMR

MRAM

2- To be commercialized (within 5 years)

STT-MRAM

Fundamental understanding of TMR and STT desired, especially at high bias. Need to reduce writing currents and size to compete with other than SRAM. Further developments on CMOS integration. Study of other magnetization switching mechanisms.

3- RF components (5 years)

Increase power output. Demonstration of phase-lockin of tens of oscillators needed. Fundamental understanding of nonlinearities

4- Spin Logics (>5-10 years)

Further material and design developments. Further improvement of nonlocal devices based on semiconducting and metallic materials. Magnetization switching with pure spin currents. Pure spin currents generation.

5- Spin Hall effects, Topological Insulators (>5-10 years)

Recently observed experimentally. Of extreme fundamental interest. Very intriguing for applications. Need focus on materials and device design.

6-Spin Thermoelectronics (>5-10 years)

Recent development. Phenomenology not understood. Possibility of developing completely new concept for large figure of merit Z.

7- Spin Qubits and Quantum Computing (>10-15 years)

Coupling between more than 2 qubits. Limit decoherence from Nuclei (e.g.in GaAs), quantum control improvement, error correction, etc. Still not clear cut technology amongst candidates.