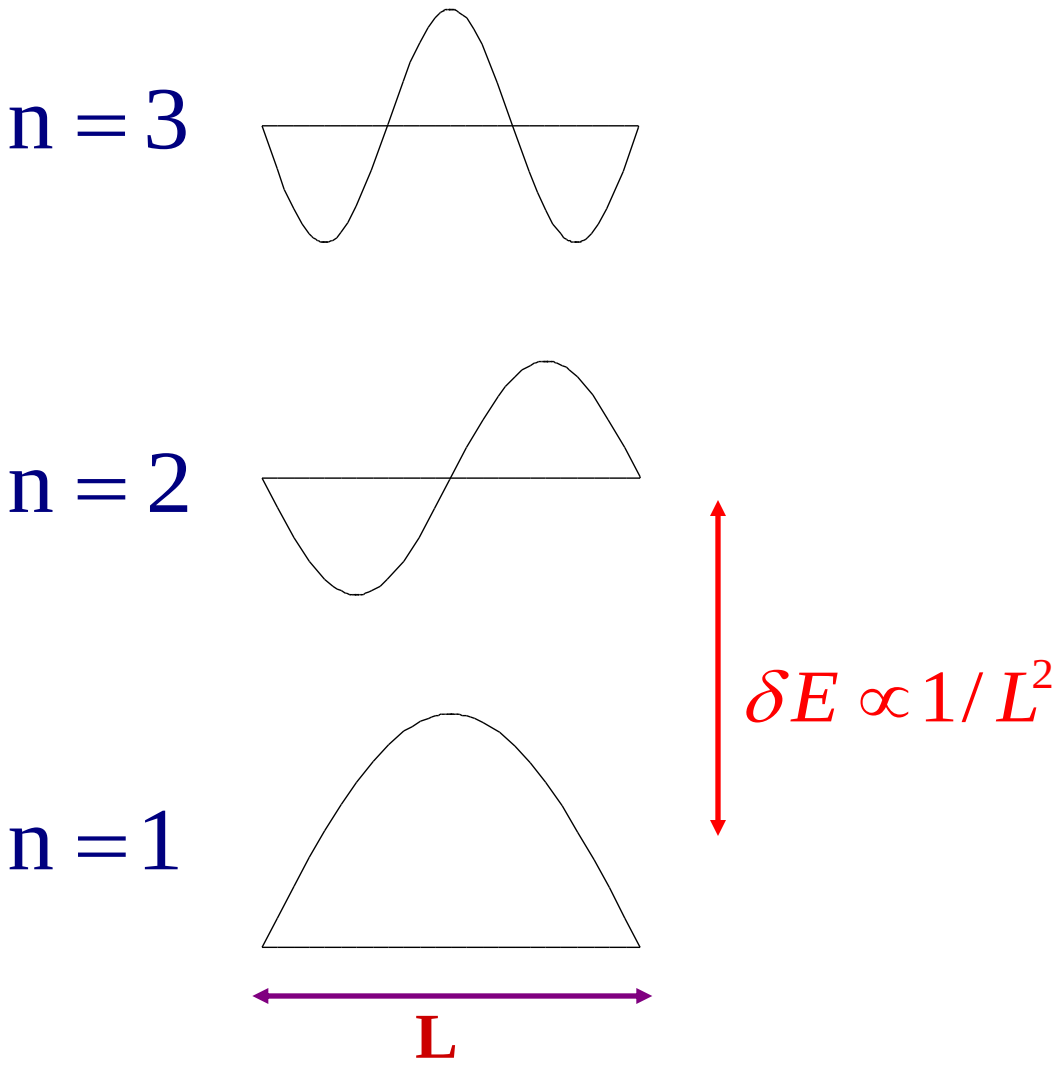
(II) Quantization

Confinement of the materials wave

Standing Wave

Quantizations

The Qauntization of Energy



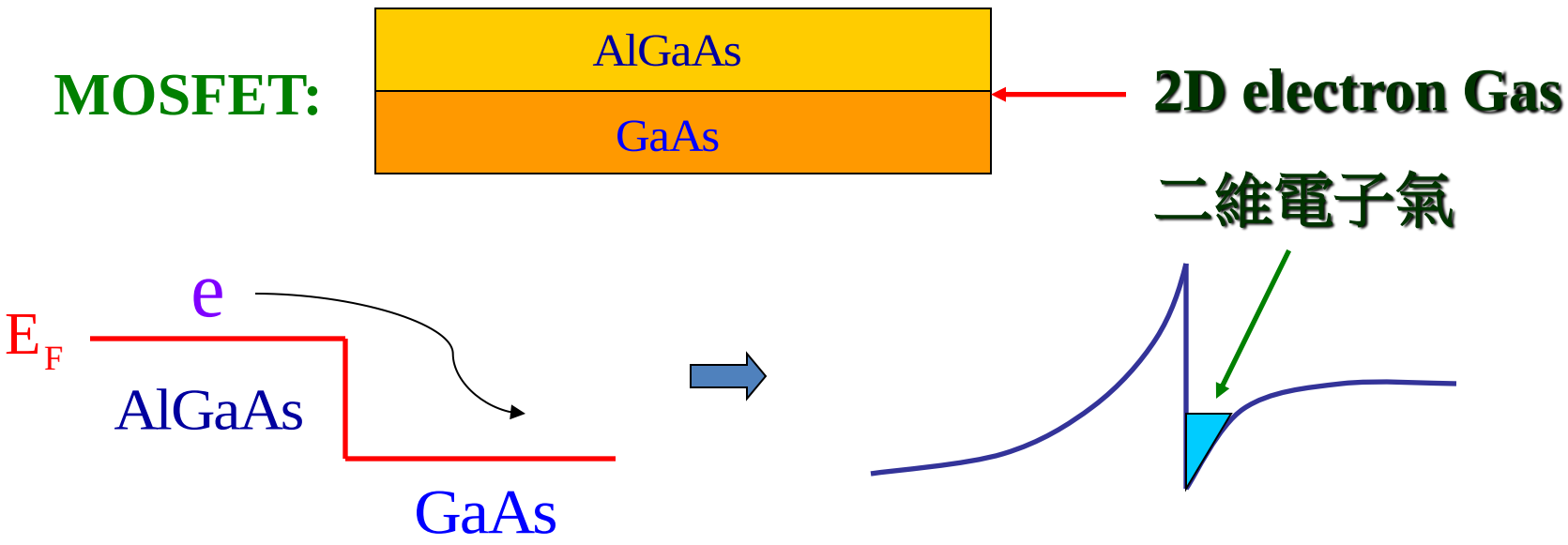
$$\delta E \propto 1/L^2$$

$$L = \frac{n}{2}\lambda$$

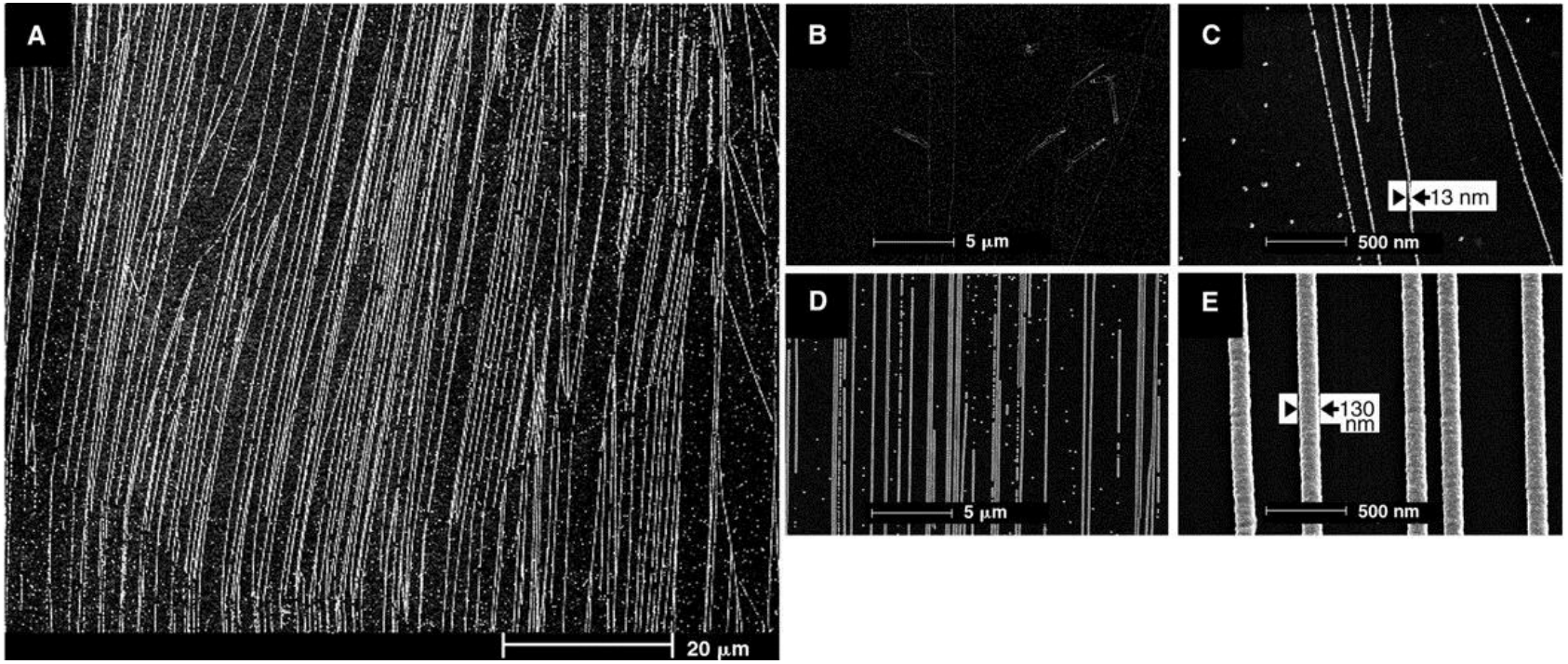
$$p = \frac{h}{\lambda} = \frac{nh}{2L}$$

$$E_n = \frac{p^2}{2m} = \frac{n^2h^2}{8mL^2}$$

Quantum well: 1D confinement



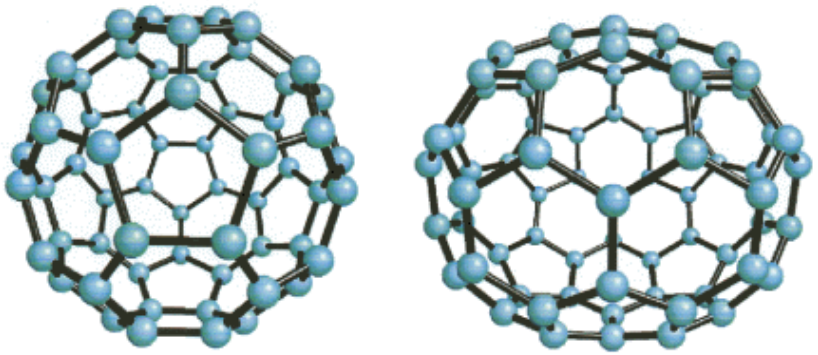
Quantum wire: 2 D-Confinement



SEM images of MoO_x nanowires on graphite surfaces

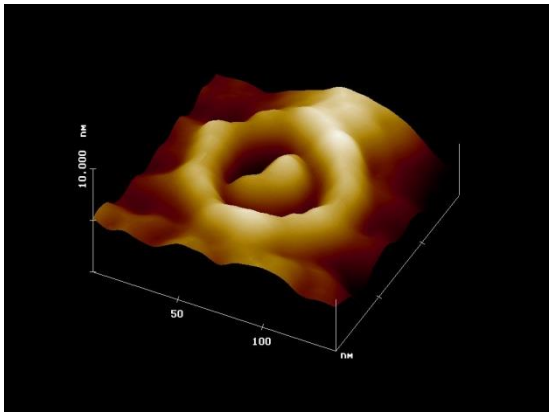
Science **290**, 2120-2123, (2000)

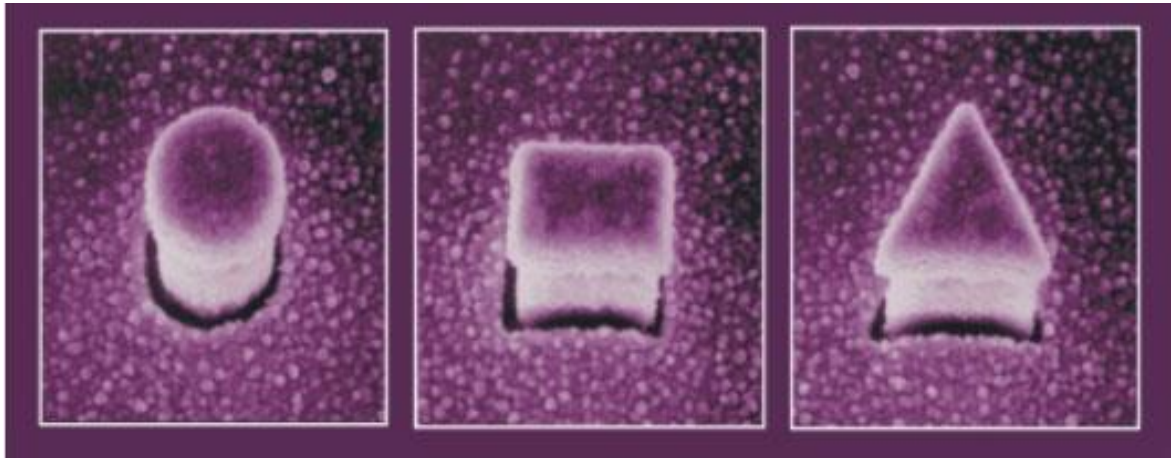
Quantum dot: 3 D - Confinement



C_{60} C_{70}

Quantum Dots of various shape

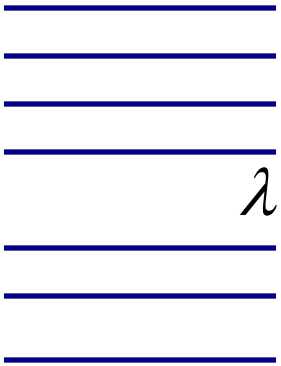




Absorption in scattering

From red to yellow

larger λ_0

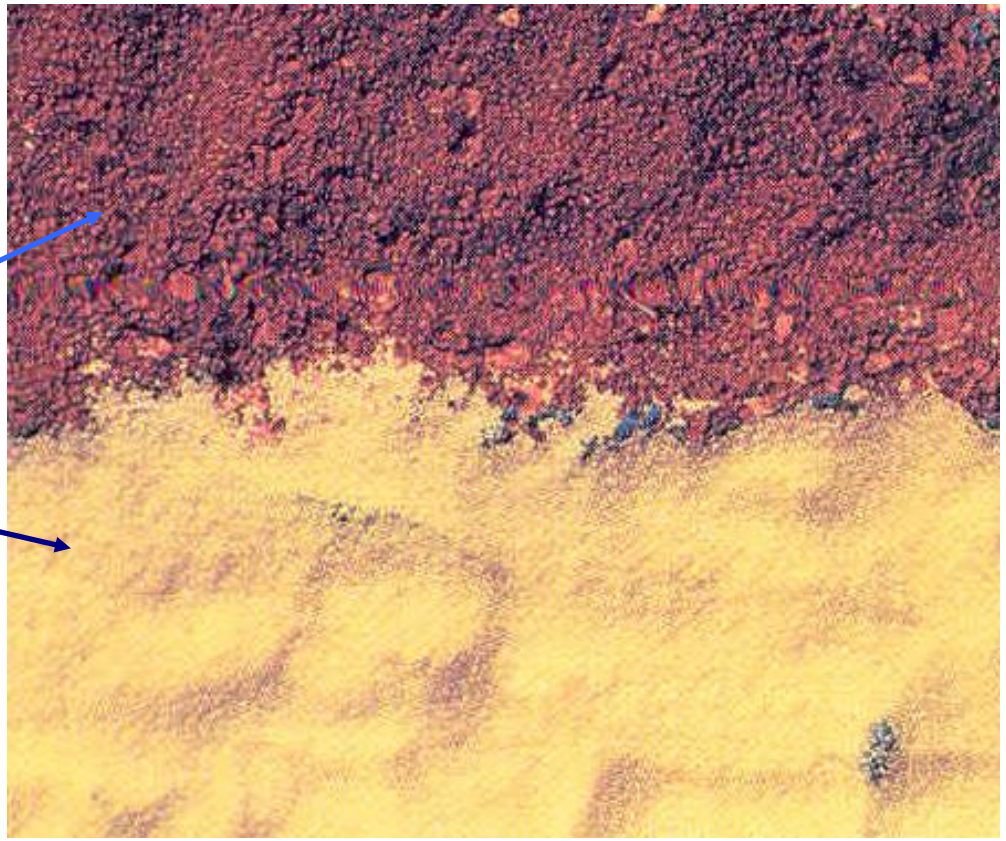


λ $E = hc/\lambda \propto 1/L^2$

powdered Cadmium Selenide

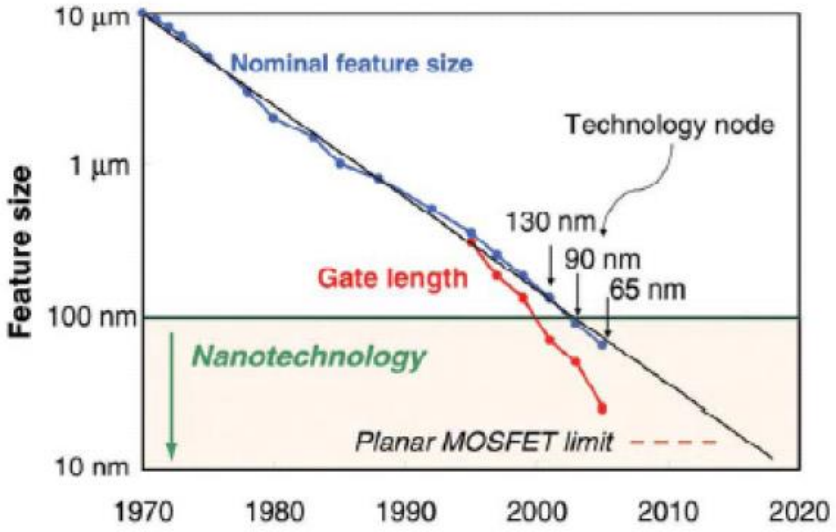
larger

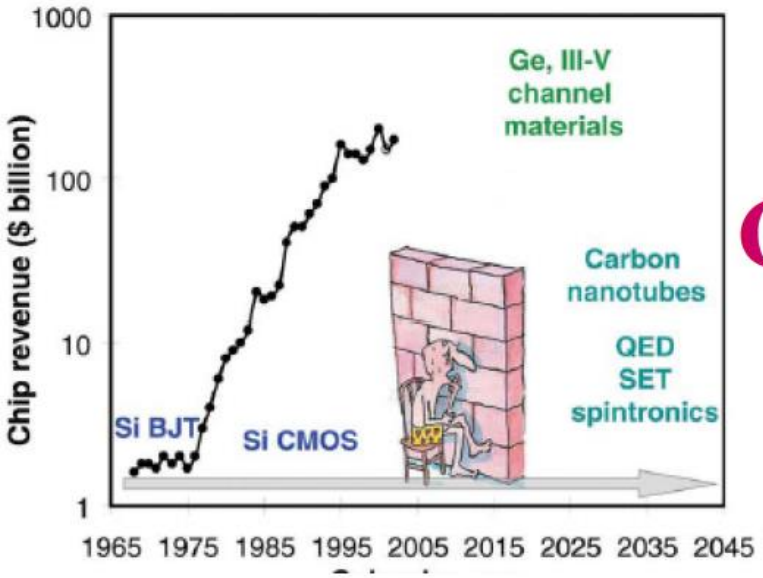
smaller



Background for search new platform

Scaling limit of Si MOSFET
& superparamagnetism





Carbon era?

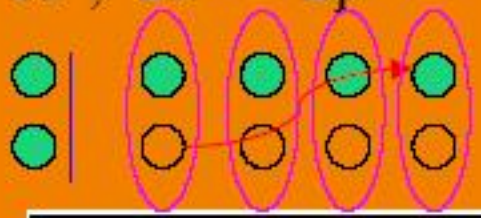
Thompson and Parthasarathy, Materialstoday 9, 20, 2006

The Advent of Carbon Era ?

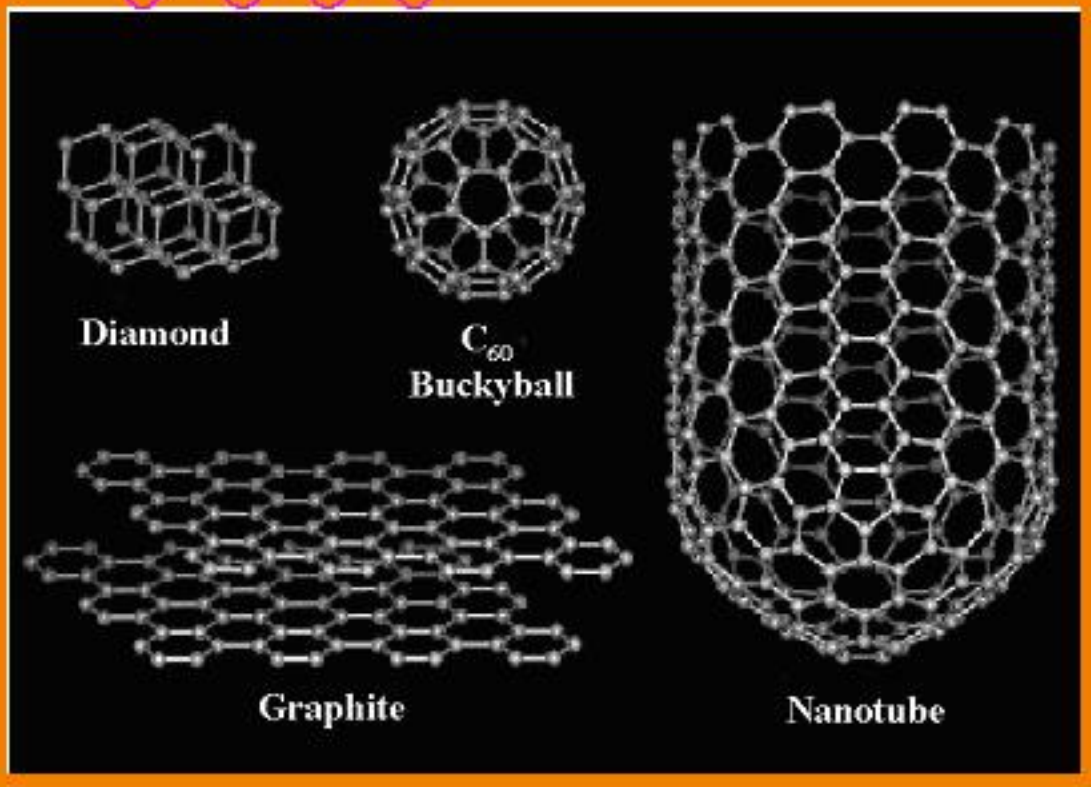
Carbon Nanotube

- Structure of carbon nonatubes

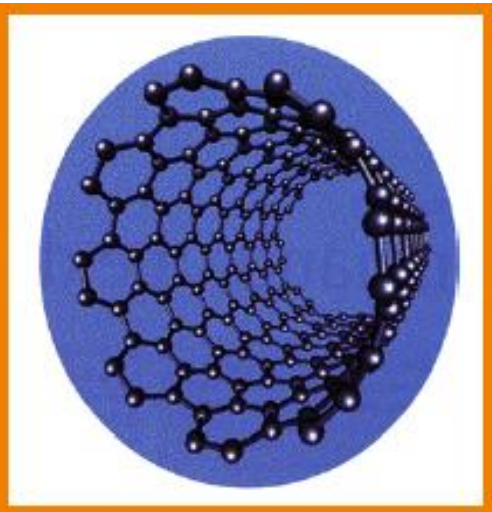
Carbon: $1s^2$, $2s^1$ $2p^3$



sp^1, sp^2, sp^3

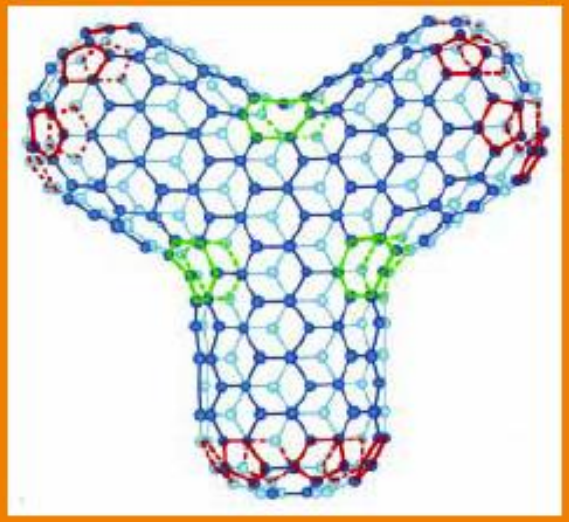


Carbon Nanotube



Sumio Iijma

Single-walled carbon nanotube, SWCNT



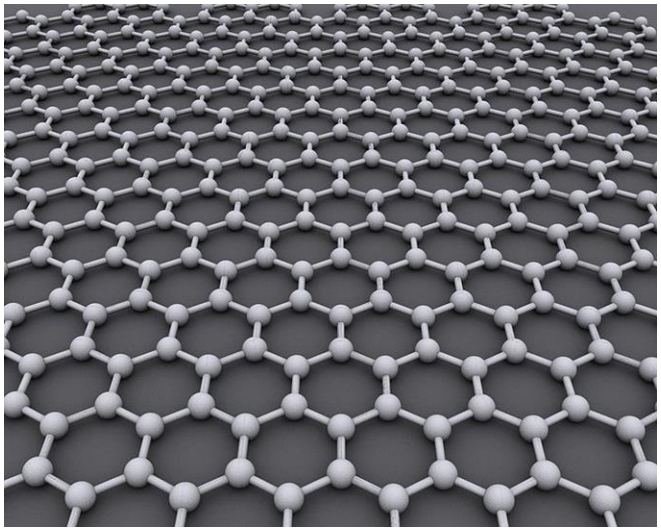
Multi-walled carbon nanotube, MWCNT

Carbon Nanotube based Transistors / Electronics

Unexpected realization of graphene sheet

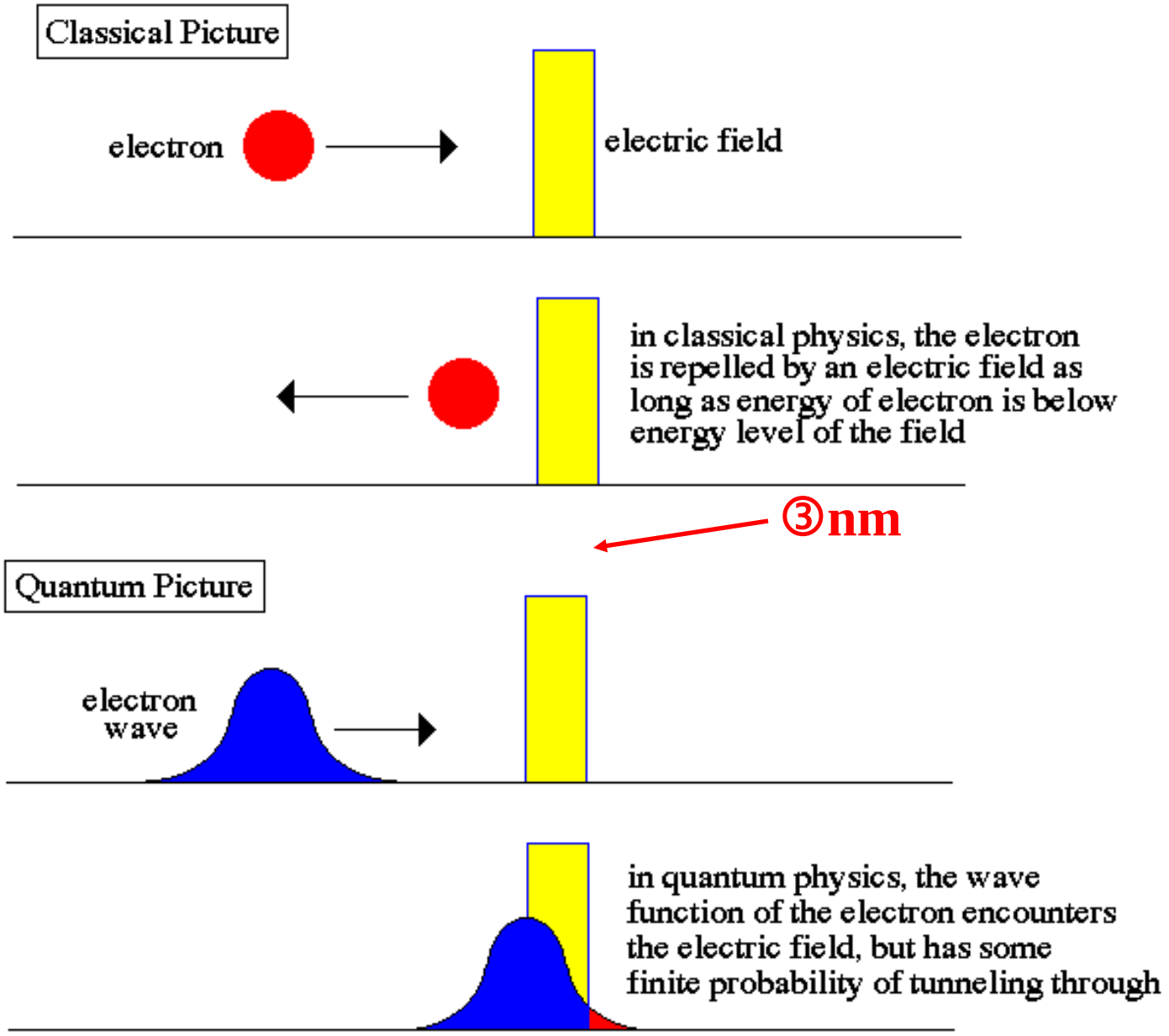
(·

mechanically exfoliated graphene sheets

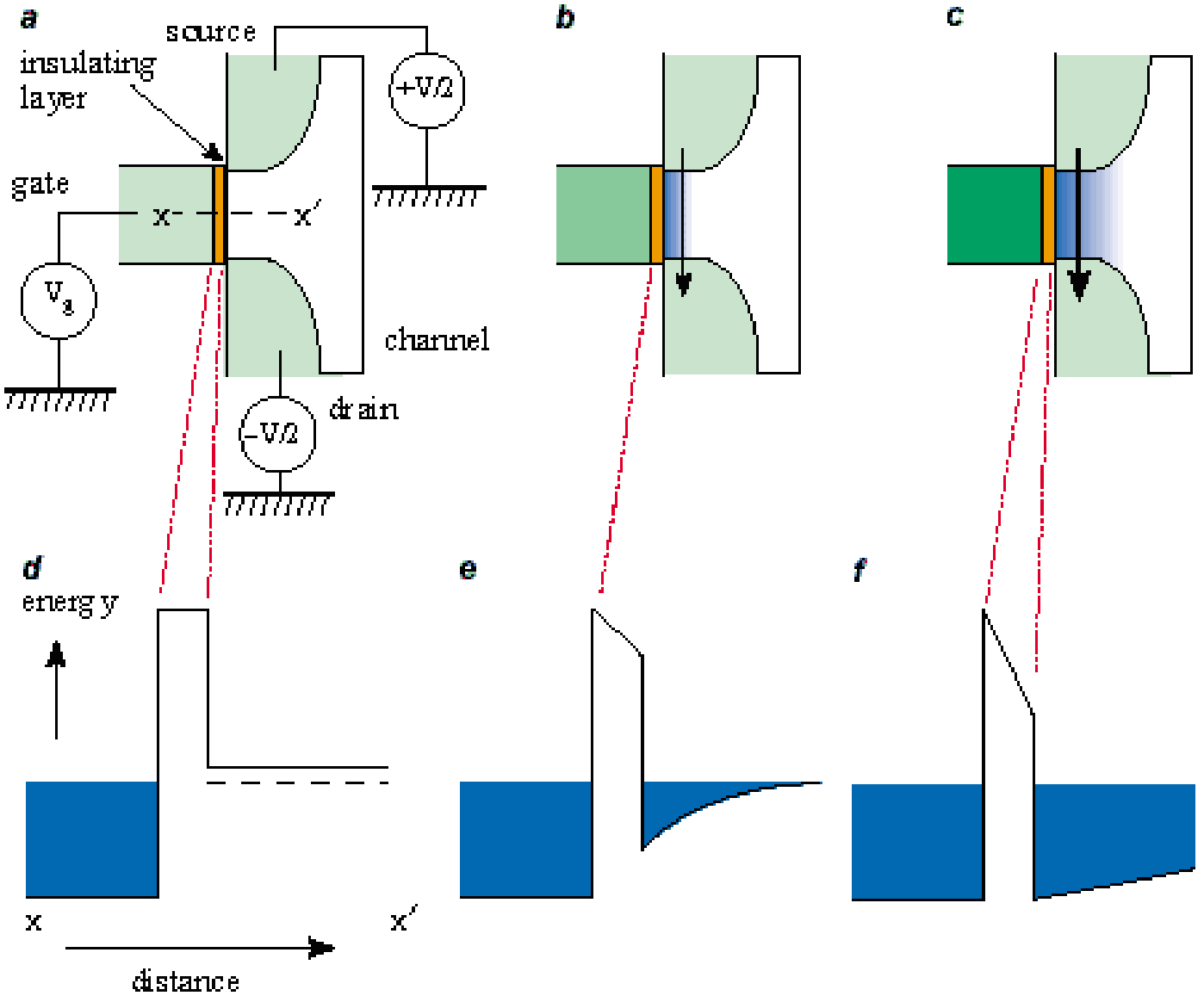


AFM image of single-layer graphene on SiO_2
K.S. Novoselove et al., Science 306, 666 (2004)

(III) Tunneling and Nano-electronics

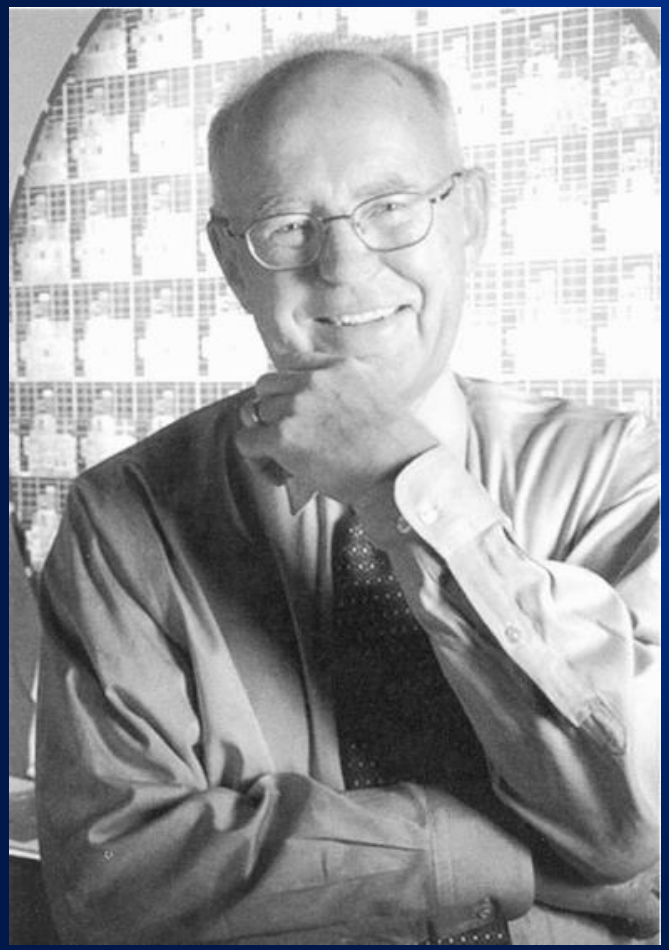

Classical Picture
electron
electric field
in classical physics, the electron is repelled by an electric field as long as energy of electron is below energy level of the field
③nm
Quantum Picture
electron wave
in quantum physics, the wave function of the electron encounters the electric field, but has some finite probability of tunneling through

Quantum Tunneling is the major effect for the failure of Transistor at nano scale



近來大力推動奈米科技的背景

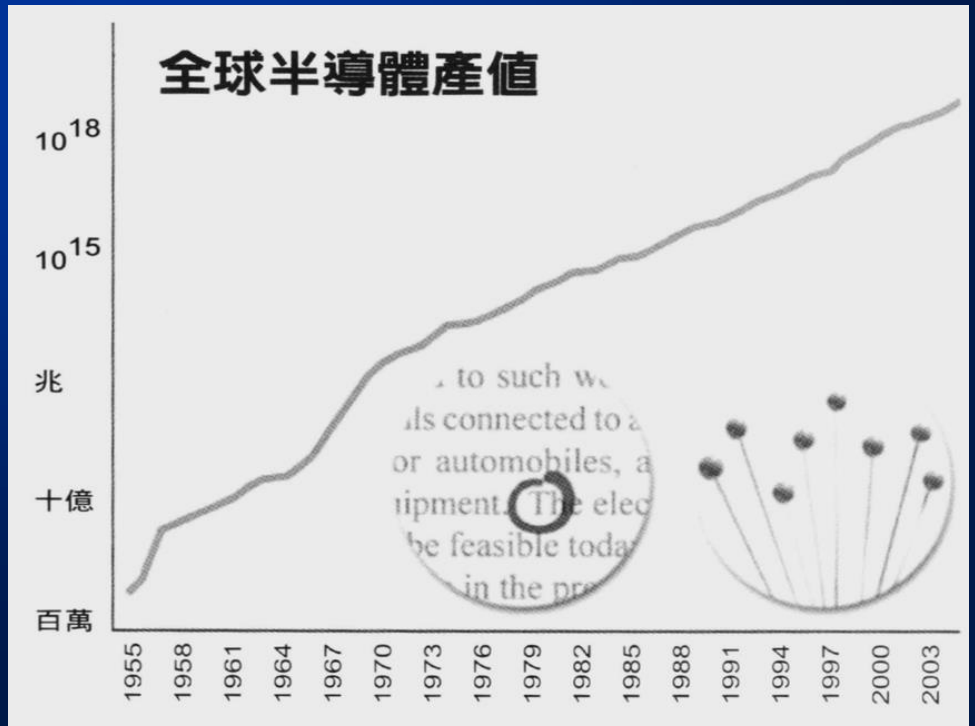
來自微電子學可能遭遇瓶頸的考慮



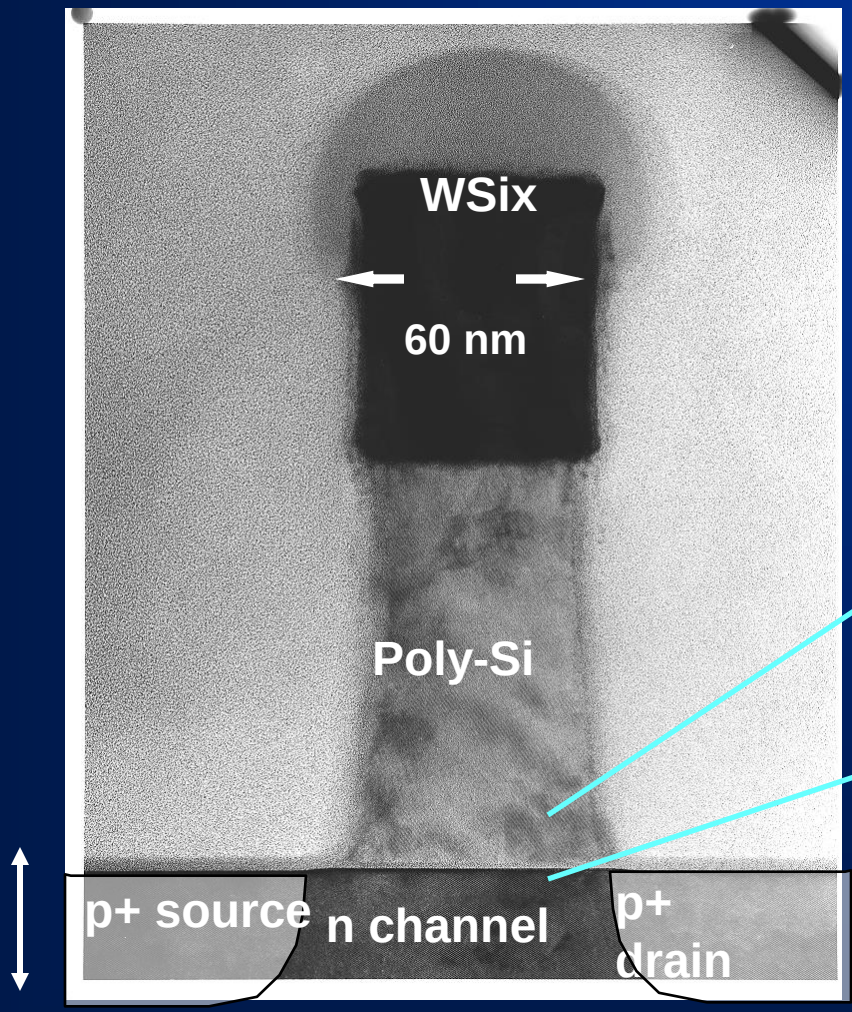
Moore‘s Law： 摩爾定律

A 30% decrease in the size of printed dimensions every 1.5 years.

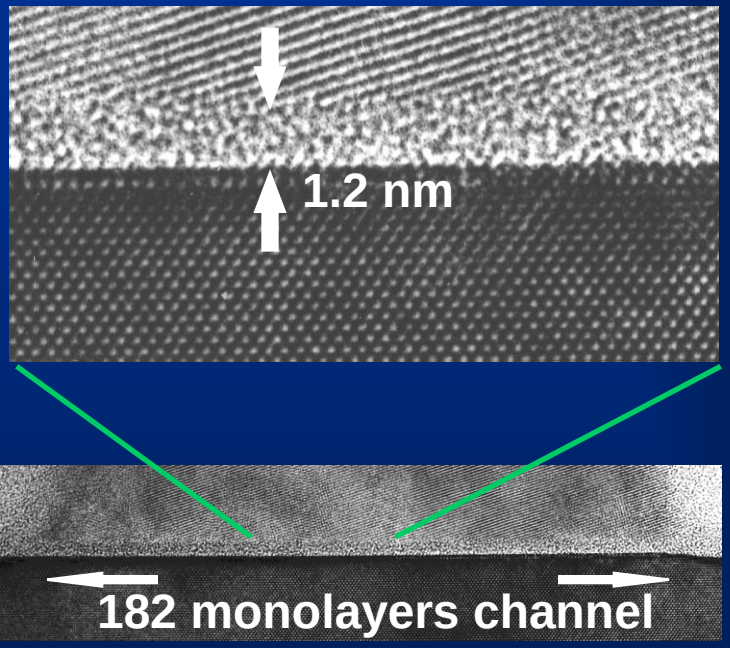
矽晶上電子原件數每1年半會增加一倍



Scaling Limits to CMOS Technology



Gate Oxide ~ 5 Si Atoms thick !



Shrinking the junction depth ➡ increasing the carrier concentration

CMOS scaling, When do we stop ?

Reliability: 25 ~~22~~ 18 ~~16~~ Å

processing and yield issue

Tunneling : 15 Å

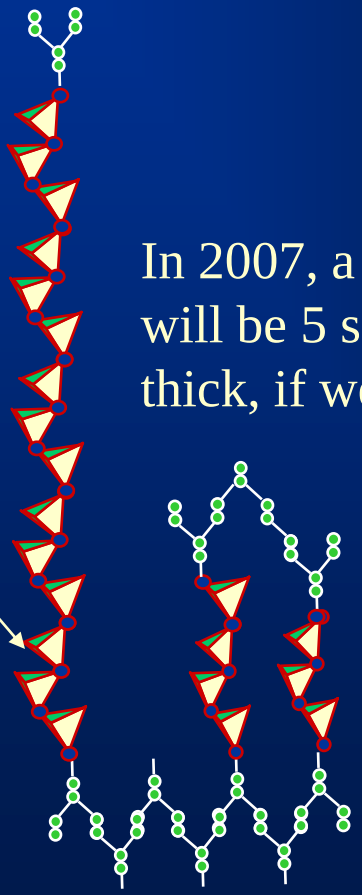
Design Issue: chosen for 1A/cm^2 leakage
I_{on}/I_{off} >> 1 at 12 Å

Bonding:

Fundamental Issues---

- how many atoms do we need to get bulk-like properties?
  EELS -- Minimal 4 atomic layers !!
- Is the interface electronically abrupt?
- Can we control roughness?

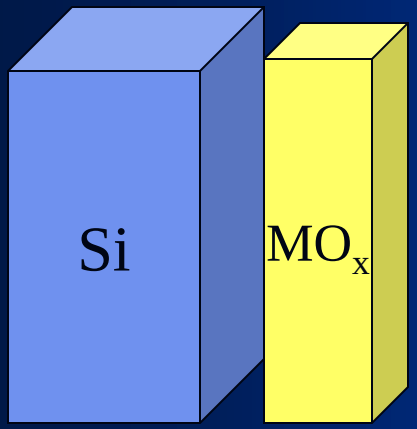
In 1997, a gate oxide was 25 silicon atoms thick.



In 2007, a gate oxide will be 5 silicon atoms thick, if we still use SiO_2

and at least 2 of those 5 atoms will be at the interfaces.

Fundamental Materials Selection Guidelines



$Si + MO_x \longrightarrow M + SiO_2$

$Si + MO_x \longrightarrow MSi_2 + SiO_2$

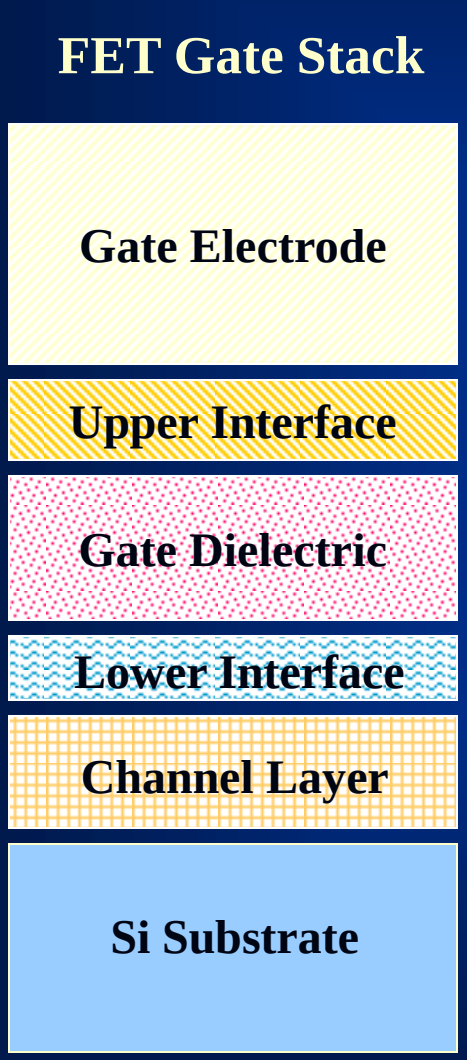
$Si + MO_x \longrightarrow MSiO_x + SiO_2$

- Thermodynamic stability in contact with Si to 750℃ and higher. **(Hubbard and Schlom)** **Alkaline earth oxide, IIIB, IVB oxide and rare earth oxide**
- Dielectric constant, band gap, and conduction band offset
- Defect related leakage, substantially less than SiO_2 at $t_{eq} < 1.5$ nm
- Low interfacial state density $D_{it} < 10^{11}\ eV^{-1}cm^{-2}$
- Low oxygen diffusivity
- Crystallization temperature >1000°C

t_{eq} : **equivalent oxide thickness (EOT) to be under 1.0 nm**

$t_{eq} = t_{ox}\ \kappa_{SiO2} / \kappa_{ox}$

Integration Issues for High κ Gate Stack



Critical Integration Issues

- Morphology dependence of leakage
  Amorphous vs crystalline films?
- Interfacial structures
- Thermal stability
- Gate electrode compatibility
- Reliability

Fundamental Limitations

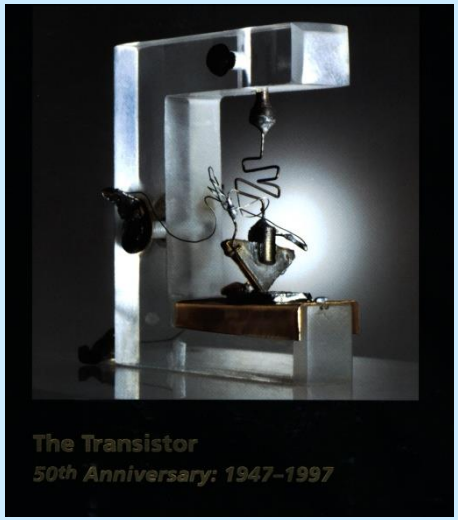
- Fixed charge
- Dopant depletion in poly-Si gate
- Dopant diffusion
- Increasing field in the channel region

Basic Characteristics of Binary Oxide Dielectrics

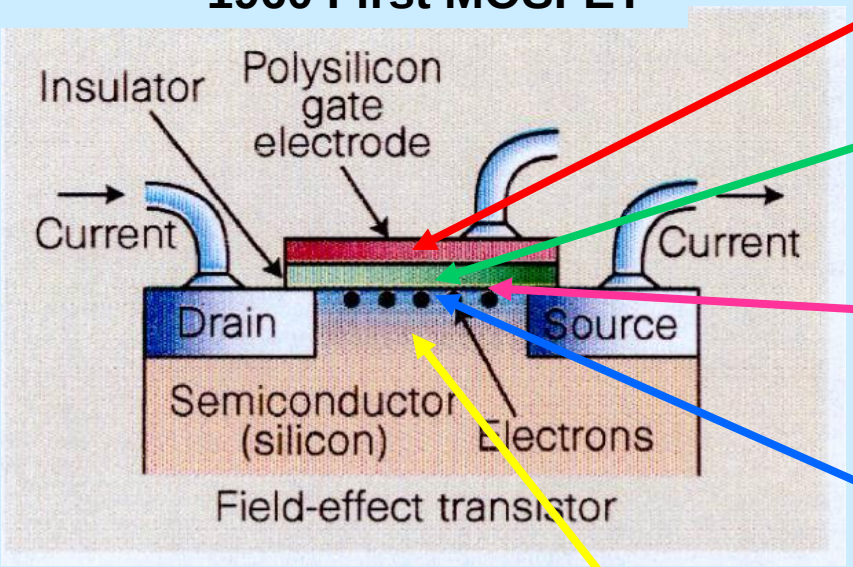
Dielectrics	SiO_2	Al_2O_3	Y_2O_3	HfO_2	Ta_2O_5	ZrO_2	La_2O_3	TiO_2
Dielectric constant	3.9	9.0	18	**20**	25	27	30	80
Band gap (eV)	9.0	8.8	5.5	**5.7**	4.5	7.8	4.3	3.0
Band offset (eV)	3.2	2.5	2.3	**1.5**	1.0	1.4	2.3	1.2
Free energy of formation $MO_x+Si_2 \rightarrow M+ SiO_2$ @727C, Kcal/mole of MO_x	-	63.4	116.8	**47.6**	-52.5	42.3	98.5	7.5
Stability of amorphous phase	High	High	High	**Low**	Low	Low	High	High
Silicide formation ?	-	Yes	Yes	**Yes**	Yes	Yes	Yes	Yes
Hydroxide formation ?	-	Some	Yes	**Some**	Some	Some	Yes	Some
Oxygen diffusivity @950C (cm^2/sec)	$2x\ 10^{-14}$	$5x\ 10^{-25}$	?	**?**	?	10^{-12}	?	10^{-13}

Si CMOS Device Scaling – Beyond 22 nm node
High κ, Metal gates, and High mobility channel

1947 First Transistor



1960 First MOSFET



Metal Gate

High κ gate dielectric

Oxide/semiconductor interface

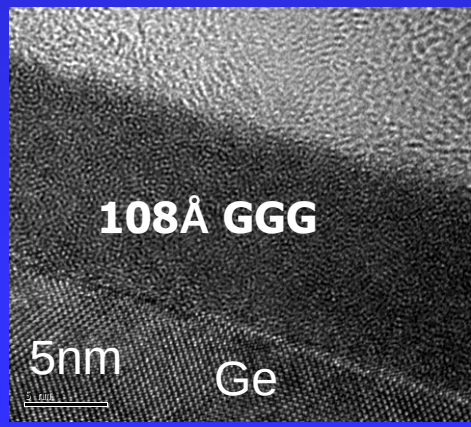
High mobility channel

Integration of Ge, III-V with Si

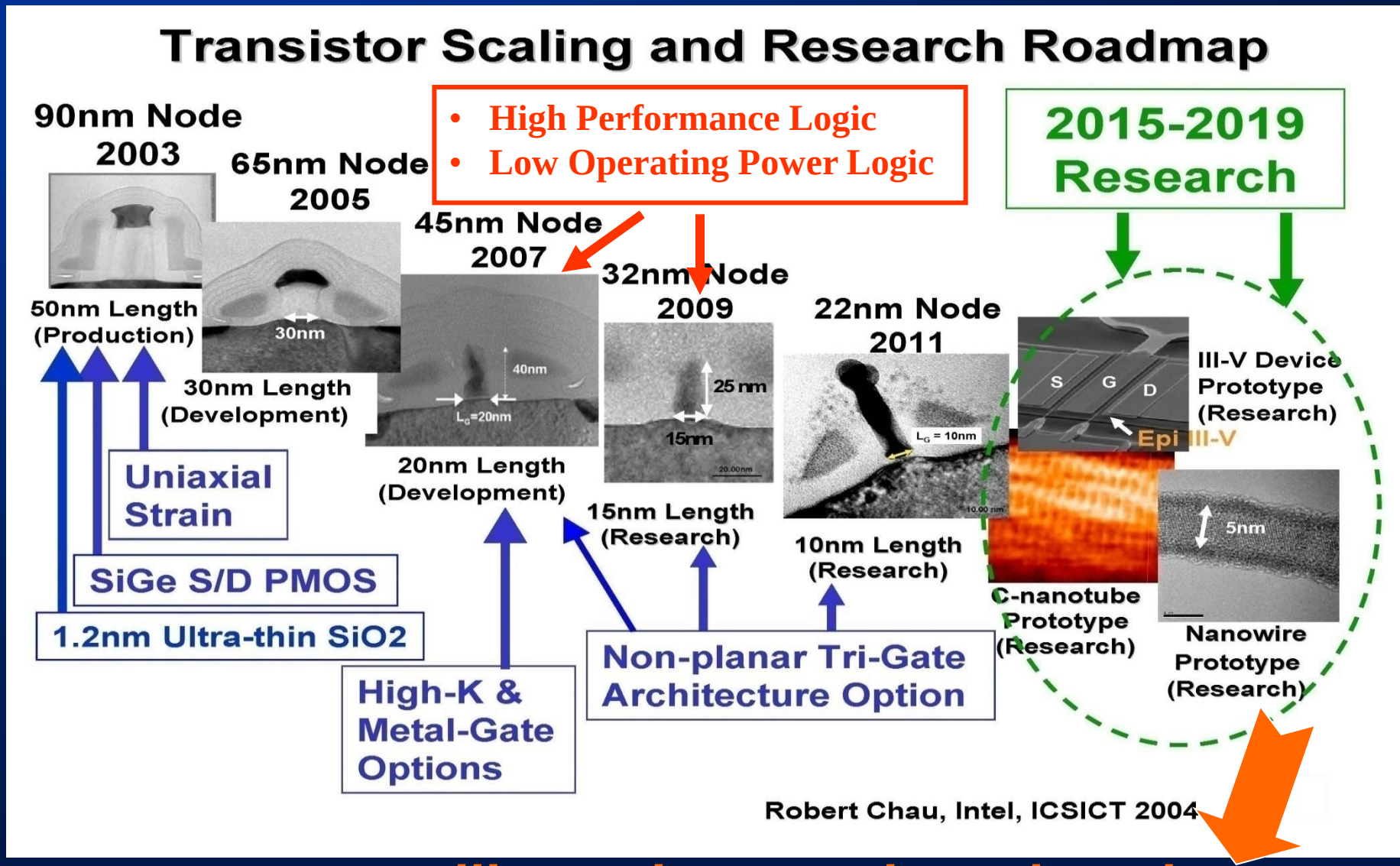
Moore's Law: The number of transistors per square inch doubles every 18 months

Shorter gate length *L*
Thinner gate dielectrics t_{ox}

Driving force :
High speed
Low power consumption
High package density



Intel Transistor Scaling and Research Roadmap



More non-silicon elements introduced

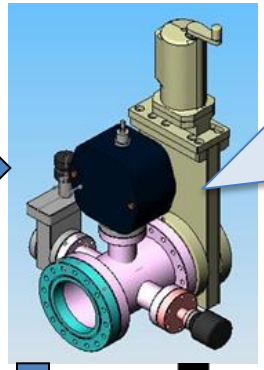
Science and Technology of Ultimate CMOS

The Ultimate CMOS – End of road map

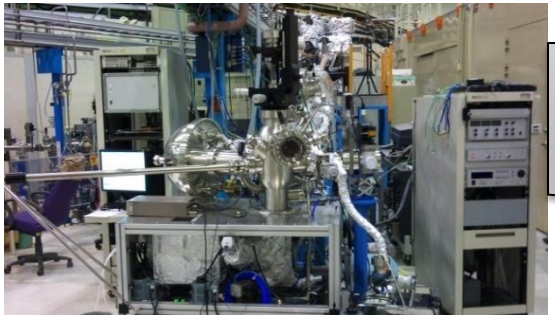
To achieve higher speed and lower power consumption

R&D of III-V InGaAs MOSFET state-of-art technology below 7 nm node,
by combining advanced analysis of spectroscopy/microscopy/quantum transport/theoretical modeling

- In-situ ALD of oxide integrated with MBE
- Tailor reconstructed surface to be Ga-rich
- Controlled chemical reaction route and species

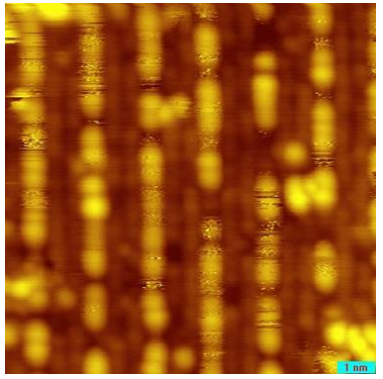


Portable UHV chamber for transfer 2”wafers in $3x10^{-10}$ torr for PES and STM analysis



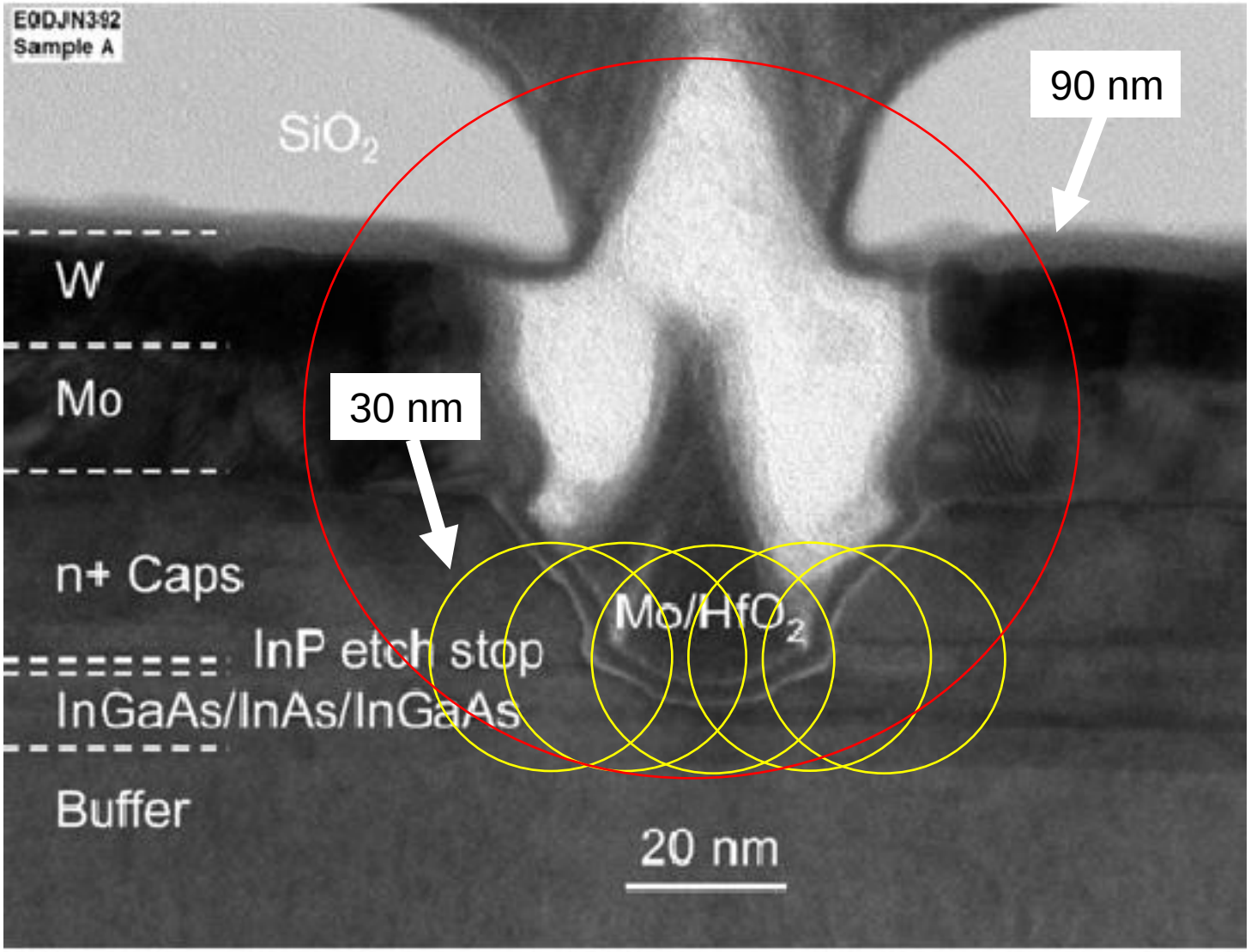
High resolution synchrotron radiation photoemission spectroscopy in NSRRC by Dr. T.W. Pi.

InGaAs surface reconstructed at 77K



RT and LT STM/STS study
by Dr. W.W. Pi at CCMS/NTU

Bragg Ptychography on III-V MOSFETs with gate length < 30 nm



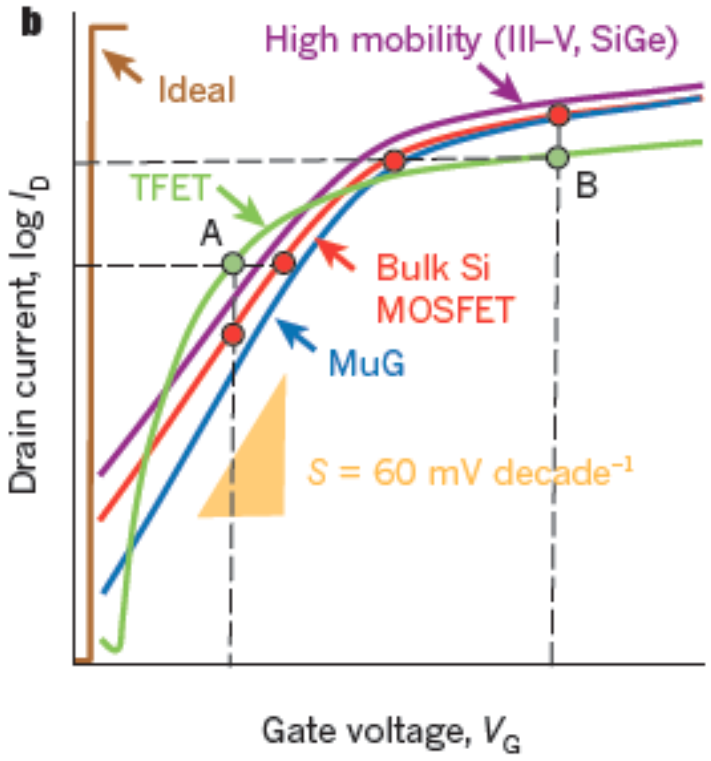
J. A. Alamo et al., IEDM 24 (2013)

TFETs offer sharper turn-on devices compared to MOSFETs

lower VDD to lower Switching Energy ($P_{active} \sim C \cdot V_{DD}^2$)

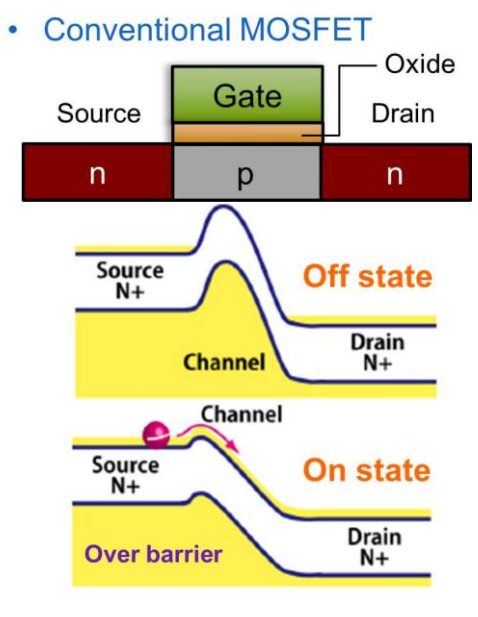
Better performance for ultra low-power applications

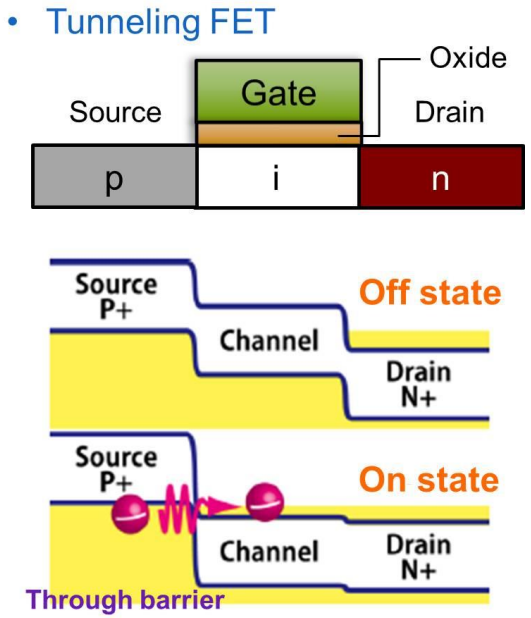
Atomic Model Prediction



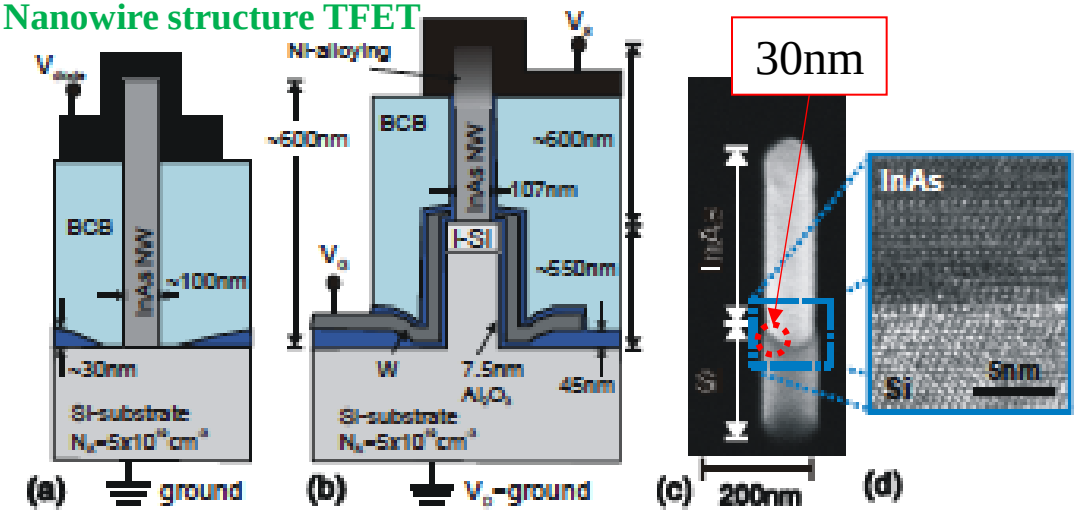
A. M. Ionescu et al.,

Nature **479**, 329 (2011).





Nanowire structure TFET

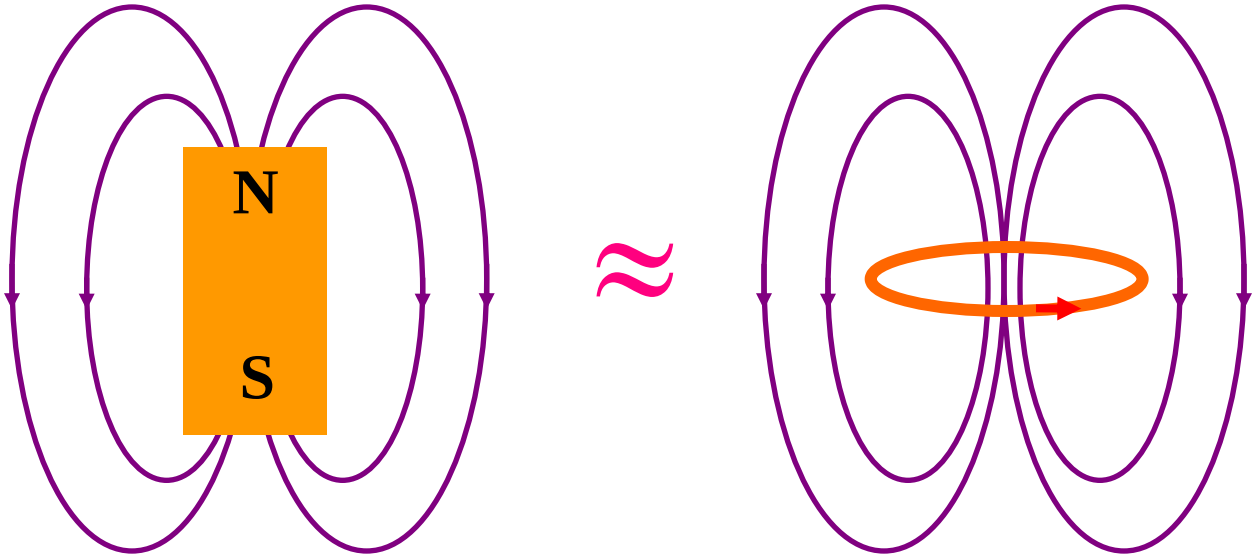


H. Riel et al., *IEDM* 391 (2012).

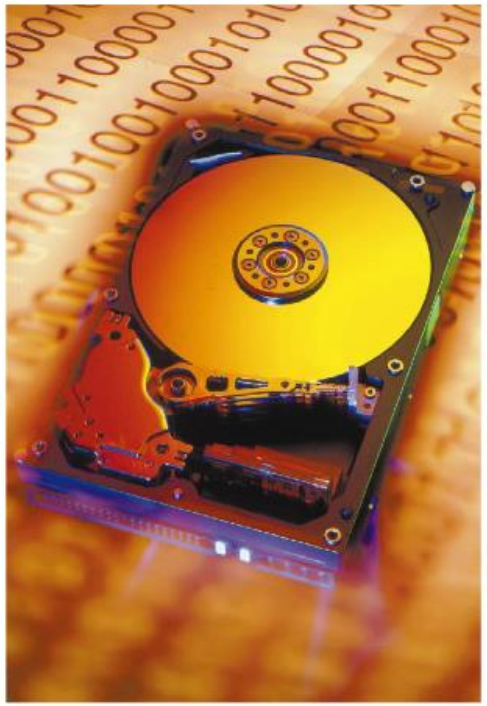
(IV) Quantum Spin

Spin and Nano technology

Electron Spin is the smallest unit of magetism, Came from Quantum Mechanics



Often being used for magnetic recording
~30 billion market



Well read: spintronics has dramatically increased data storage densities in hard drives.

Spintronics ⇔ Electronics

Magnetic Tunnel Junctions(MTJ)

New generation of computer

Compulttion and storage in one shot

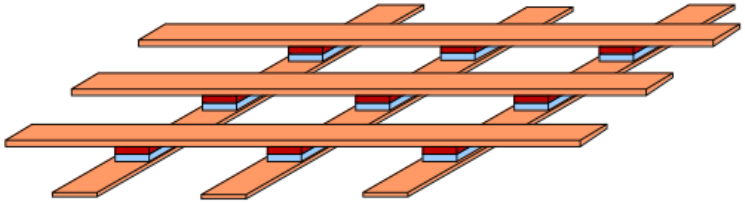
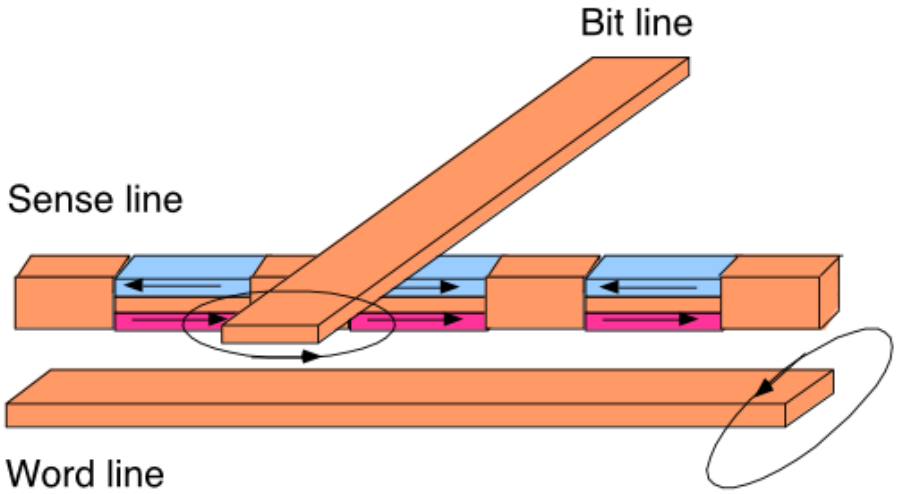


Fig. 7. A schematic representation of RAM that is constructed of magnetic tunnel junctions connected together in a point contact array. The conducting wires provide current to the junctions and permit voltage measurements to be made. They also enable the manipulation of the magnetization of the elements by carrying currents both above and below the magnetic junctions to create magnetic fields.

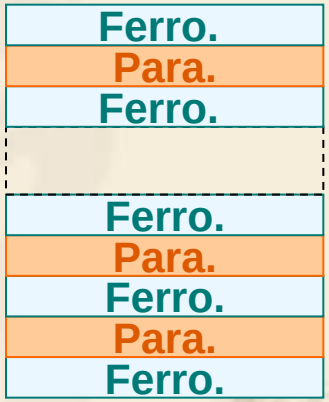


When turn-on, it is ready!

Giant Magnetoresistance(GMR)

What is GMR?

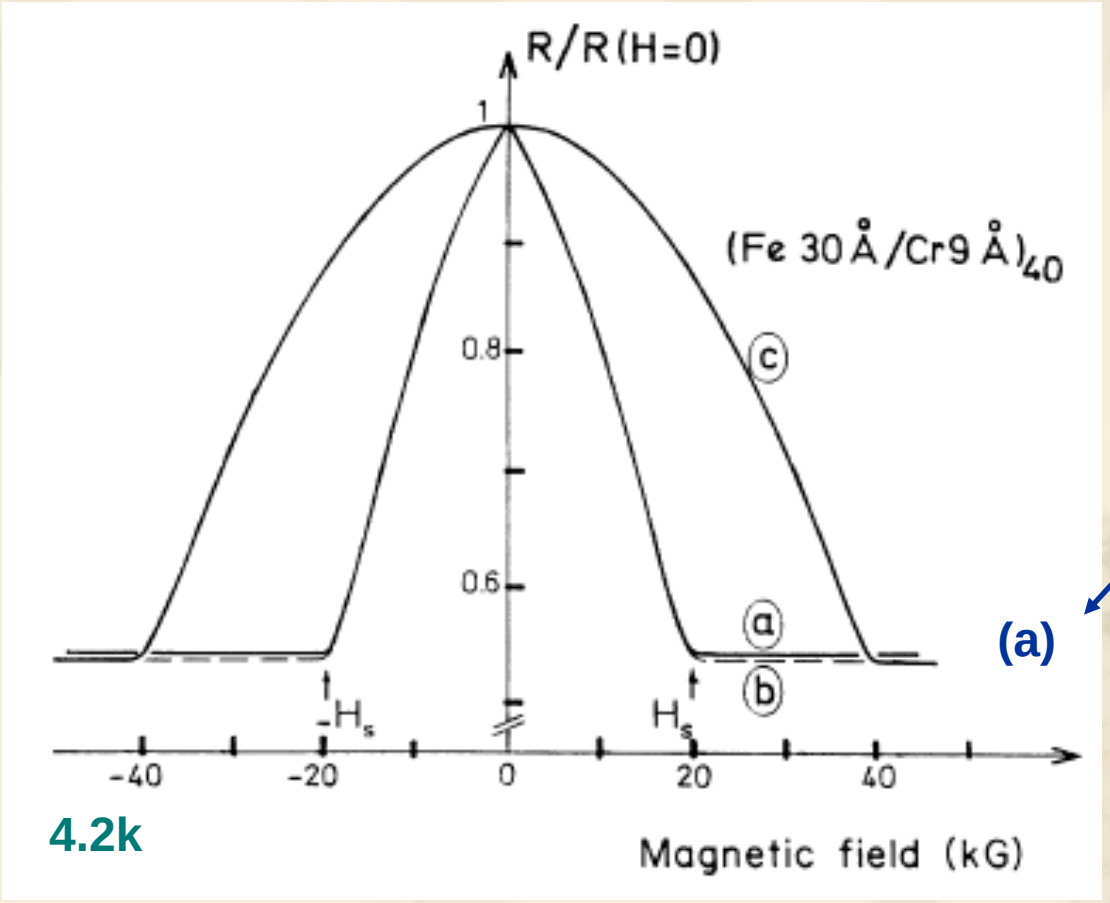
- GMR is a very large change in electrical resistance that is observed in a ferromagnet/paramagnet multilayer structure.

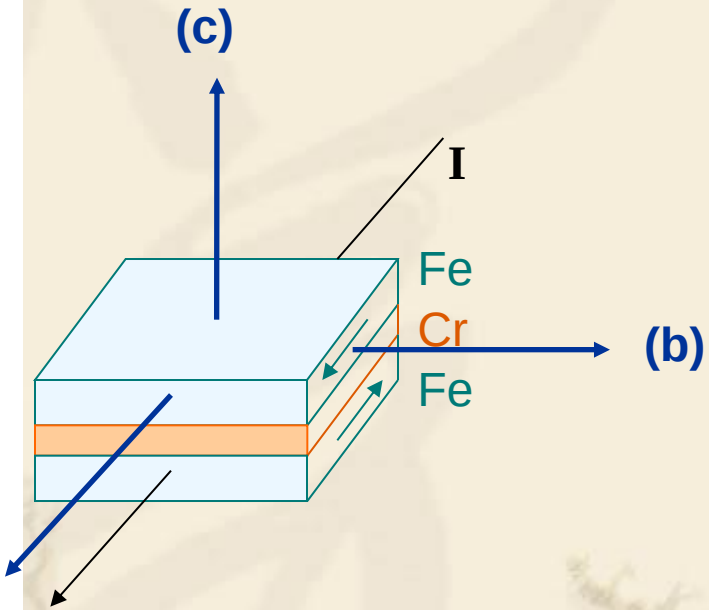


- Resistance change occurs when the relative orientations of the magnetic moments in alternate ferromagnetic layers change as a function of applied field.

- The total resistance of this material is lowest when the magnetic orientations of the ferromagnetic layers are aligned, is highest when the orientations are anti-aligned.

First Evidence of GMR





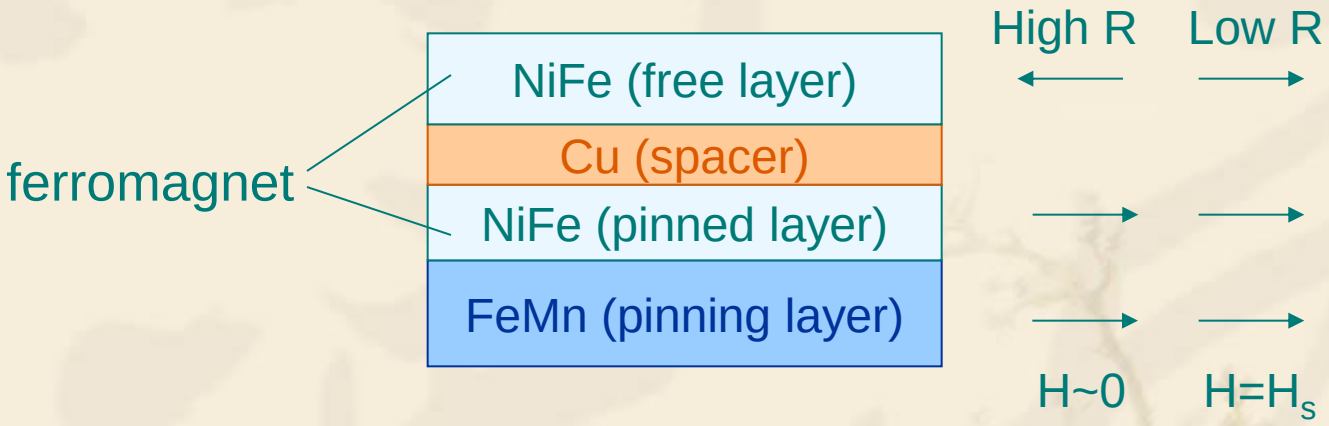
Hs **corresponds to the field at which all layer magnetizations point along the field direction.**

M. N. Baibich, J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff，
Phys. Rev. Lett.，**61**，2472 (1988)

Spin-Valve GMR

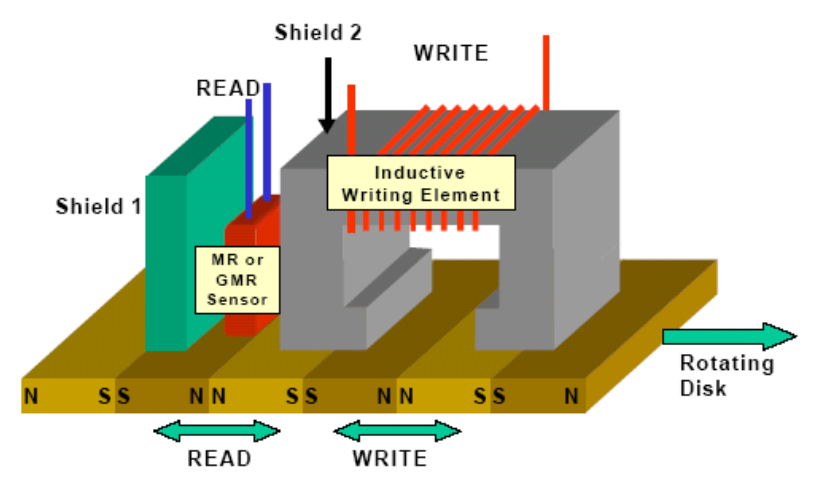
What is Spin-Valve GMR ?

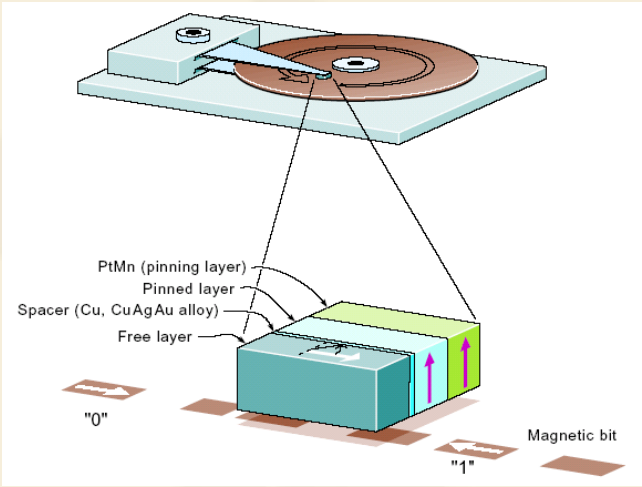
- **The simple structure of Spin-valve GMR is**



- **The magnetisation of the top permalloy layer is free to rotate as the field is varied, Second permalloy layer is fixed due to its exchange interaction with the iron–manganese layer.**

GMR Spin Valve Reading Head



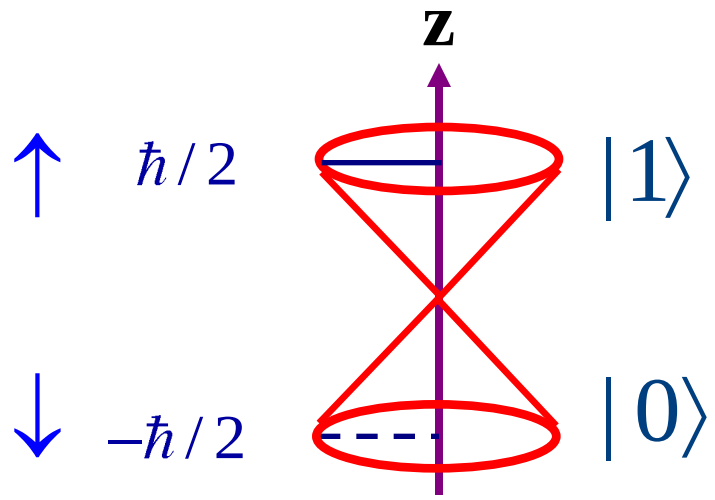


- Magnetization is stored as a “0” in one direction and as a “1” in the other. This is the magnetic field sensed by the GMR head.
- When the head passes over these magnetic bits, the magnetization direction of the free layer in the head responds to the fields in each bit by rotating either up or down.
- The resulting change in the resistance is sensed by the voltage acrossing the GMR head (current passing through the GMR element is constant).

Dr. K. Gilleo, Cookson Electronics ; N. Kerrick and G. Nicholls, AMPM

Quantum behavior of ferromagnets

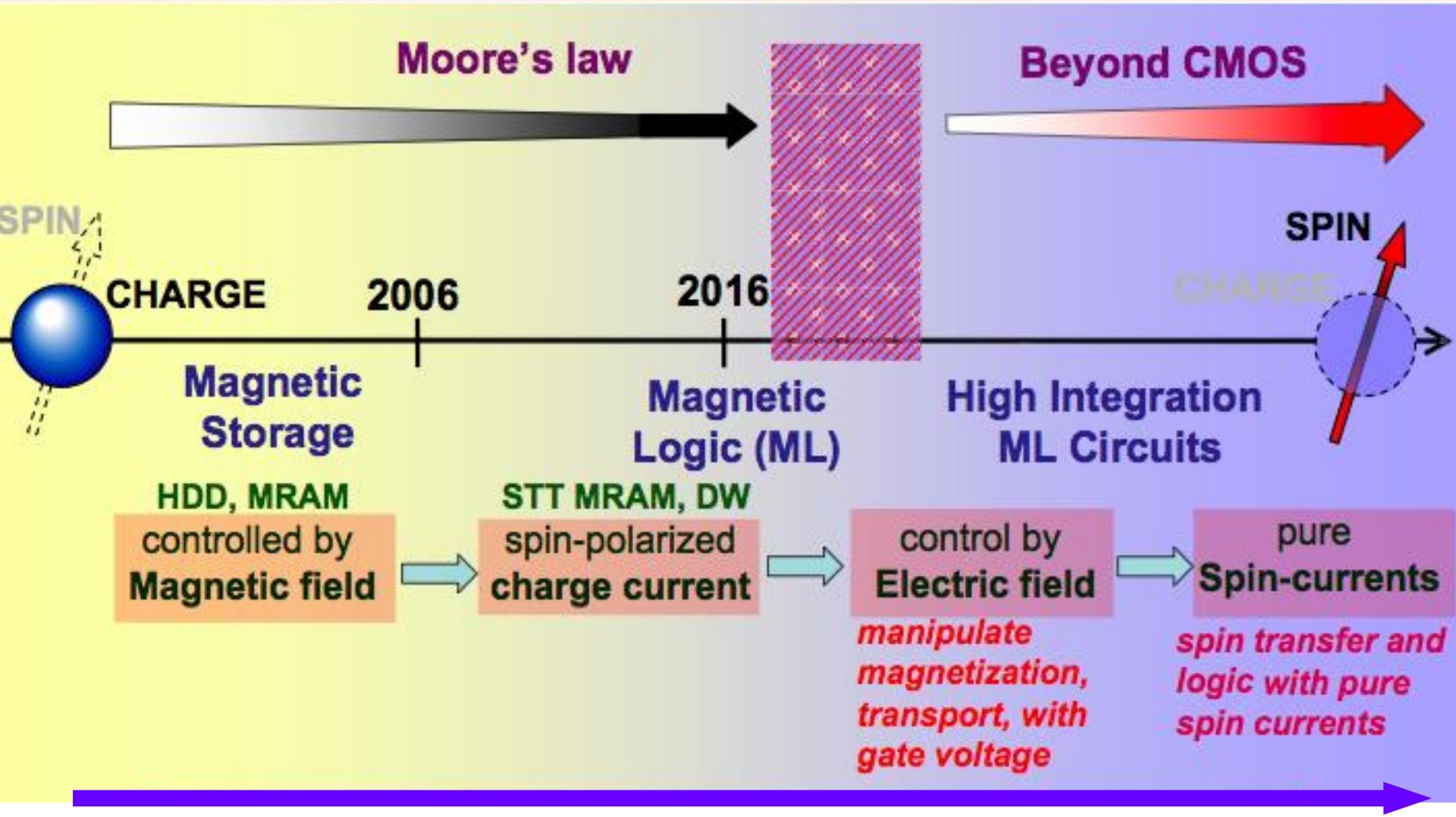
-Spin as a quantum qubit



$$qubit = \alpha|0\rangle + \beta|1\rangle$$

Due to superposition
More information!

Tentative roadmap



Can we take the "charge" out of Spintronics ?

To generate pure spin current !

Courtesy Claude Chappert, Université Paris Su, INTERMAG 2008, Madrid, Spain

Spintronics vs Electronics

- ✓ Reducing the heat generated in traditional electronics is a major driving force for developing spintronics.
- ✓ Spin-based transistors do not strictly rely on the raising or lowering of electrostatic barriers, hence it may overcome scaling limits in charge-based transistors.
- ✓ Spin transport in semiconductors may lead to dissipationless transfer of information by pure spin currents.
- ✓ Allow computer speed and power consumption to move beyond limitations of current technologies.

Reliable generation of pure spin currents !

- ✓ Spin Hall effect (2004)
- ✓ Spin Pumping (2006)
- ✓ Inverse Spin Hall effect (2006)
- ✓ Spin Seebeck effect (2008)
- ✓ Spin Caloritronics (2010)

Major Qauntum Effect at the nano scale

- **Interference**
- **Quantization**
- **Tunneling**
- **Quantum Spin**