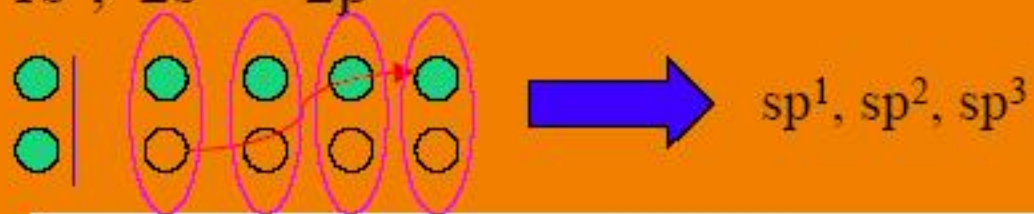
The Advent of Carbon Era ?

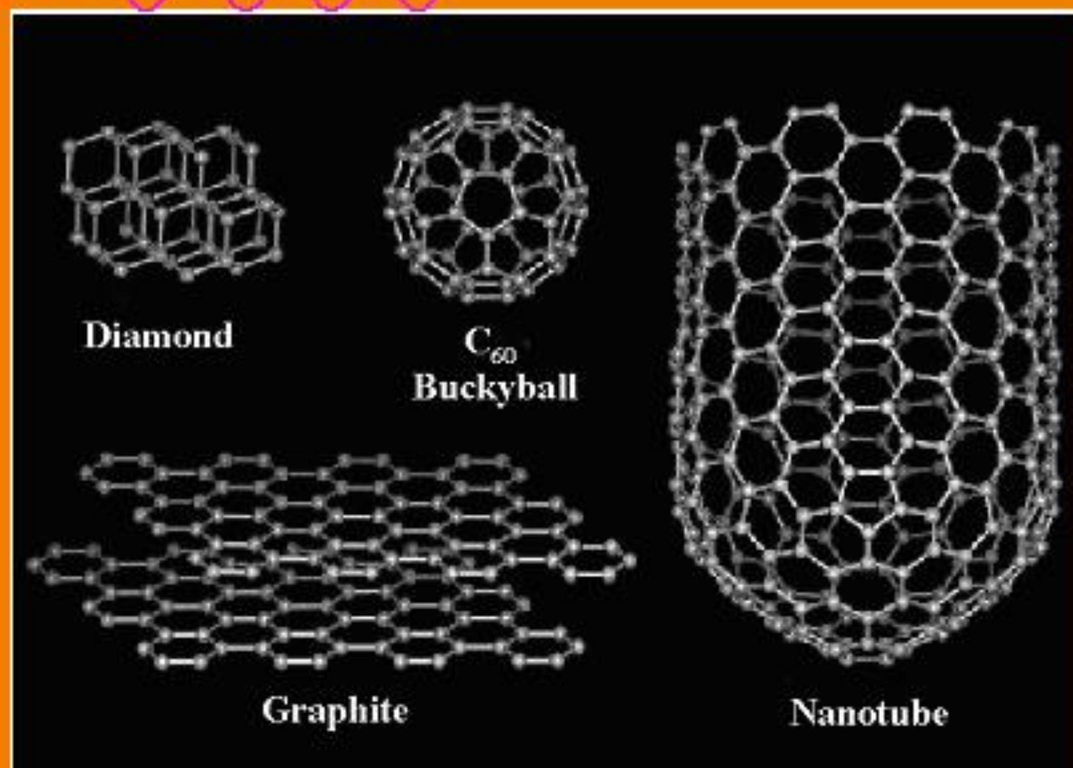
The Physics of Graphene:
- Possibility of relativistic electronics and spintronics

Carbon Nanotube

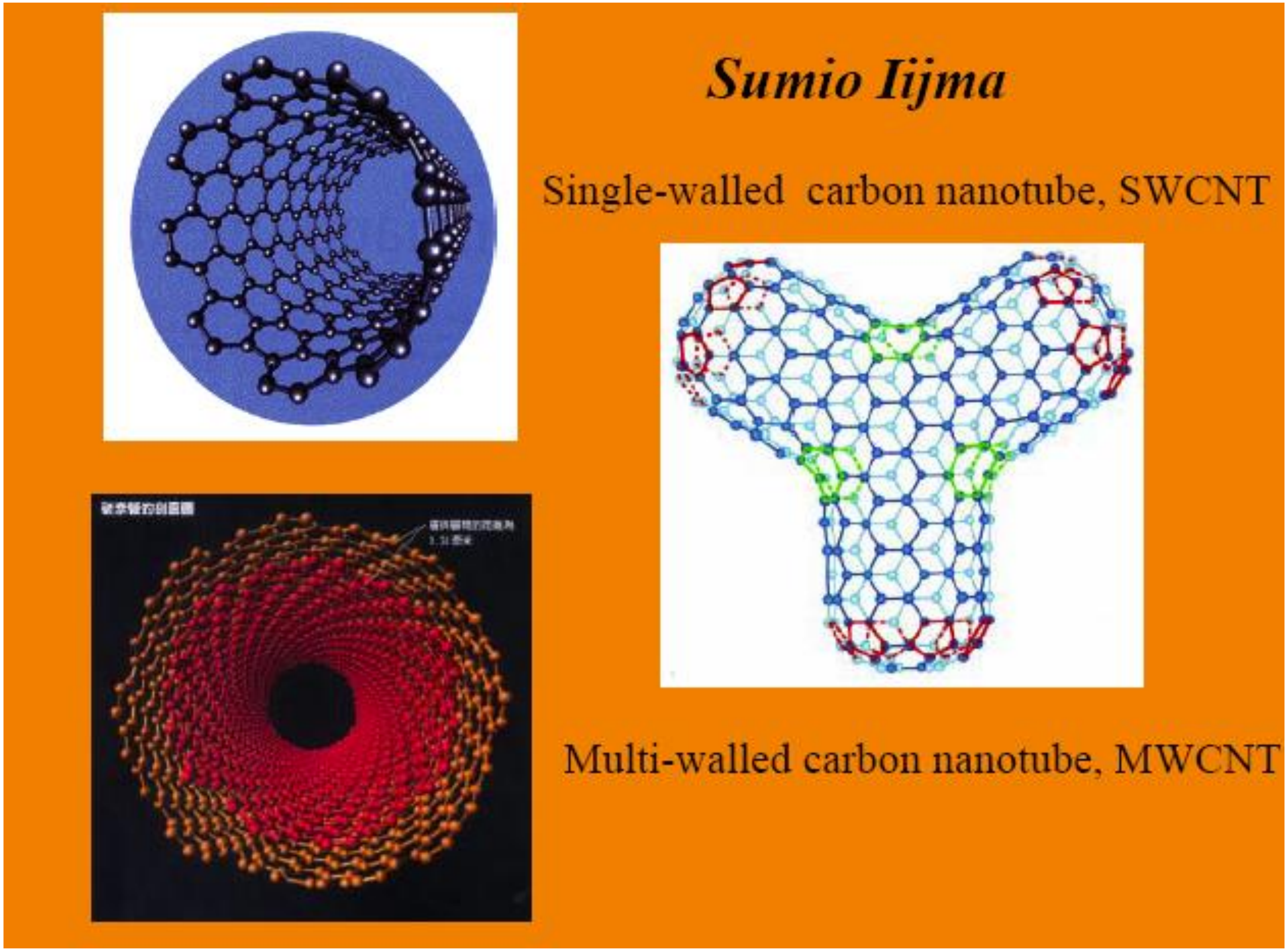
- Structure of carbon nonatubes

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





Carbon Nanotube

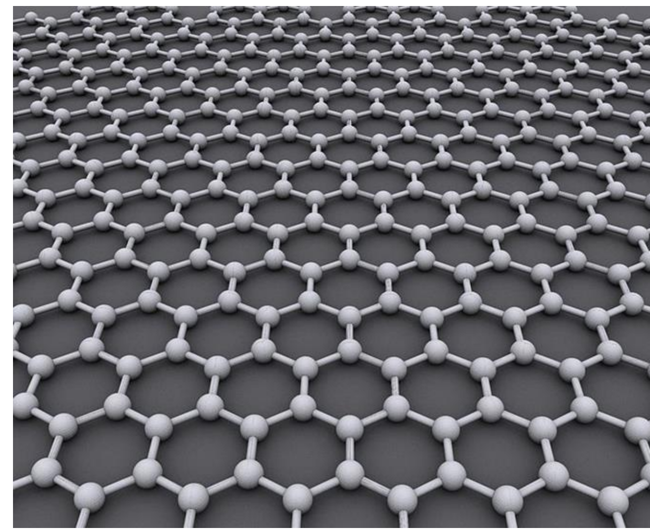


Carbon Nanotube based Transistors / Electronics

Unexpected realization of graphene sheet

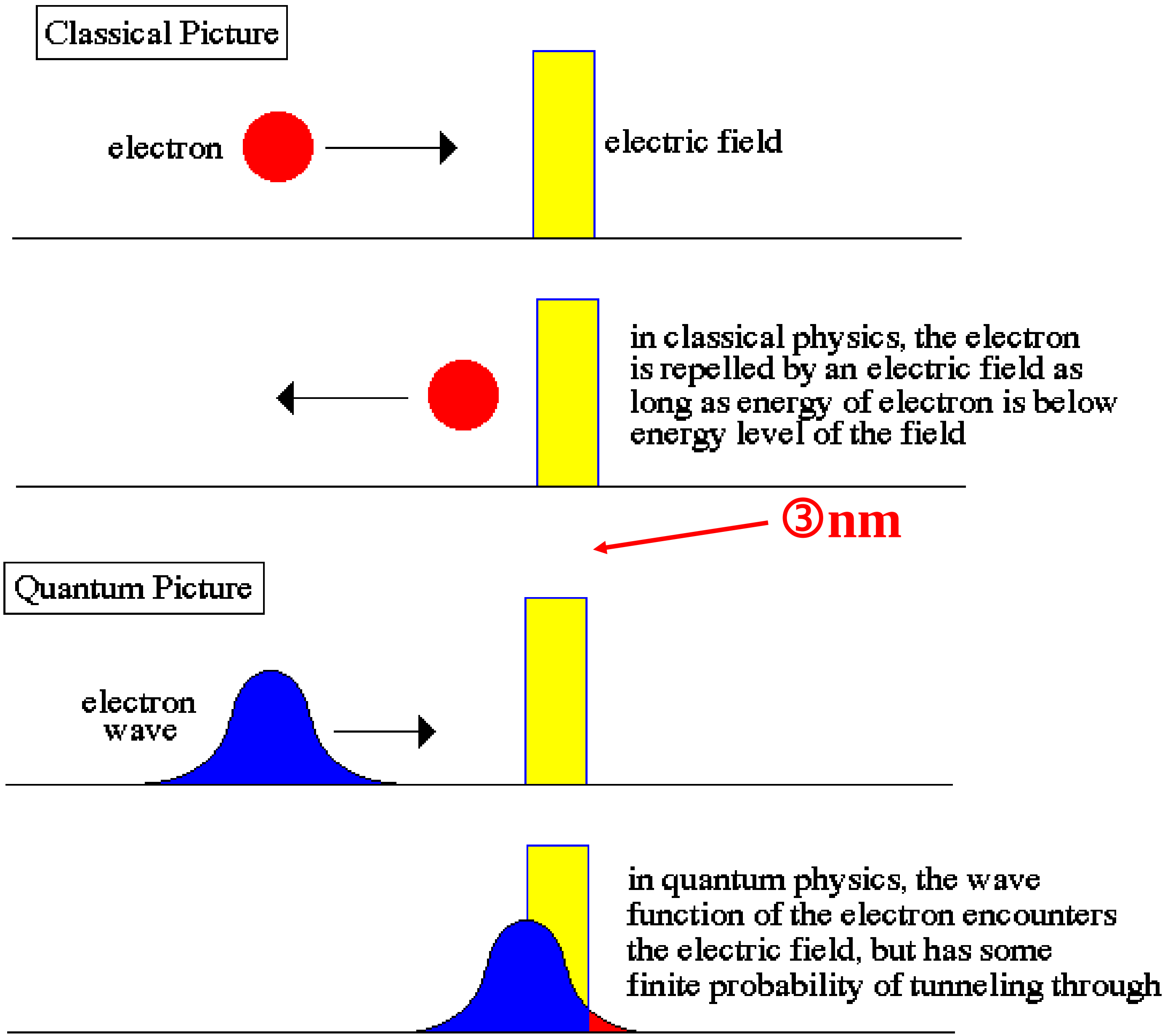
(⇐

mechanically exfoliated graphene sheets



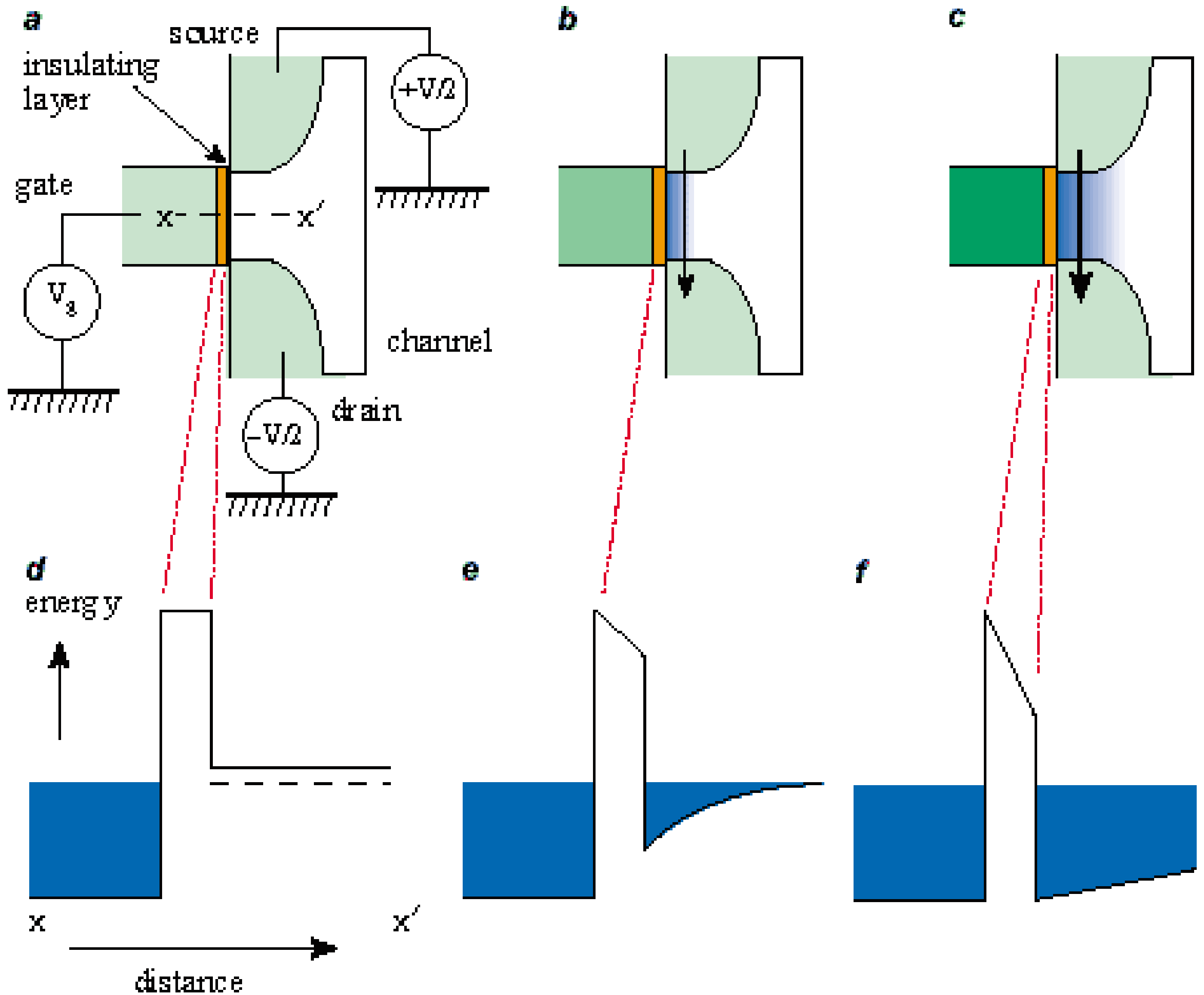
AFM image of single-layer graphene on SiO_2
K.S. Novoselove et al., Science 306, 666 (2004)

(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



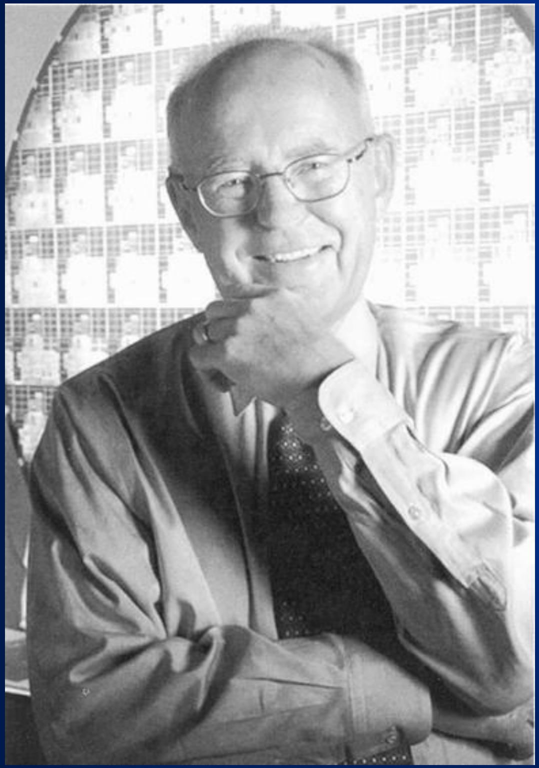
近來大力推動奈米科技的背景

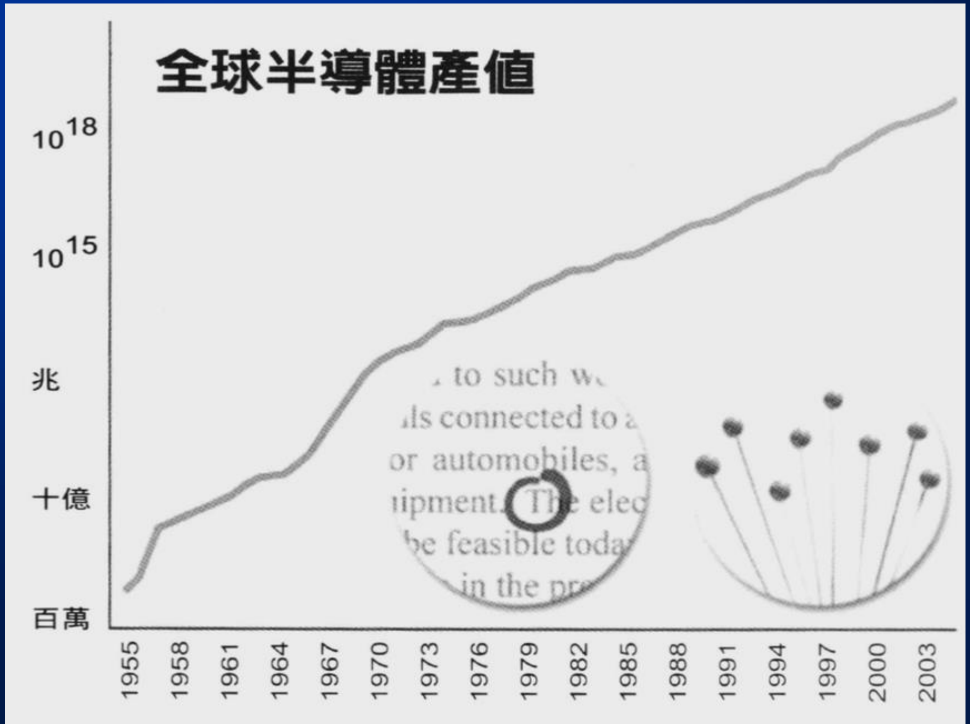
來自微電子學可能遭遇瓶頸的考慮

Moore's Law：摩爾定律

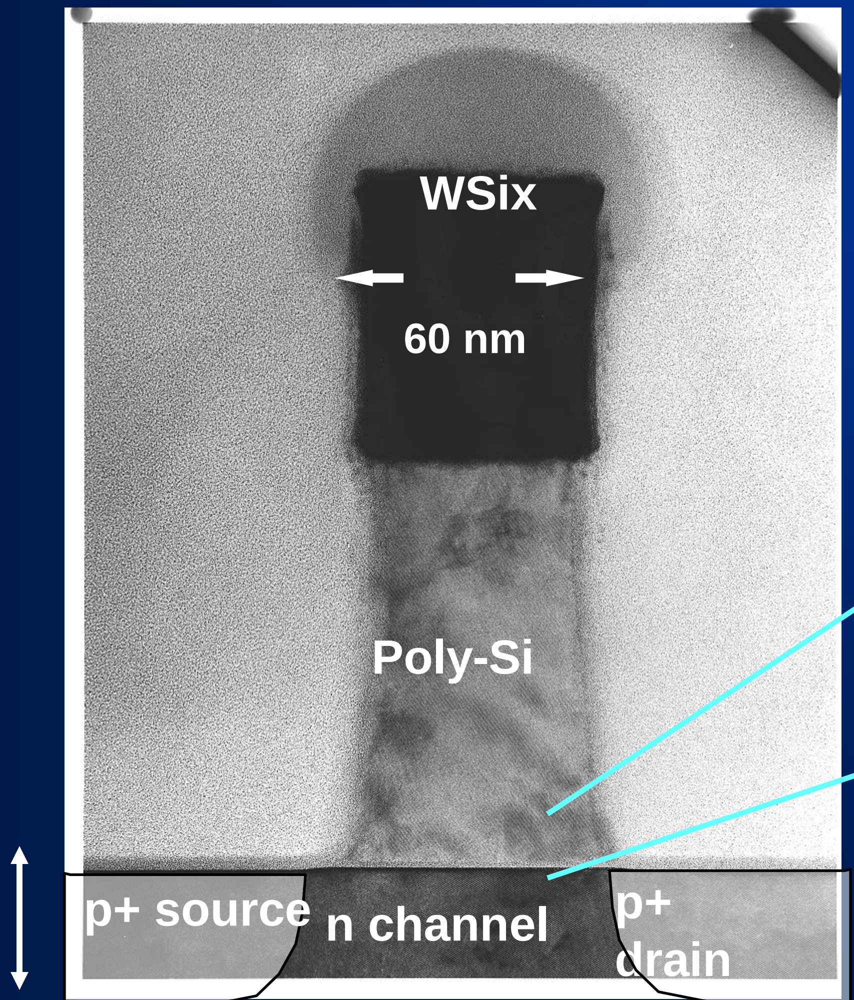
A 30% decrease in the size of printed dimensions every 1.5 years.

矽晶上電子原件數每1年半會增加一倍

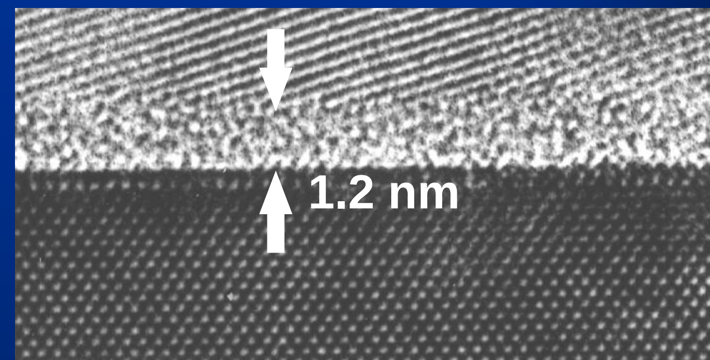


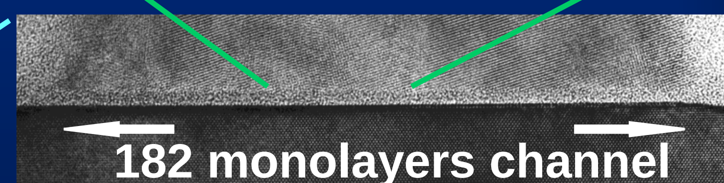


Scaling Limits to CMOS Technology



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

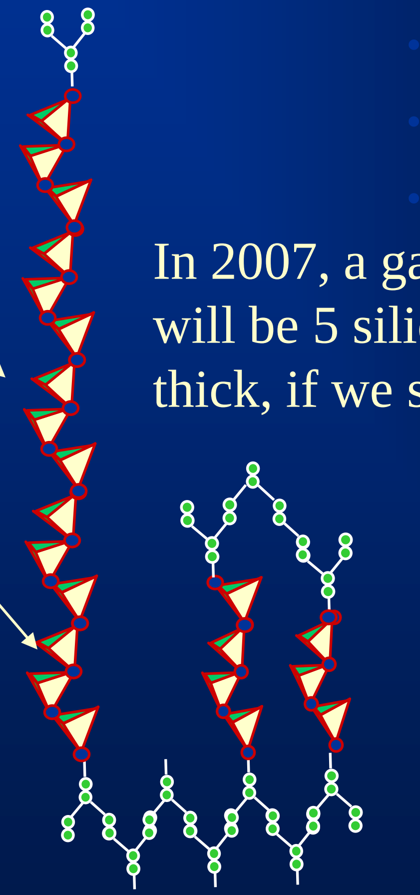
Design Issue: chosen for $1 A/cm^2$ leakage
$I_{on}/I_{off} >> 1$ at 12 Å

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?

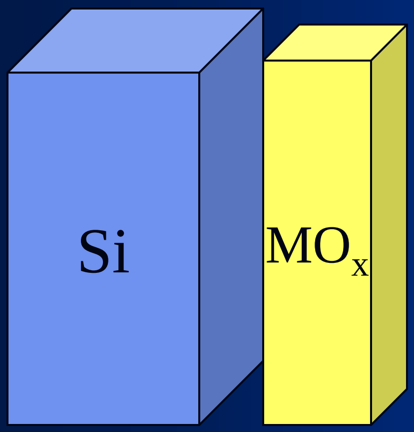
In 1997, a gate oxide was 25 silicon atoms thick.



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**

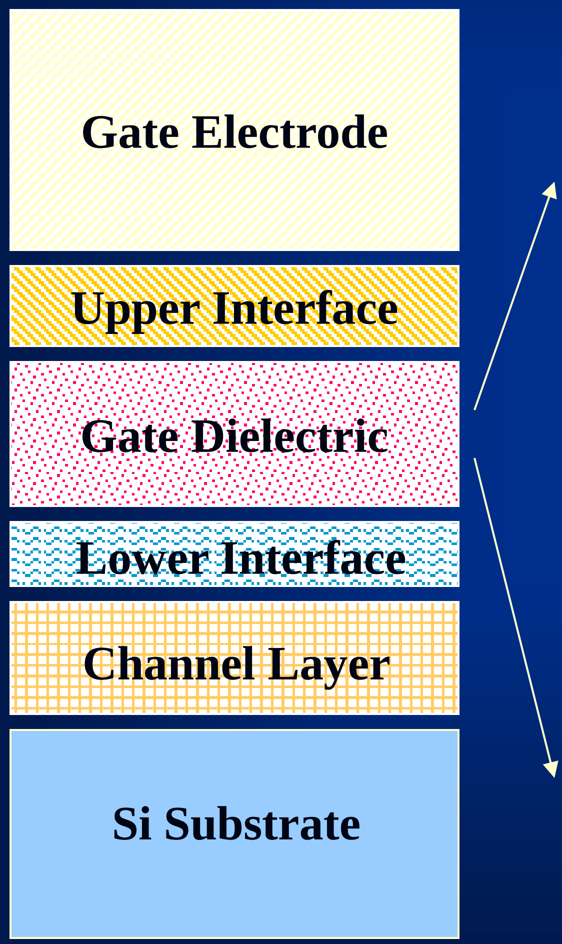
$t_{eq} = t_{ox}\, \kappa_{SiO2} / \kappa_{ox}$

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) Band offset (eV)	9.0 3.2	8.8 2.5	5.5 2.3	5.7 1.5	4.5 1.0	7.8 1.4	4.3 2.3	3.0 1.2
Free energy of formation MO_x+Si_2 $\longrightarrow$ 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}

Integration Issues for High κ Gate Stack

FET Gate Stack



Critical Integration Issues

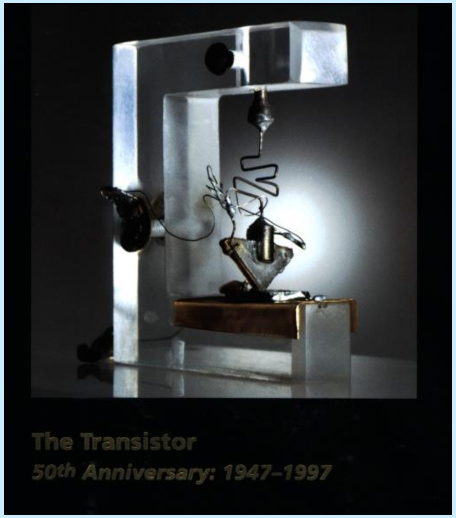
- Morphology dependence of leakage
  Amorphous vs crystalline films?
- Interfacial structures
- Thermal stability
- Gate electrode compatibility
- Reliability

Fundamental Limitations

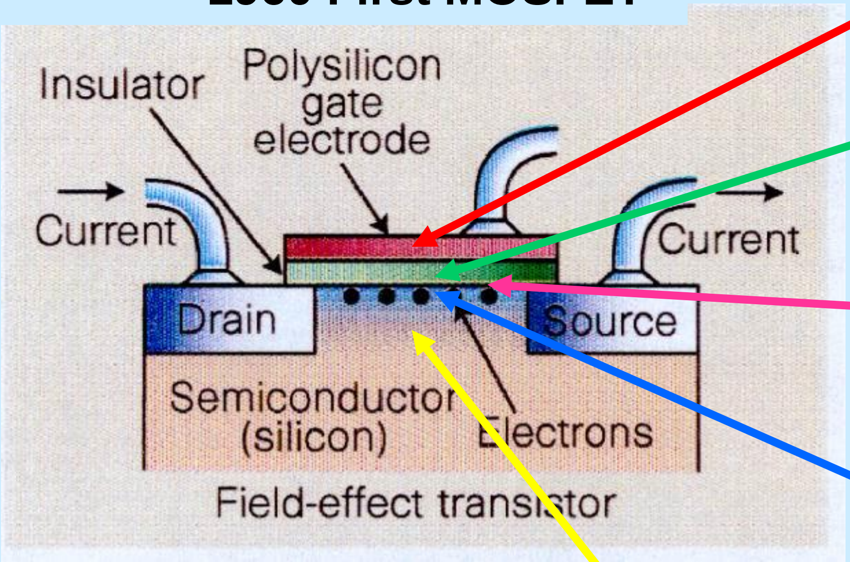
- Fixed charge
- Dopant depletion in poly-Si gate
- Dopant diffusion
- Increasing field in the channel region

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

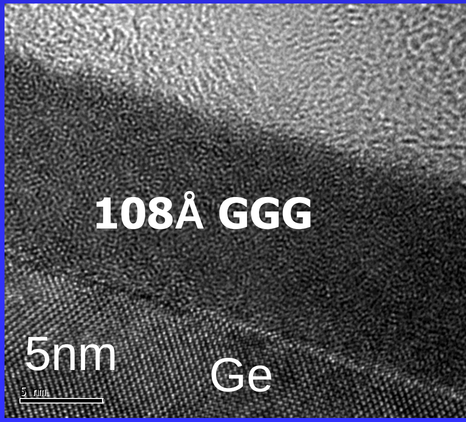
High mobility channel

Integration of Ge, III-V with Si

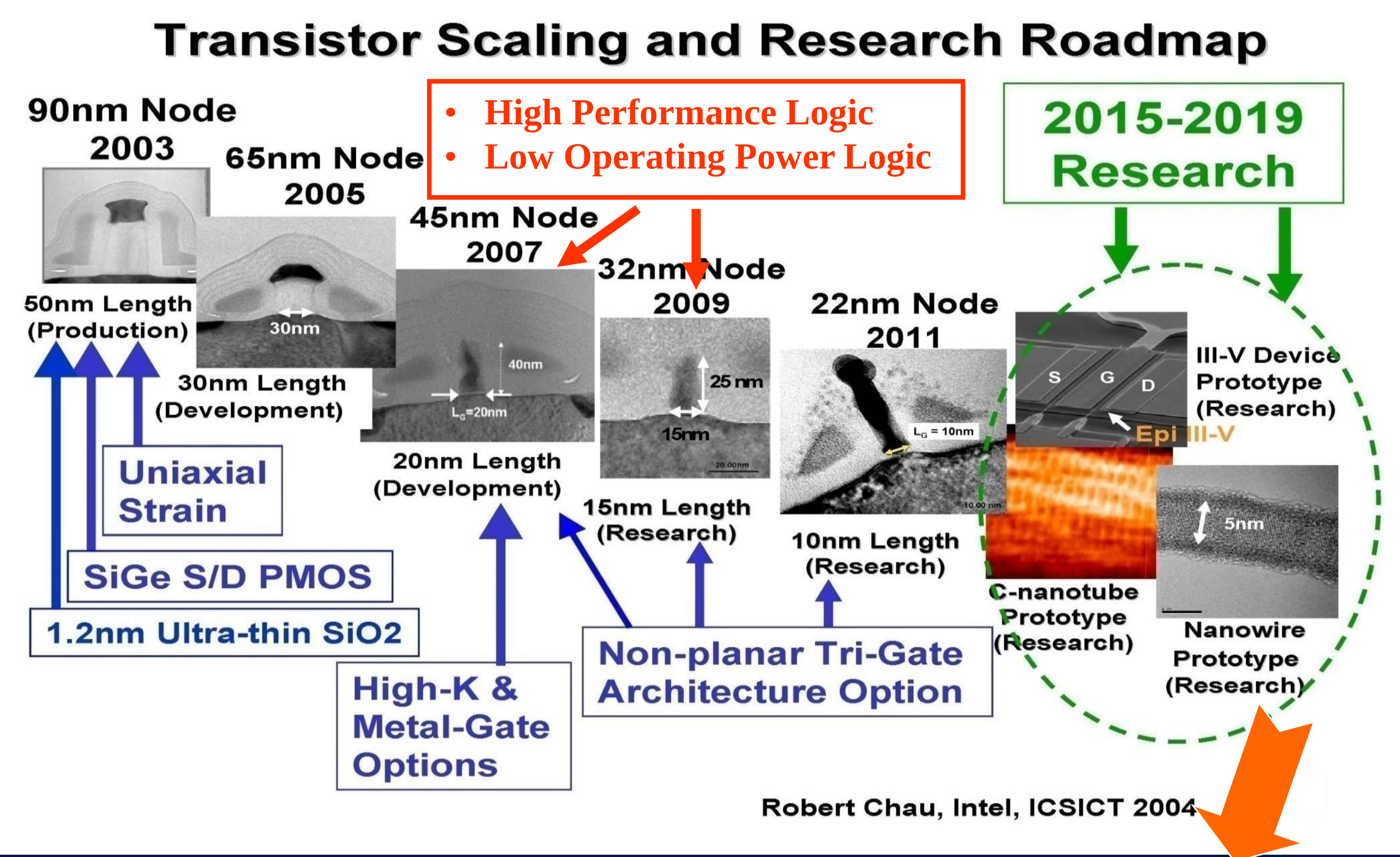
Moore's Law: The number of transistors per square inch doubles every 18 months

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

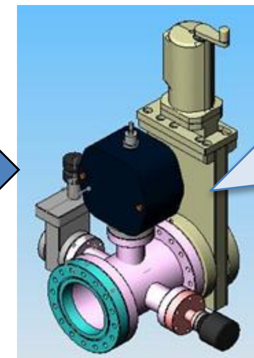
Science and Technology of Ultimate CMOS

The Ultimate CMOS – End of road map

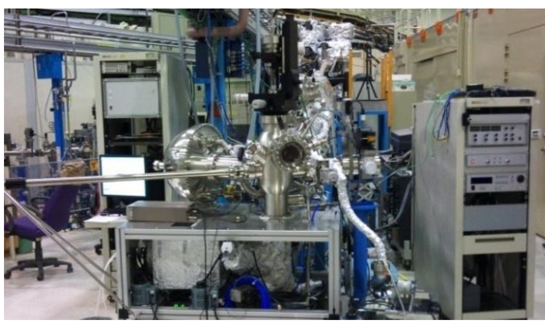
To achieve higher speed and lower power consumption

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



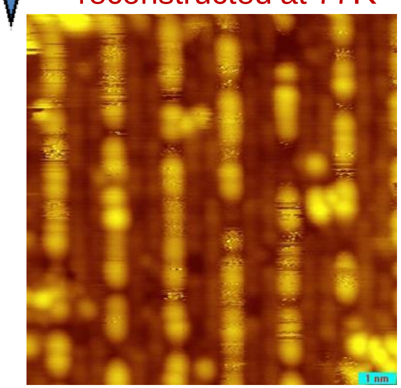
Portable UHV chamber for transfer 2"wafers in 3x10^{-10} torr for PES and STM analysis



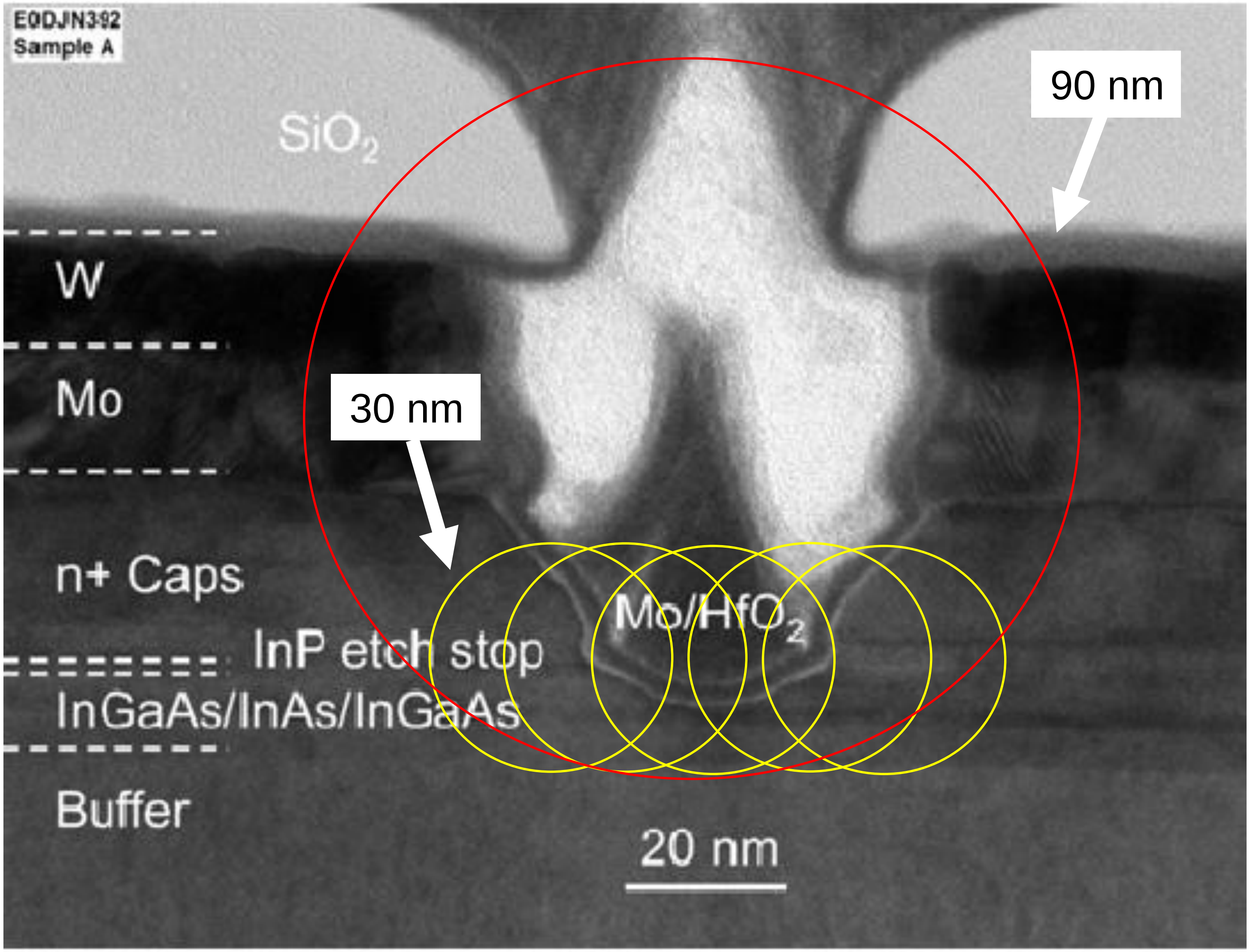
High resolution synchrotron radiation photoemission spectroscopy in NSRRC by Dr. T.W. Pi.

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

InGaAs surface reconstructed at 77K



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



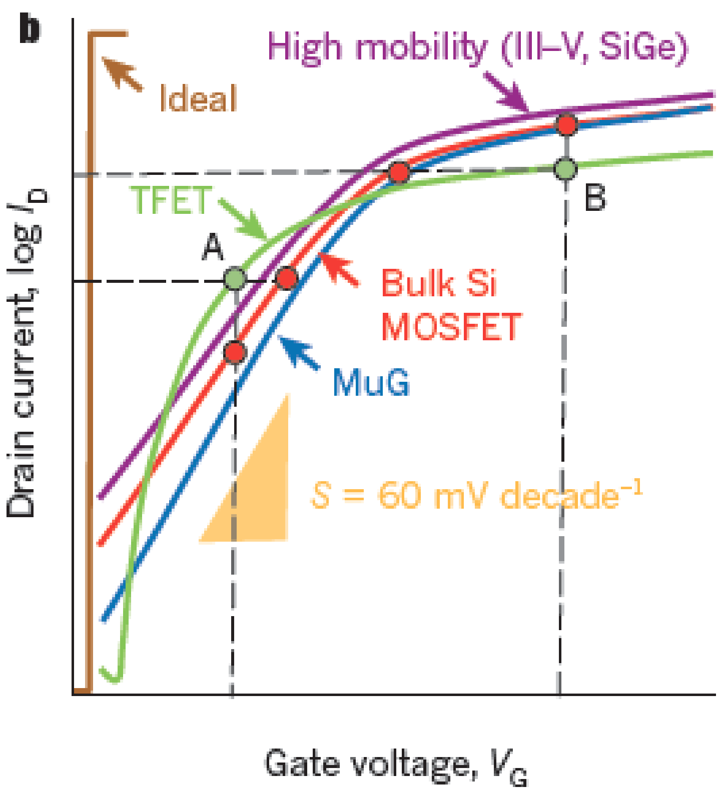
J. A. Alamo et al., IEDM 24 (2013)

Tunneling-FETs offer sharper turn-on devices compared to MOSFETs

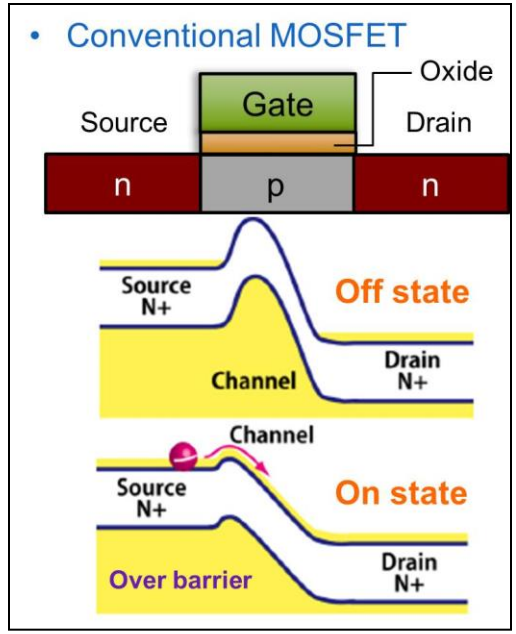
Lower VDD to lower switching energy ($P_{active} \sim C \cdot V_{DD}^2$)

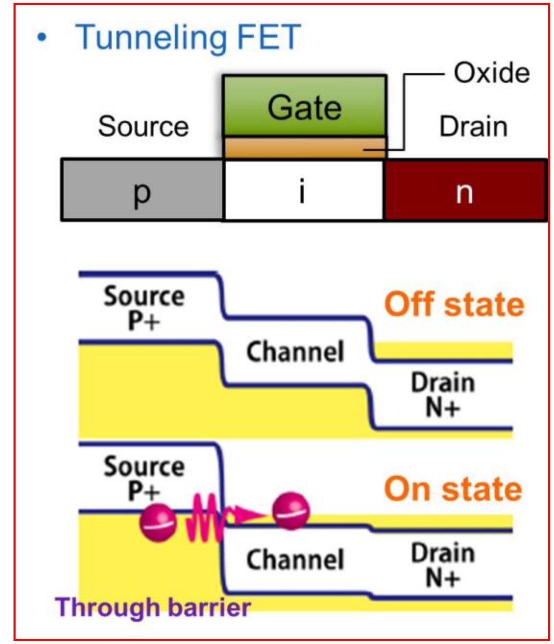
Better performance for ultra low-power applications

Atomic Model Prediction

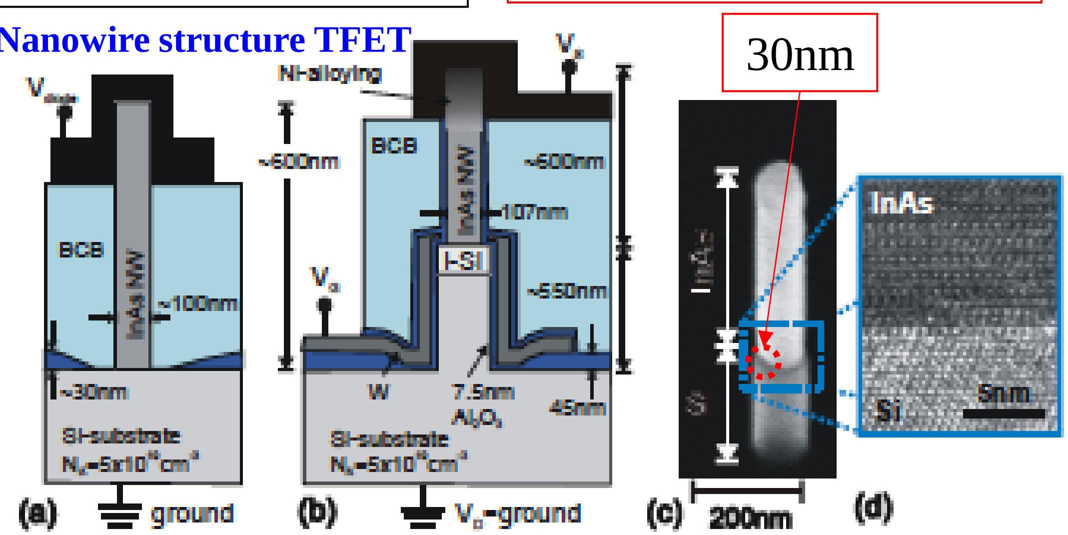


A. M. Ionescu et al., *Nature* **479**, 329 (2011).





Nanowire structure TFET

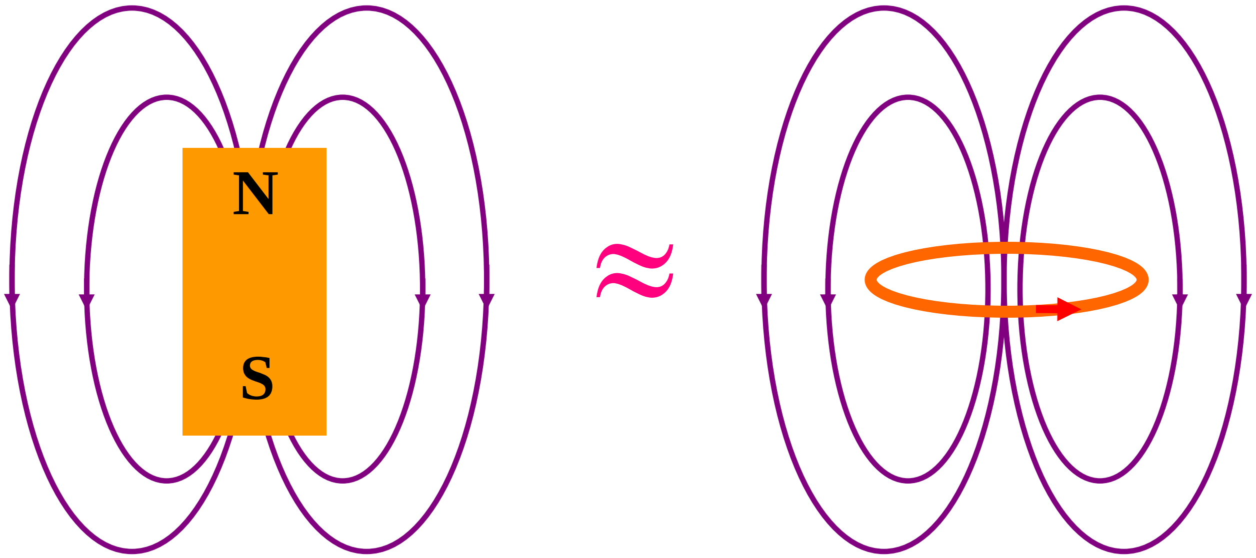


H. Riel et al., *IEDM* 391 (2012).

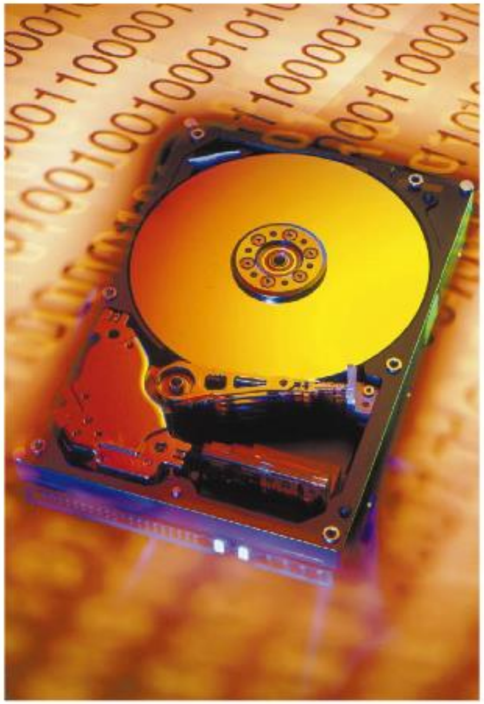
(IV) Quantum Spin

Spin and Nano technology

Electron Spin is the smallest unit of magnetism, 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 $\Leftrightarrow$ Electronics

New generation of computer

Computation and storage in one shot

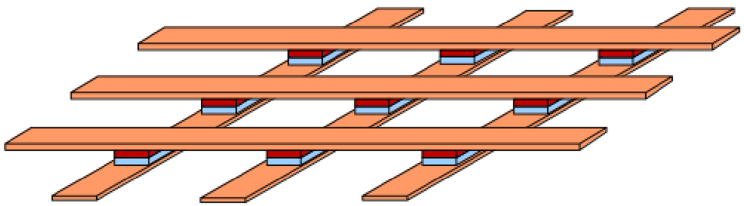
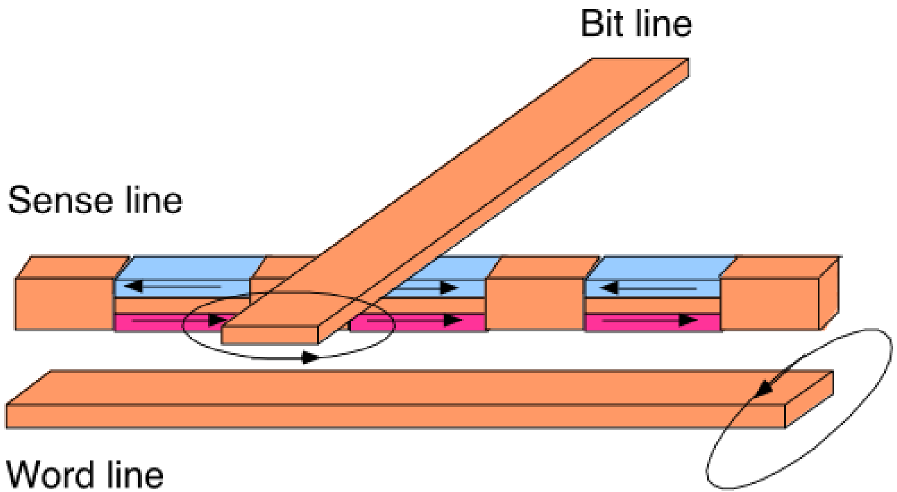


Fig. 7. A schematic representation of RAM that is constructed of magnetic tunnel junctions connected together in a point contact array. The conducting wires provide current to the junctions and permit voltage measurements to be made. They also enable the manipulation of the magnetization of the elements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

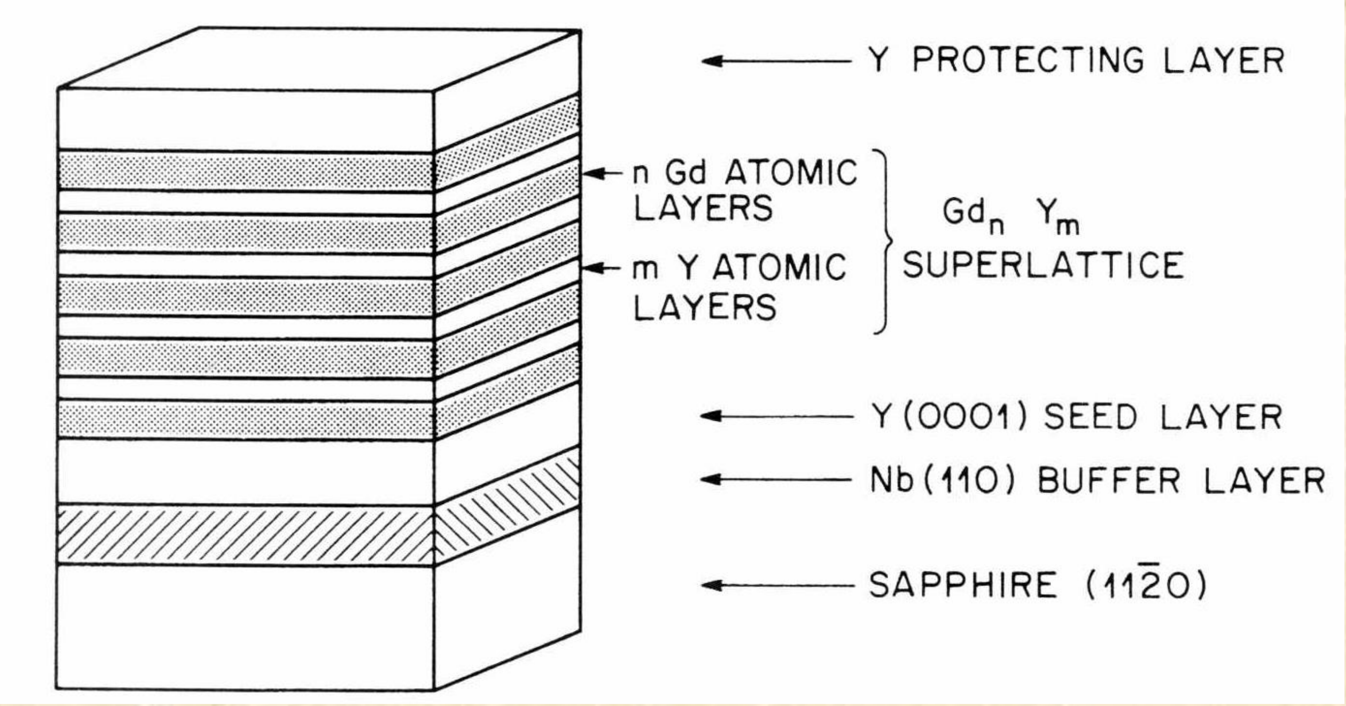


When turn-on, it is ready!

Artificial Superlattice

--- Matching the structural periodicity with physical length scale of **superconductivity and magnetism**

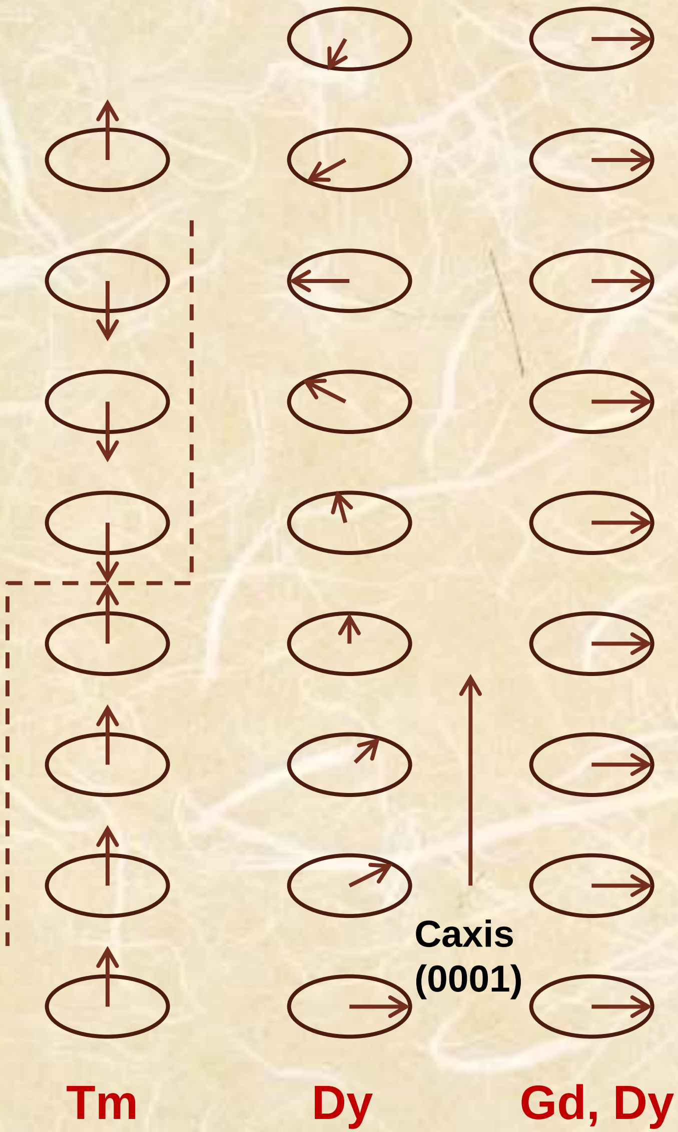
-- **Modulation of physical properties**



Invention of metal molecular beam epitaxy in 1981

-- Single crystal epitaxial superlattices with Atomically abrupt interfaces

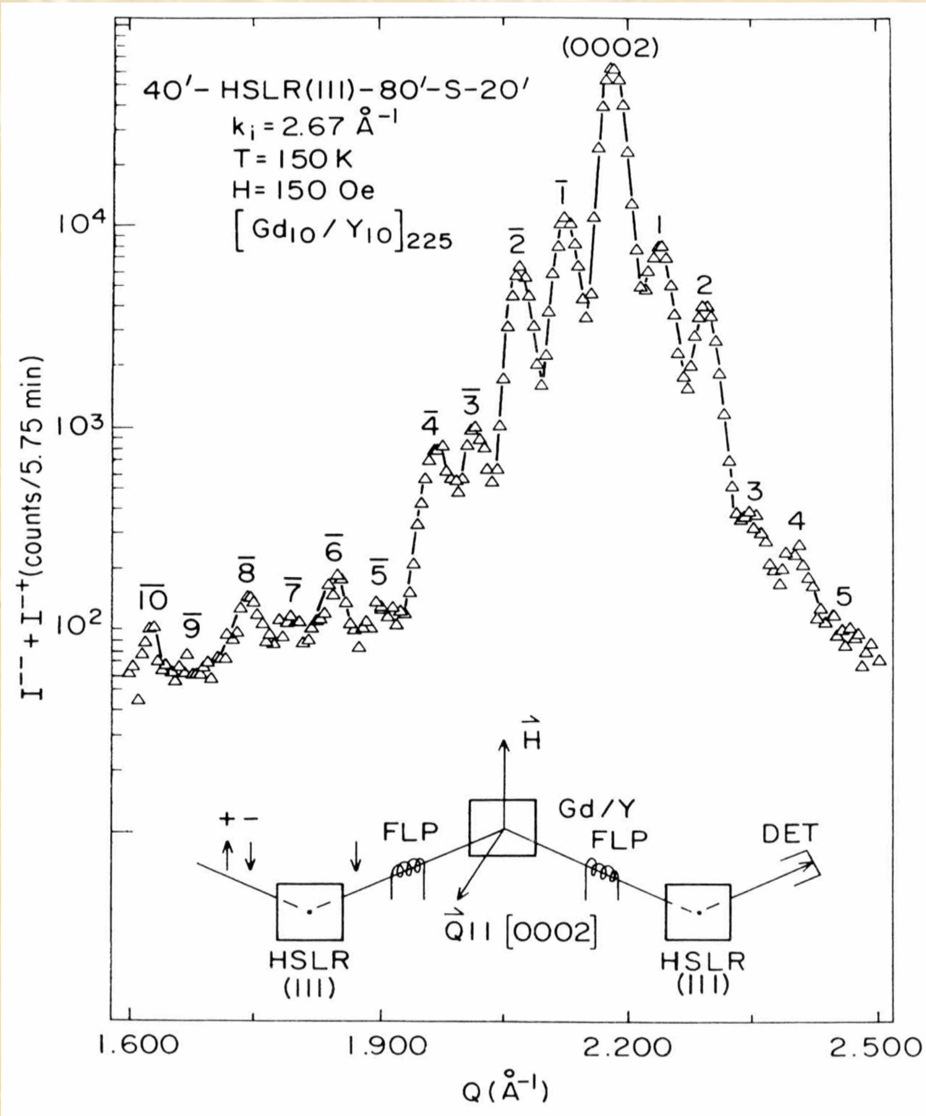
HCP crystal structure

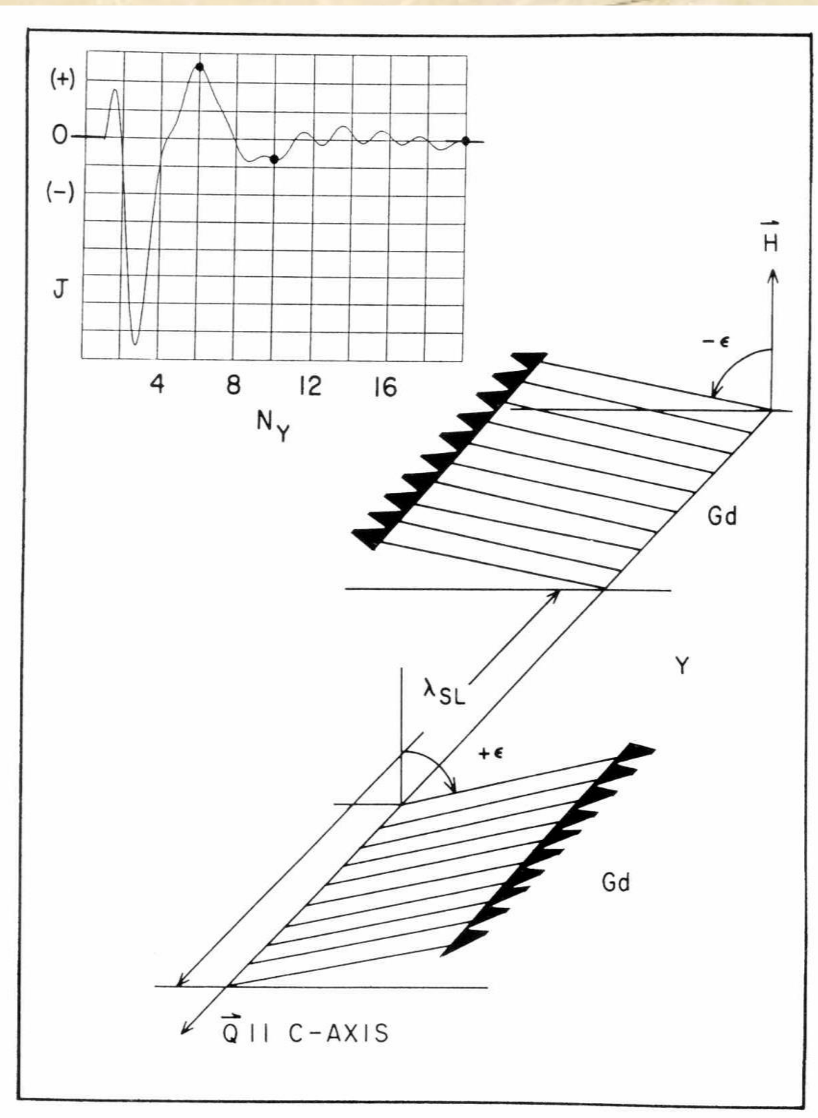


Spin structures of heavy rare - earths

- Similar crystal- chemical nature of rare earth forms coherent superlattices
- Metallic superlattice effect
  - Long range nature of the indirect exchange interaction
  - Magnetic coupling of magnetic rare earth through non – magnetic Y, Lu
  - Modulation of magnetic properties of Gd - Y Superlattices
  - Spin structure modification of Tm - Y, Dy - Y Superlattices
- 2-dimensional magnetism
- Interfacial magnetism

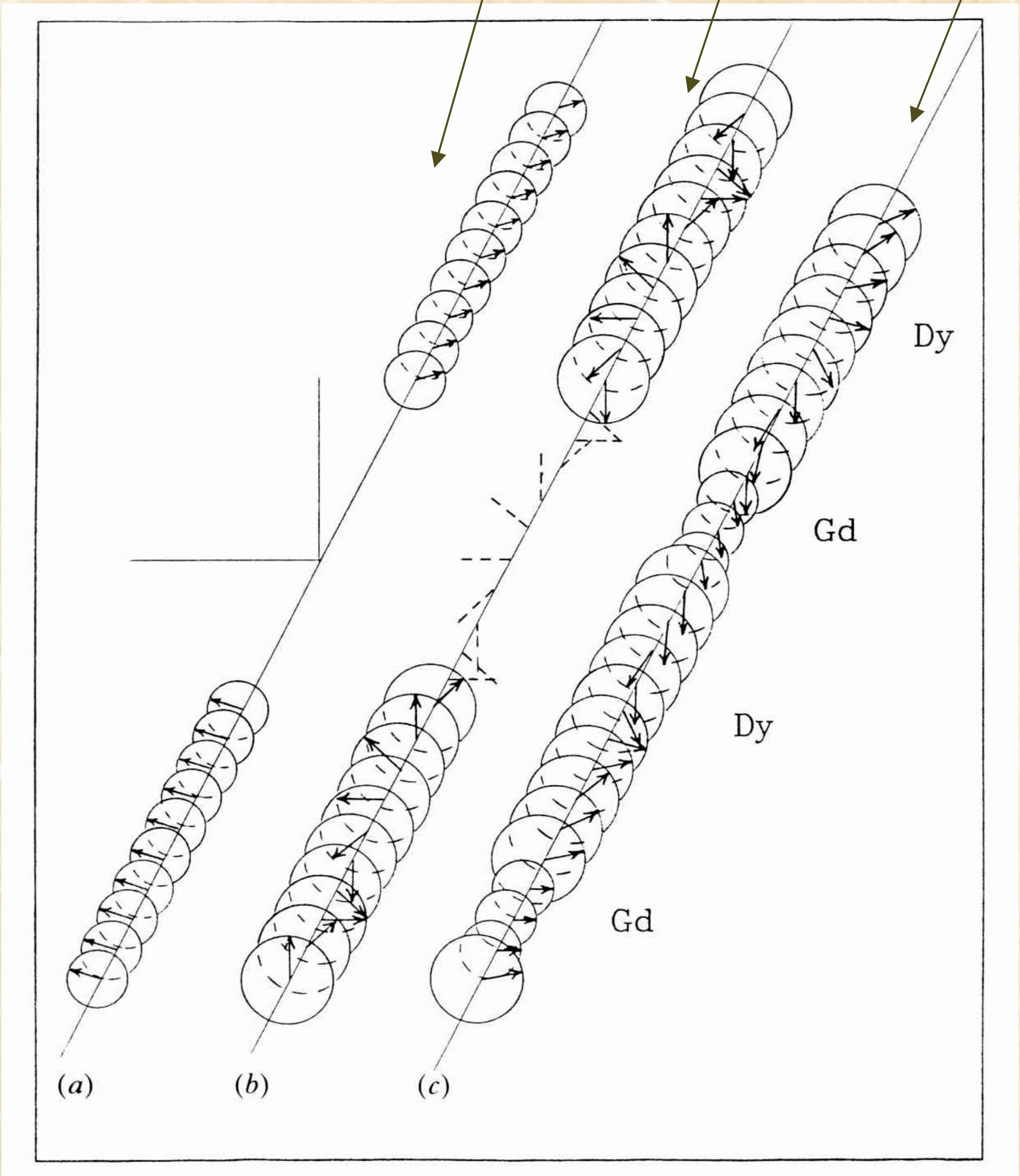
Neutron Diffraction Studies of the Gd_5-Y_{10} Magnetic Superlattice – Antiferromagnetically coupled





Spin Structure Tailoring in artificial Superlattices

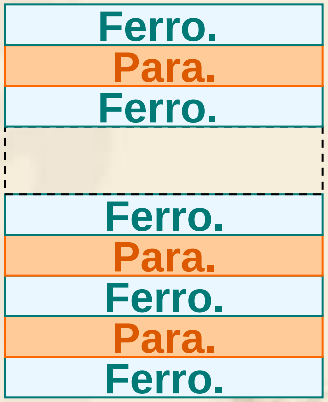
Gd-Y Dy-Y Gd-Dy



1984-1989

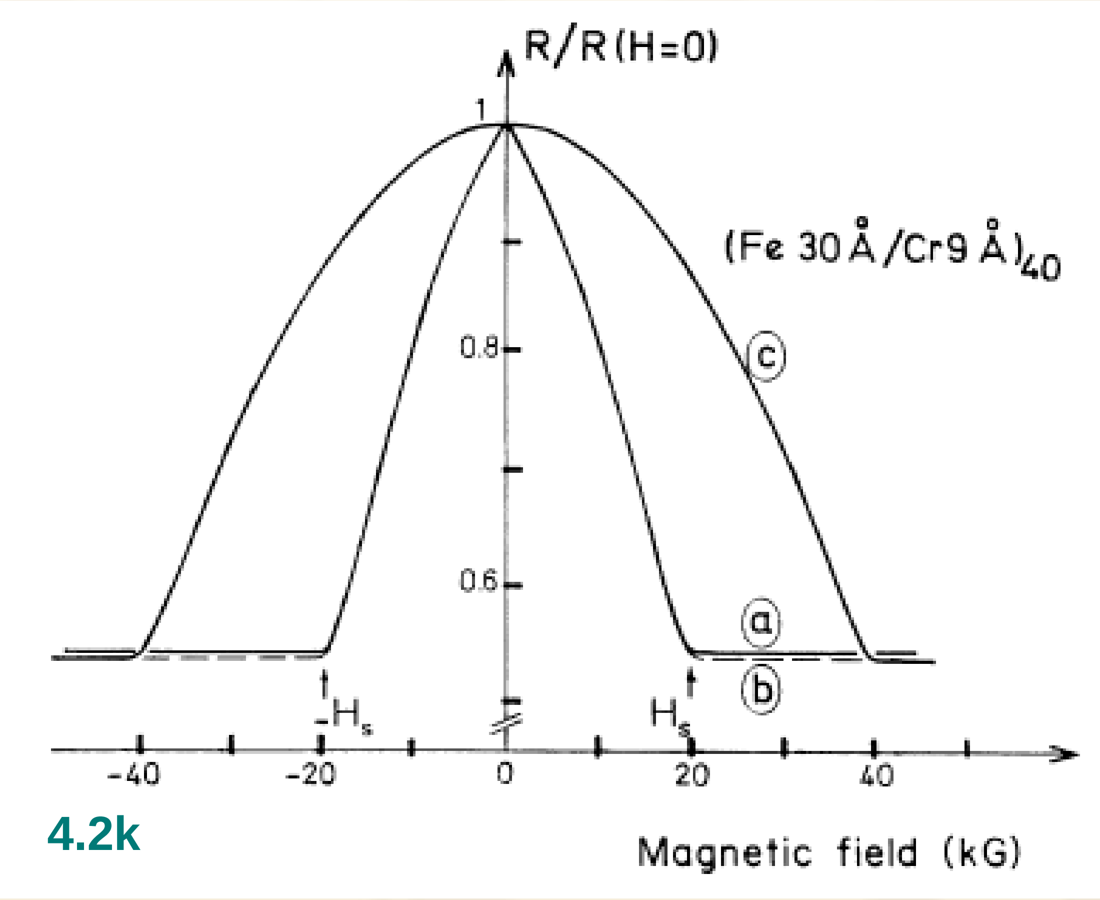
Giant Magnetoresistance(GMR)

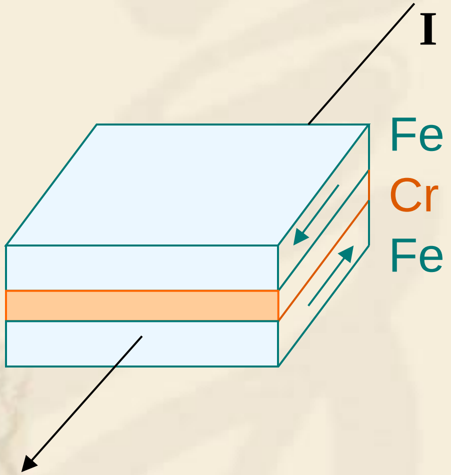
- **What is GMR?**
  - **GMR is a very large change in electrical resistance that is observed in a ferromagnet/paramagnet multilayer structure.**
  - **Resistance change occurs when the relative orientations of the magnetic moments in alternate ferromagnetic layers change as a function of applied field.**
  - **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.**



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

First Evidence of GMR

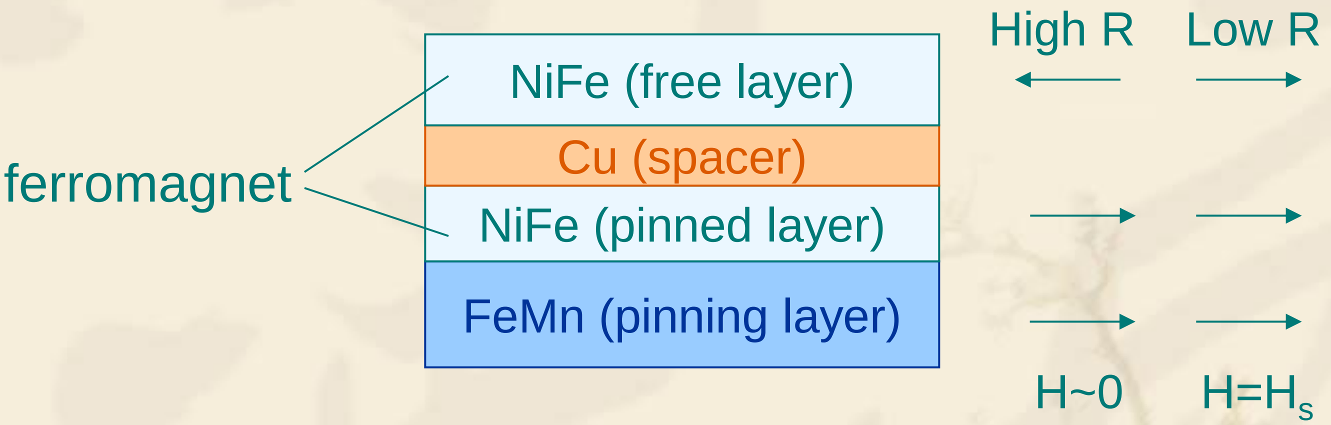




***Hs* corresponds to the field at which all layer magnetizations point along the field direction.**

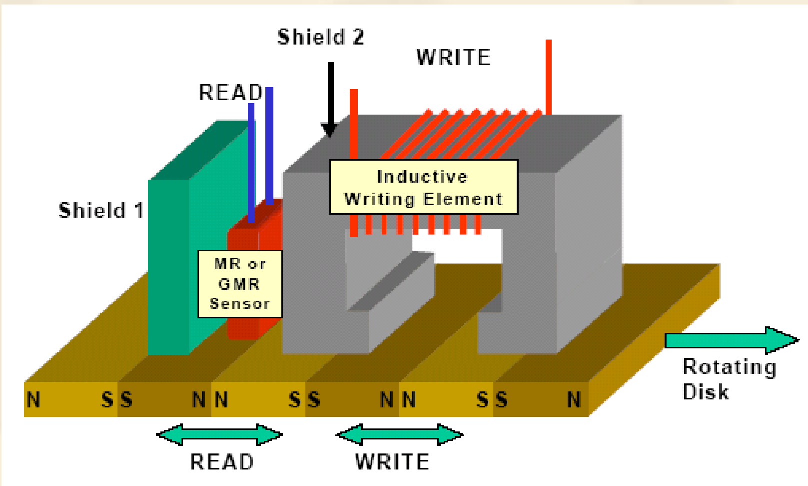
Spin-Valve GMR

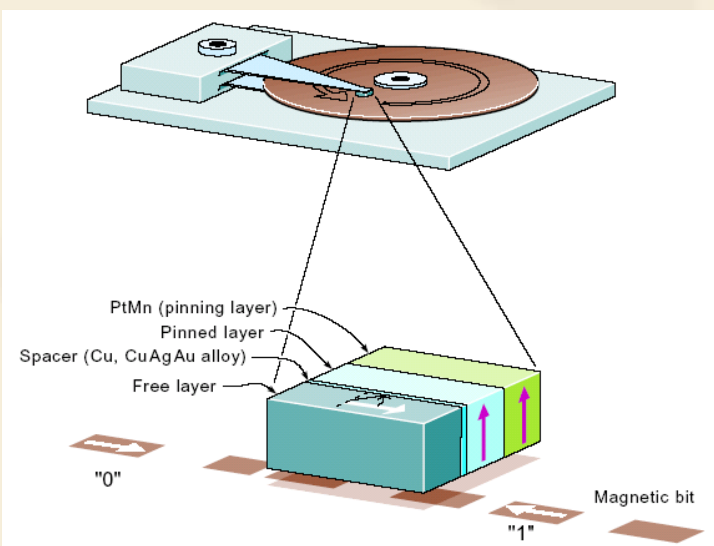
- The simple structure of Spin-valve GMR is



- 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





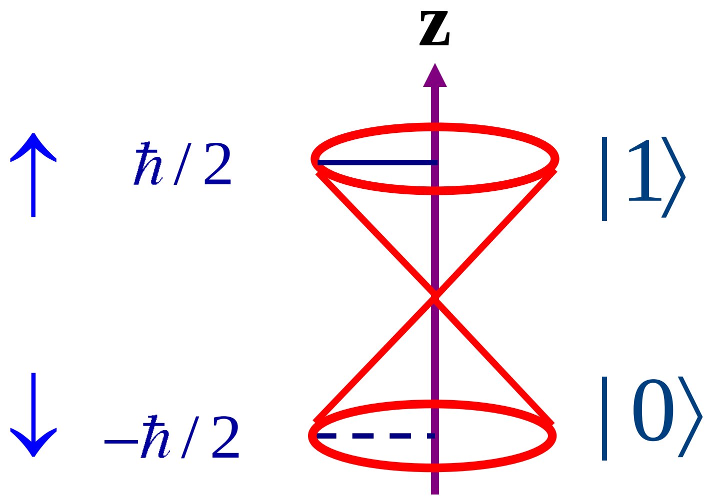
- Magnetization is stored as a “0” in one direction and as a “1” in the other. This is the magnetic field sensed by the GMR head.

- When the head passes over these magnetic bits, the magnetization direction of the free layer in the head responds to the field in each bit by rotating either up or down.

- The resulting change in the resistance is sensed by the voltage across the GMR head (current passing through the GMR element is constant).

Quantum behavior of ferromagnets

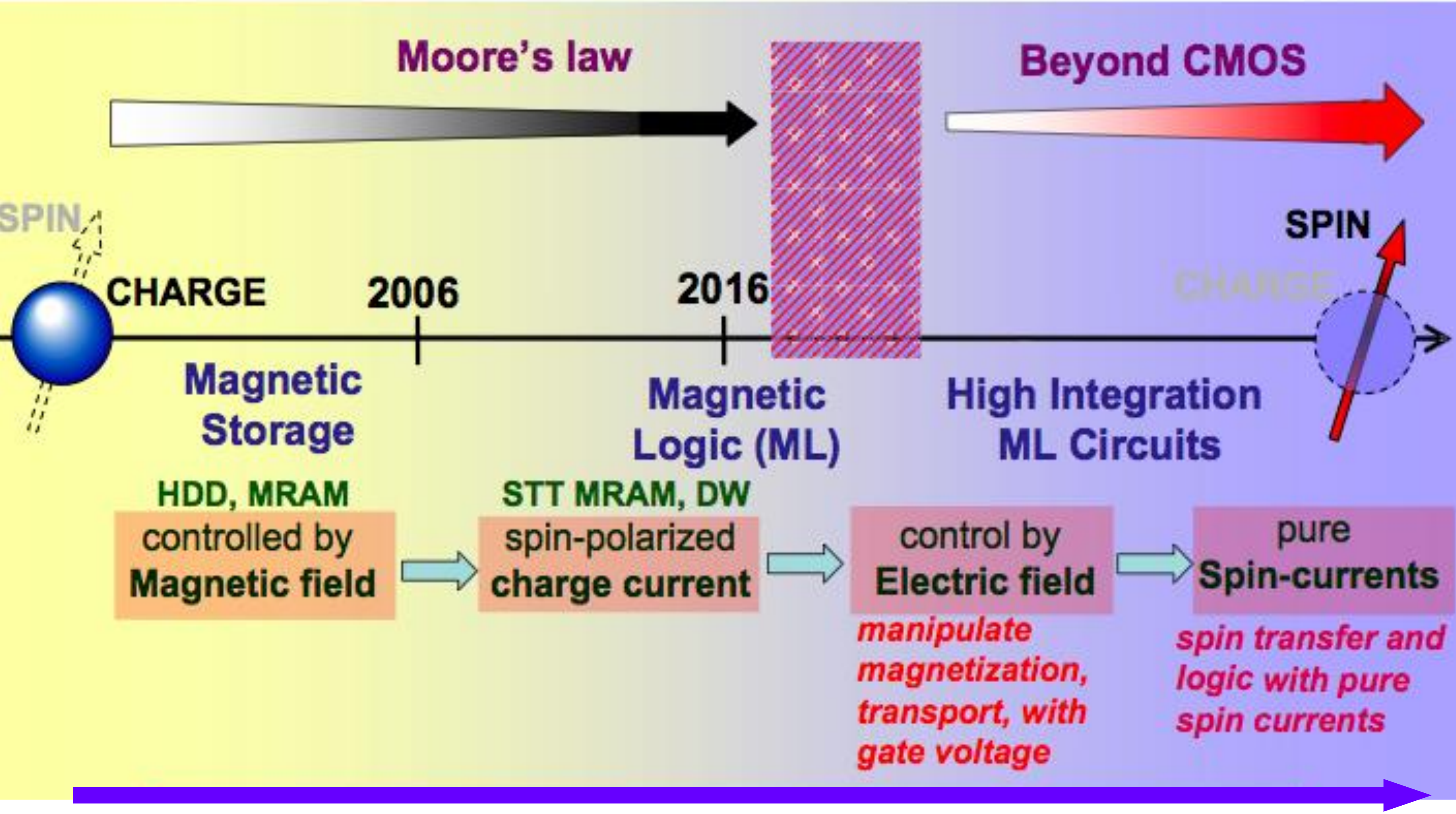
-Spin as a quantum qubit



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

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)

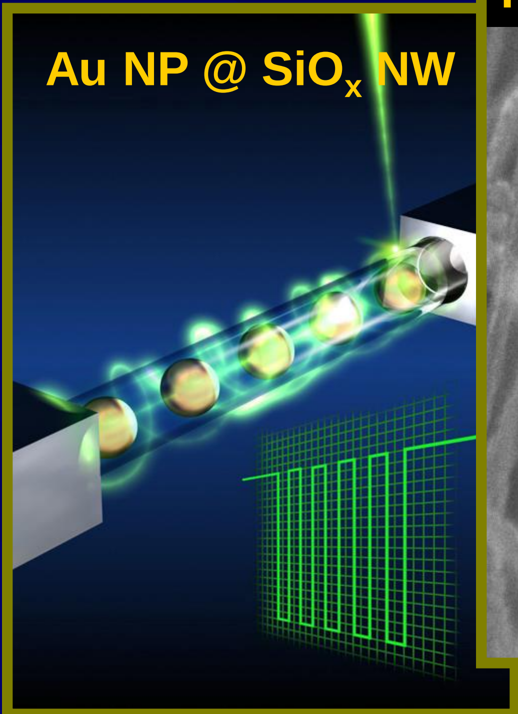
Major Qauntum Effect at the nano scale

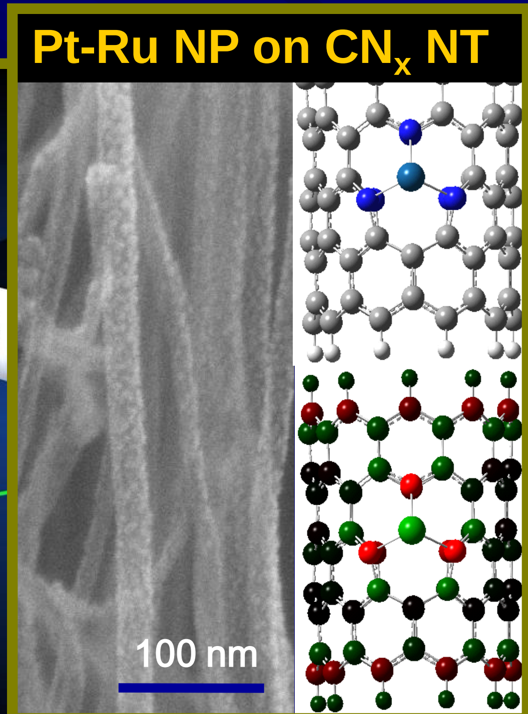
- Interference
- Quantization
- Tunneling
- Quantum Spin

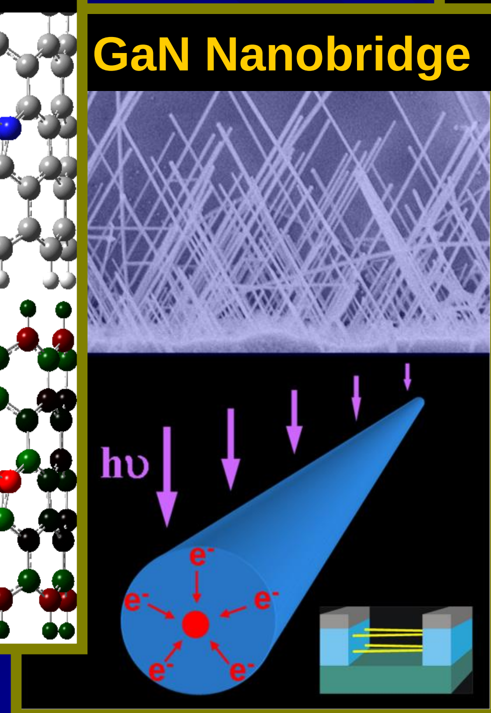
The Fourth Lesson:

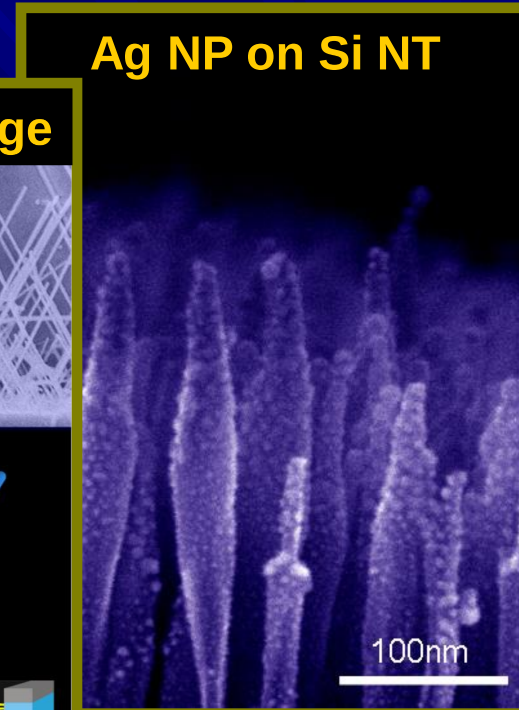
Innovations of nano structures and nano materials for various applications

Overview of Advanced Materials Laboratory









Color-selective Optical Switch, SPR-enhanced Sensor

Fuel Cells, Supercapacitors

High-gain Photo-detector, Solar Cells, Bio-sensor

SERS: Molecule/Bio-sensing

Li-Chyong Chen
Center for Condensed Matter Sciences
National Taiwan University

The Nano-world at CCMS-AML:

a Fruitful Research Field with Technology Implications

Wire/Rod

JACS 123, 2791 (2001)
APL 81, 22 (2002)
JACS 127, 2820 (2005)
APL 88, 241905 (2006)
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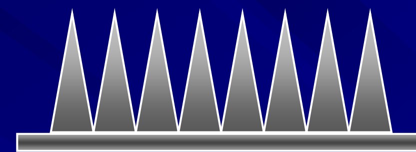

Nanotip

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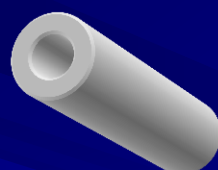
Nature Nanotech. 2, 170 (2007)
Nano Lett. 9, 1839 (2009

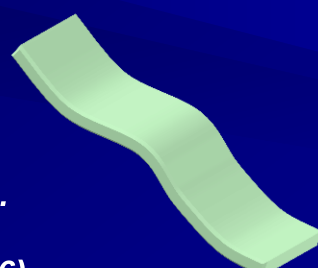


Tube

APL 79, 3179 (2001)
APL 81, 4189 (2002)
Adv. Func. Mater. 12, 687 (2002)
APL 86, 203119 (2005)
Chem. Mater. 17, 3749 (2005)
JACS 128, 8368 (2006)
PRB 75, 195429 (2007)
JACS 130, 3543 (2008)

Core-shell

APL 81, 1312 (2002)
Nano. Lett. 3, 537 (2003)



Belt

Chapter 9, pp. 259-309, Nanowires and nanobelts, Z.L. Wang Ed., Kluwer (2004)
Adv. Func. Mater. 16, 537 (2006)
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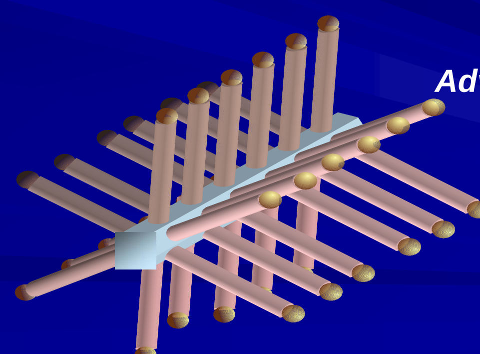
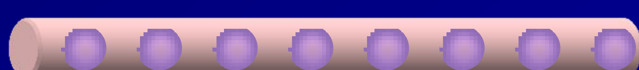


Brush

Adv. Func. Mater. 14, 233 (2004)

Other Thin Films:
APL 86, 21911 (2005)
APL 86, 83104 (2005)
APL 86, 161901 (2005)
APL 87, 261915 (2005)
JVST B 24, 87 (2006)
APL 88, 73515 (2006)
Adv. Mater. 21, 759 (2009)



Peapod

Adv. Mater. 14, 1847 (2002)
Nature Mater. 5, 102 (2006)

A Color-selective Nanoswitch

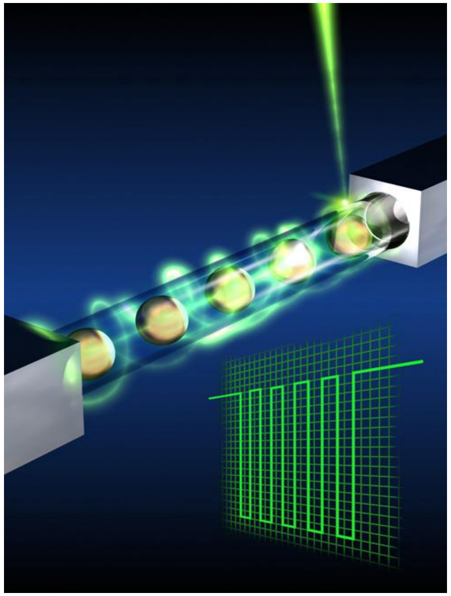
Photosensitive Gold Nanoparticle-embedded Dielectric Nanowires

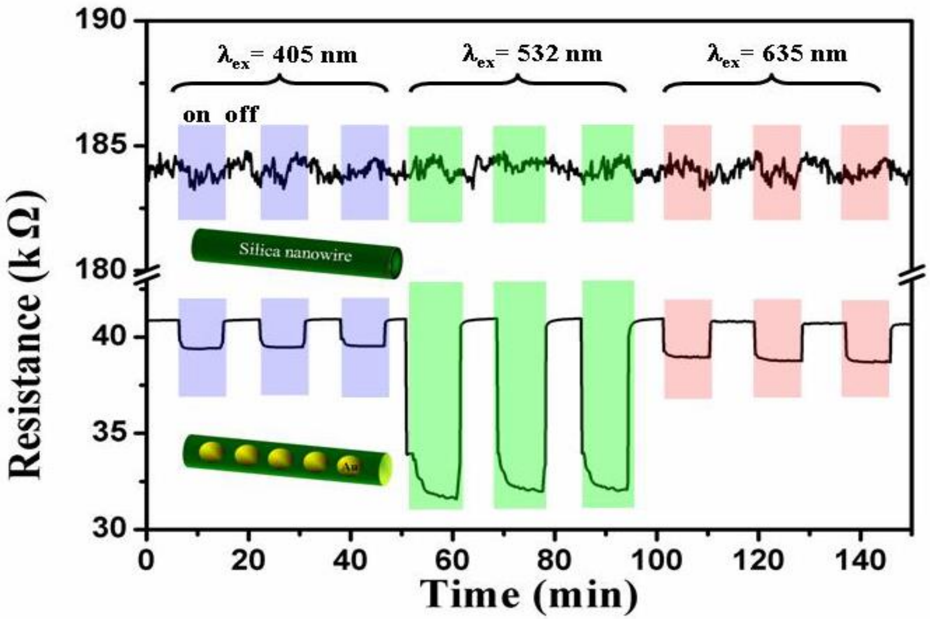
M. S. Hu, et al., Nature Materials 5, 102-106 (2006)

A Fast Breaking Paper

(in each individual field, only 1 was selected bimonthly among the Highly Cited Papers)

(http://esi-topics.com/fbp/2007/august07-Li-ChyongChen.html)





In ancient Arabian story of "Ali Baba and the Forty Thieves", the treasure is in a cave, of which the mouth is sealed by magic. It opens on the words "Open Sesame" and seals itself on the words "Close Sesame".
The nanopeapod (i.e., gold nanoparticle-embedded dielectric nanowire) will open to green light but shut for lights of other colors.

Si Nanotips-Array and their Hetero-junctions: On-chip, IC-compatible

* Antireflection:

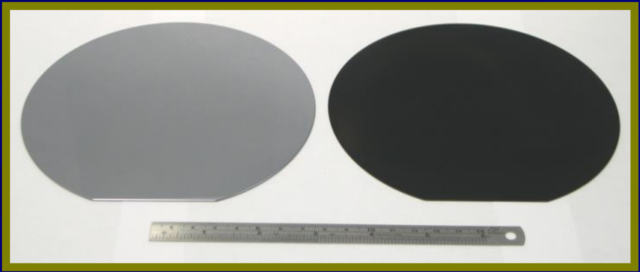
  Broadband (uv-terahertz), Omnidirectional (>70°)

* Electroluminescence in ZnO/SiNTs:

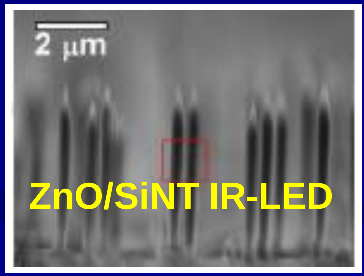
  IR emission, x10 higher; turn-on ~3V, x2 lower than film

* Magneto-resistance in LSMO/SiNTs:

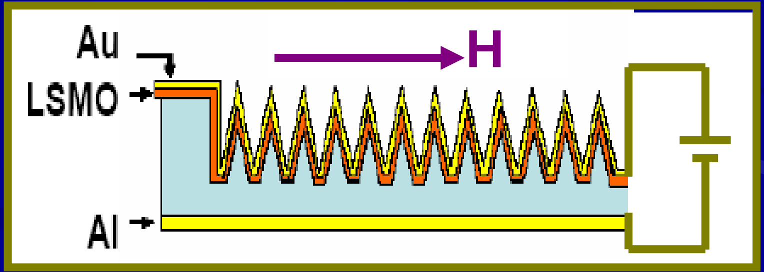
  Room-temp. MR at lower bias and magnetic field



Nature-Nanotechnology
2 (2007) 770



Nano Letters
9 (2009) 1839



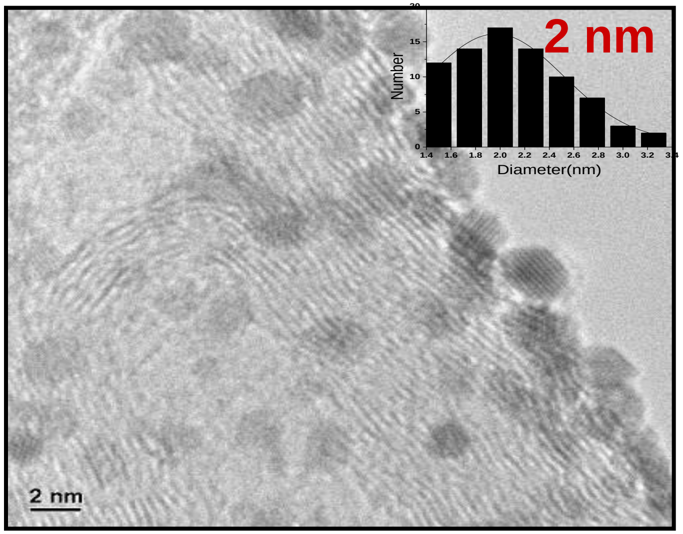
Promising high-density memory:
On-going

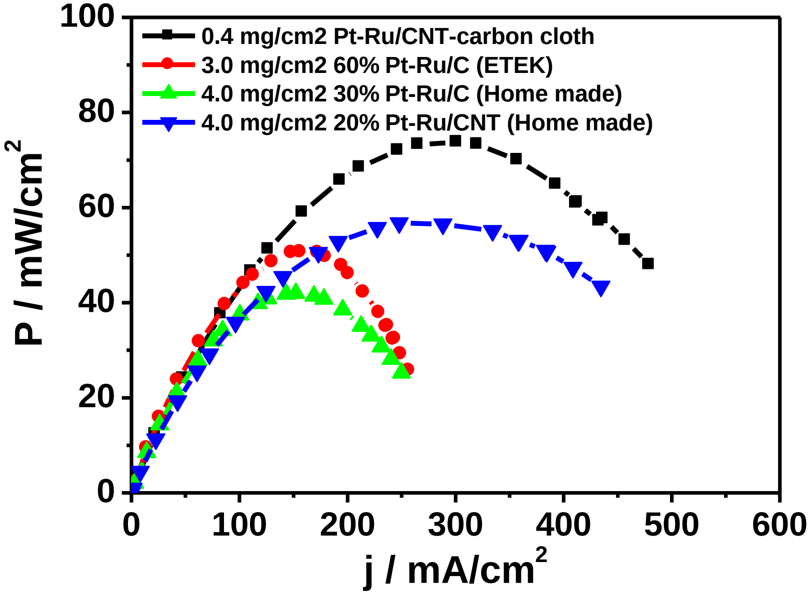
Next-generation Energy Solution (I): Fuel Cell with Low-loading of Precious Metals

Ultrafine Pt Nanoparticles Uniformly Dispersed on Arrayed Carbon Nanotubes with High Electrochemical Activity at Low Loading of Precious Metal

C. L. Sun, et al., Chemistry of Materials 17, 3749-3753 (2005)

C. H. Wang, et al., J. Power Sources 171, 55-62 (2007)





• Direct methanol fuel cell is promising power generator with a wide range of applications from portable electronic devices to automobiles.

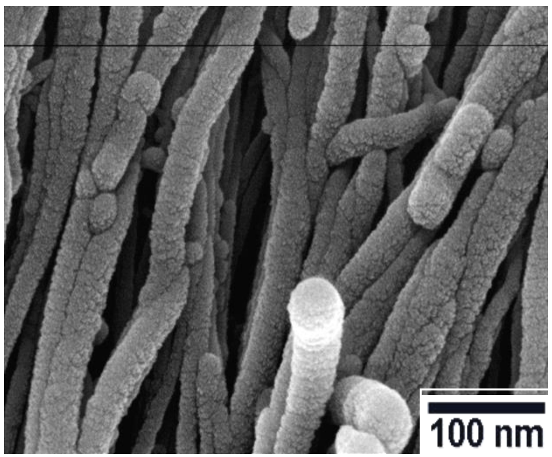
• Nanotubes-Pt/Ru composites are highly efficient in loading precious metals. Only **one tenth** of metal loading, in comparison to the conventional, is needed.

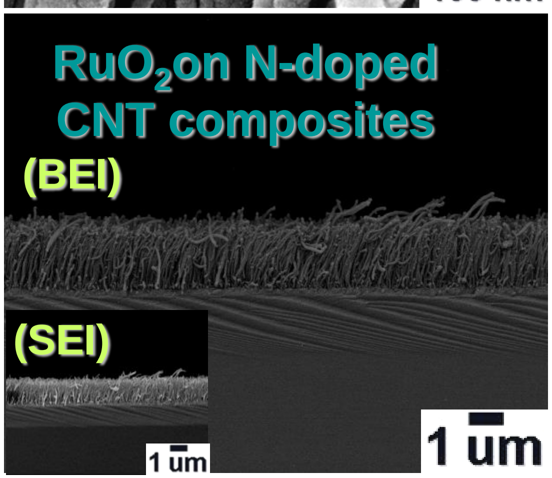
Next-generation Energy Solution (II): High-performance Supercapacitor

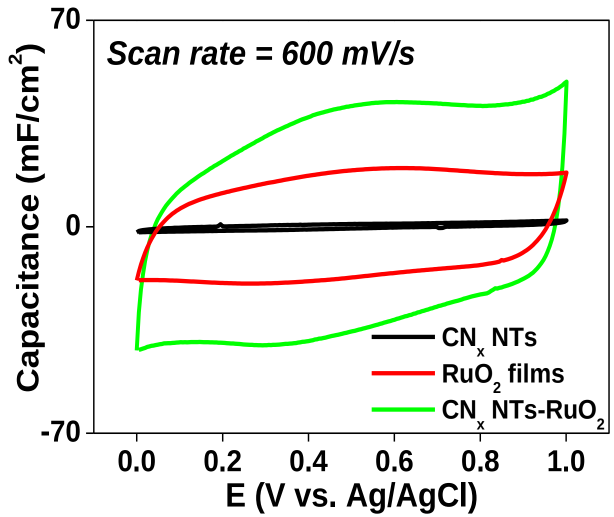
Ultrafast Charging-discharging Capacitive Property of RuO_2 Nanoparticles on Carbon Nanotubes Using Nitrogen Incorporation

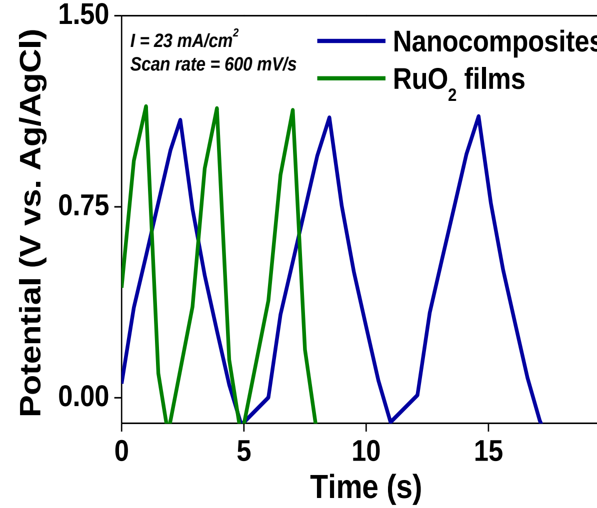
W. C. Fang, et al., Electrochemistry Communications 9, 239-244 (2007)

W. C. Fang, et al., J. Electrochemical Society 155, K15-K18 (2008)









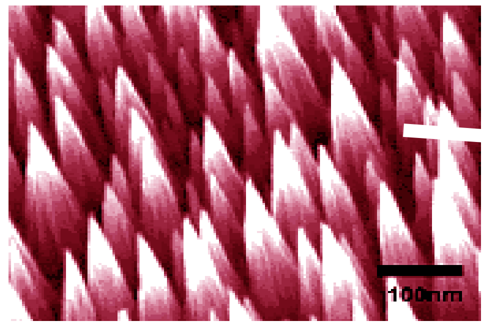
- 4 fold increase in capacitance
- Optimal capacitance of *1380 F/g at 600 mV/s* (theory: 1450 F/g)
- Output current as high as *23 mA/cm²*
- Stable at high scan rate
- 10 fold increase in charge-discharge rate

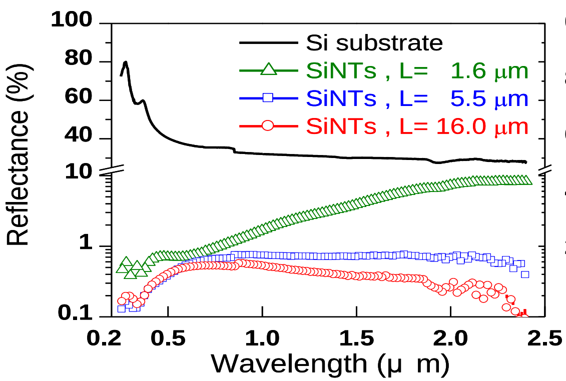
A Man-made Moth Eye

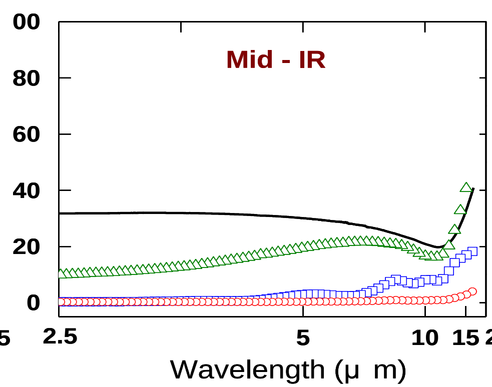
Broadband and Quasi-omni-directional Anti-reflection Properties with Biomimetic Silicon Nanostructure

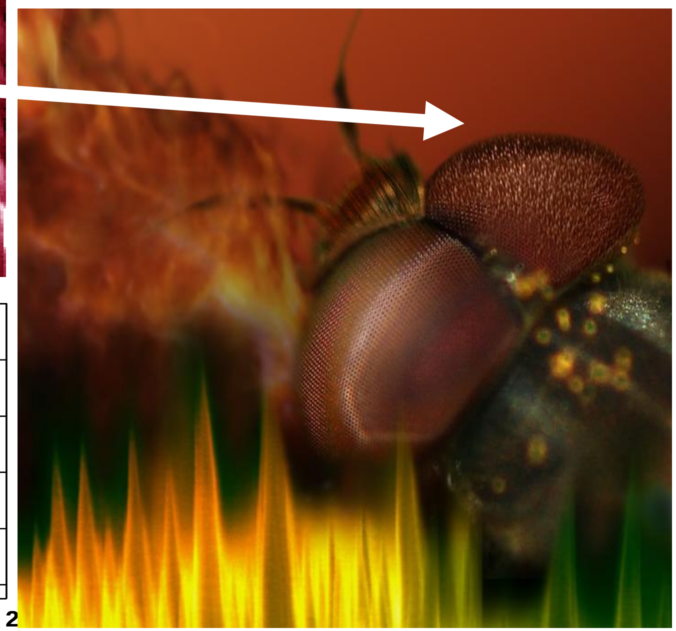
Y. F. Huang, et al., Nature Nanotechnology 2, 770-774 (2007) & US Patent 2005

Featured by NPG Asia Materials, March 2008









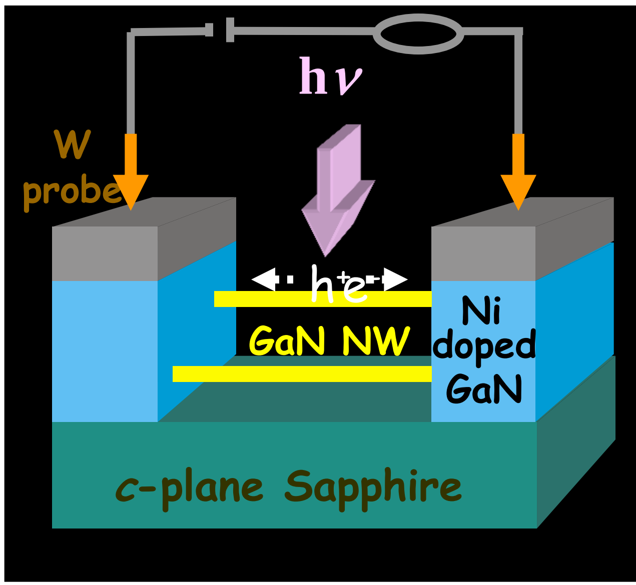
Many plants and animals have tiny surface structures that absorb certain wavelengths of light. These naturally formed nanostructures provide the colors in butterfly wings, camouflage for cicadas and enable moths to capture as much light as possible when flying at night.

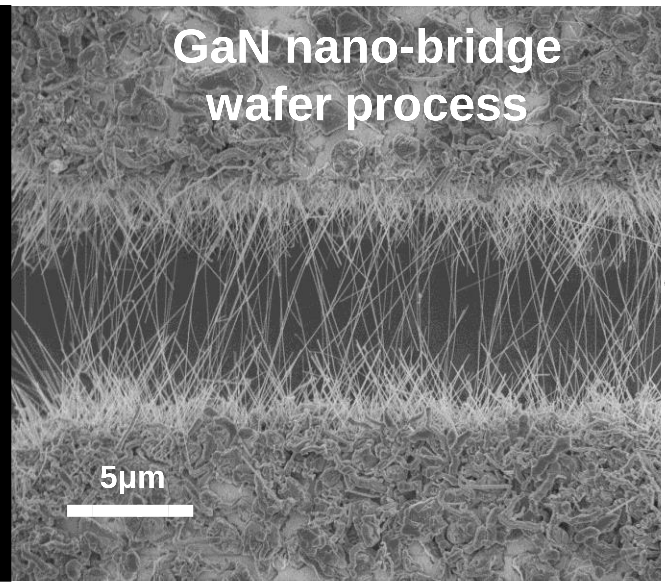
Now, we have created nanostructure surfaces which mimic moth eye and surpass its function in anti-reflection in that they absorb almost all incident light.

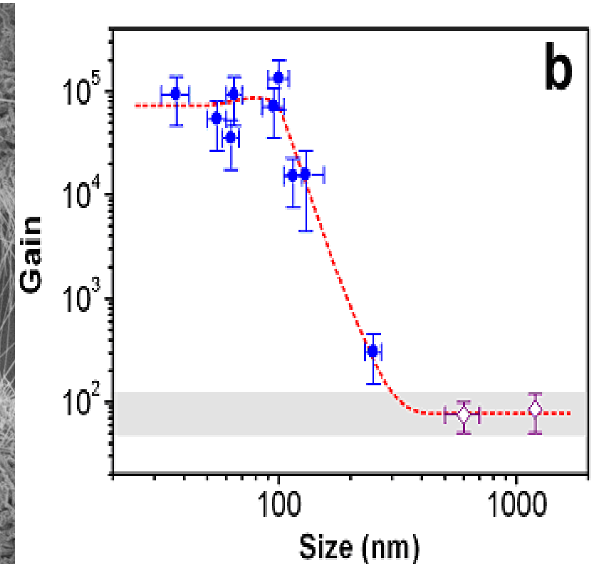
Building a Nano-scale Bridge On-chip

On-chip Fabrication of Well Aligned and Contact Barrier-Free GaN Nanobridge Devices with Ultrahigh Photocurrent Responsivity

R. S. Chen, et al., Small 4, 925-929 (2008)







- Nanowire: Naturally formed core-shell structure, 1D electron gas-like property
- On-chip process for building GaN nanobridge devices, which provide a large surface area, short transport path, and high responsivity for next-generation sensors and detectors

The Fifth Lesson:

Nano photonics

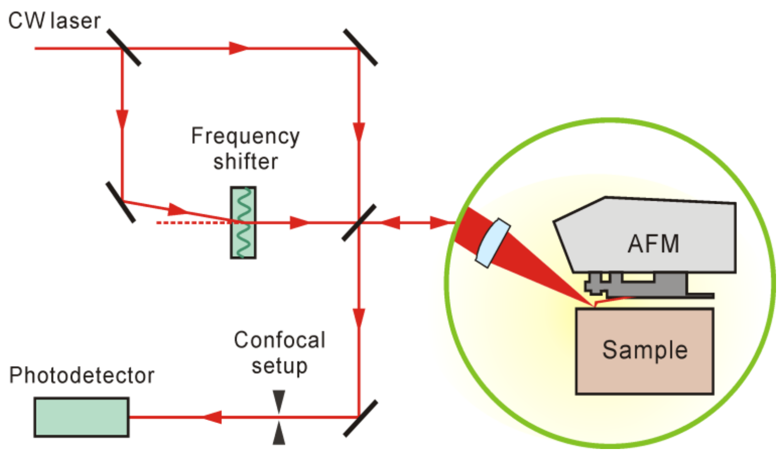
and

Bio-applications

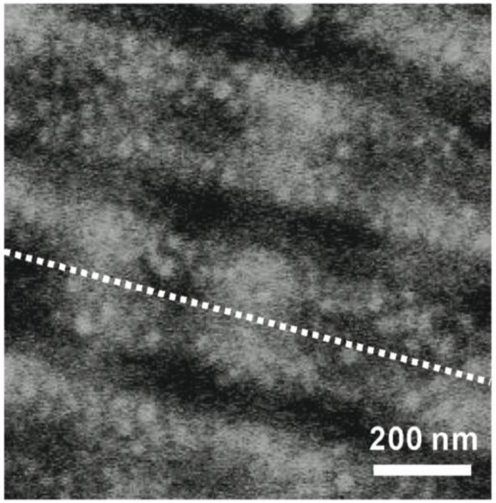
Nano-photonics and Plasmonics
Near-field examination of blue-ray discs

Dr. Juen-Kai Wang, CCMS, NTU

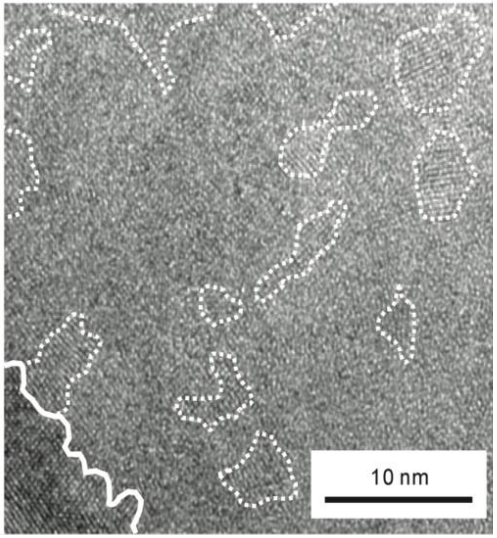
S-SNOM setup



Near-field image of recorded disc



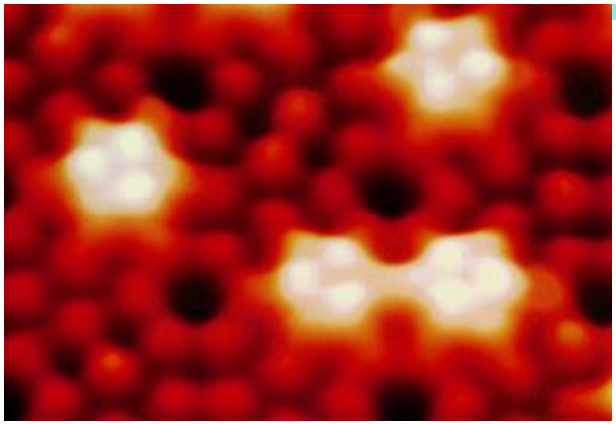
TEM image of recorded mark

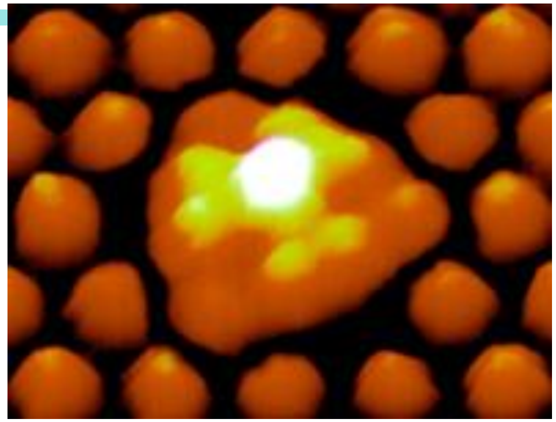


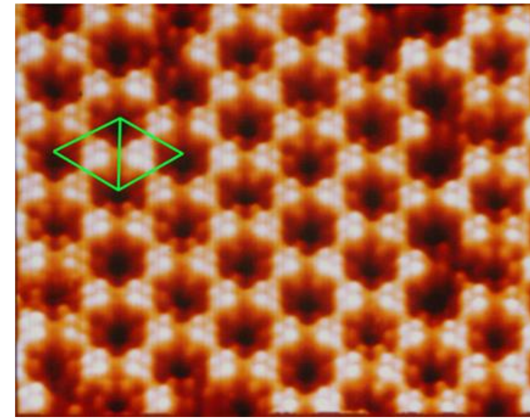
- **Scattering-type SNOM reveals sub-10 nm optical signature.**
- The optical contrasts of the dark and the bright regions in near-field image of phase-change layer correspond to amorphous and polycrystalline AgInSbTe, respectively.
- Small bright spots with a size of ~30 nm emerge within the dark region, corresponding to the nano-sized ordered domains in the TEM image.
- **s-SNOM provides a direct optical probe in nanometer scale for high density optical storage media.**

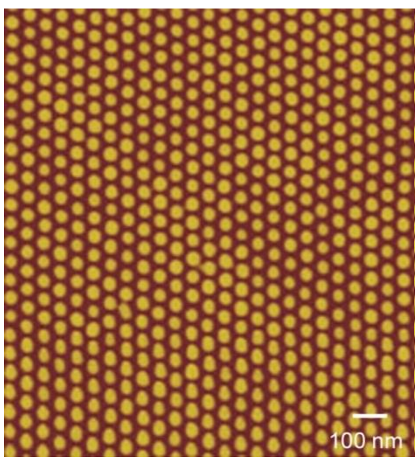
J. Y. Chu et al., Appl. Phys. Lett. 95, 103105 (2009).

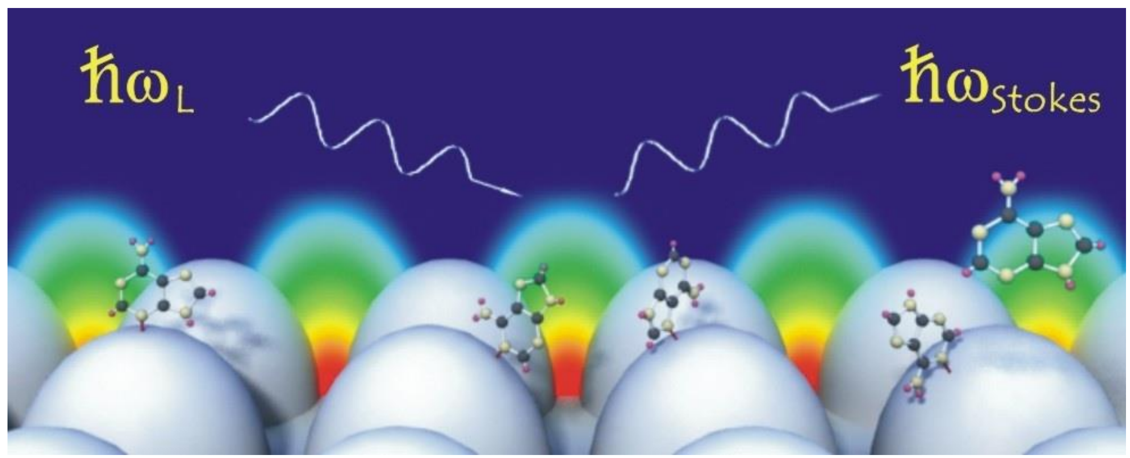
Creating Monodispersed Ordered Arrays of Surface-Magic-Clusters and Anodic Alumia Nanochannels by Constrained Self-organization





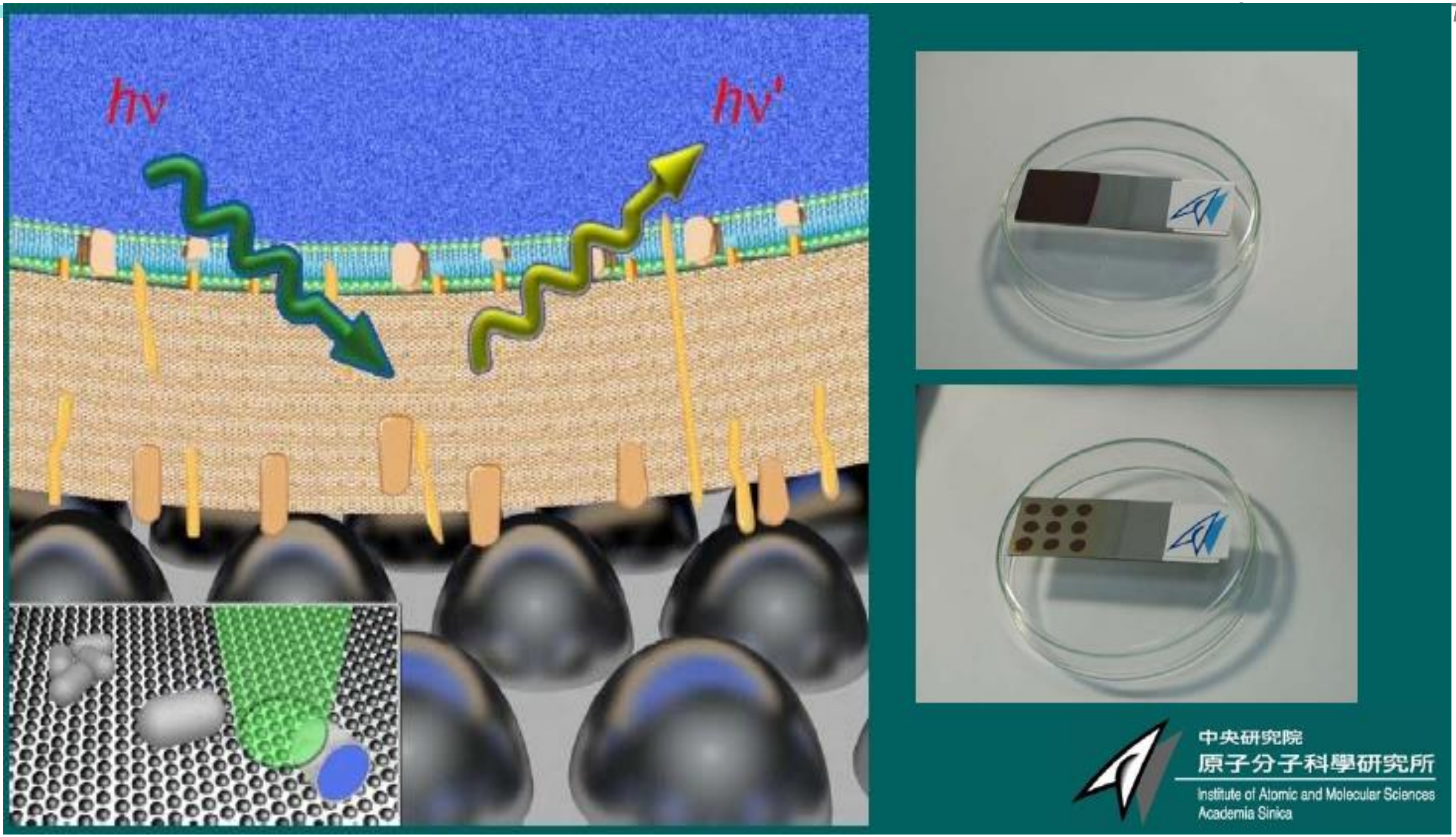






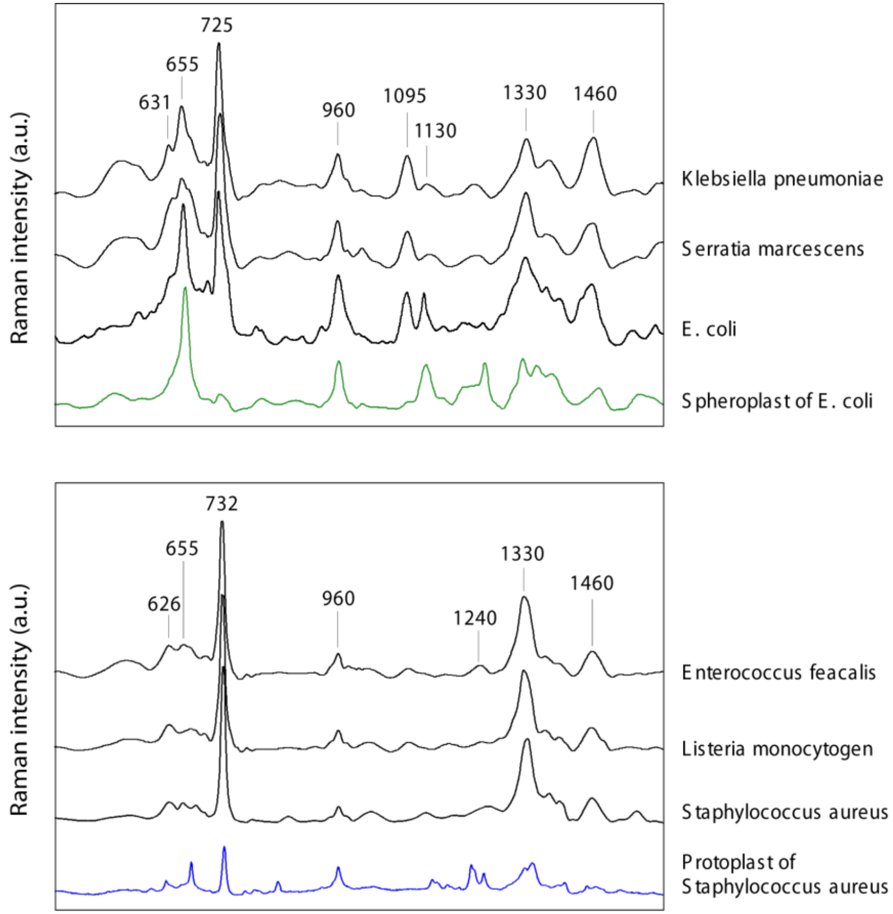
Prof. Yuh-Lin Wang 王玉麟
IAMS Academia Sinica, Taiwan

A High Sensitivity and High Speed Biomedical Diagnostic Technology using SERS

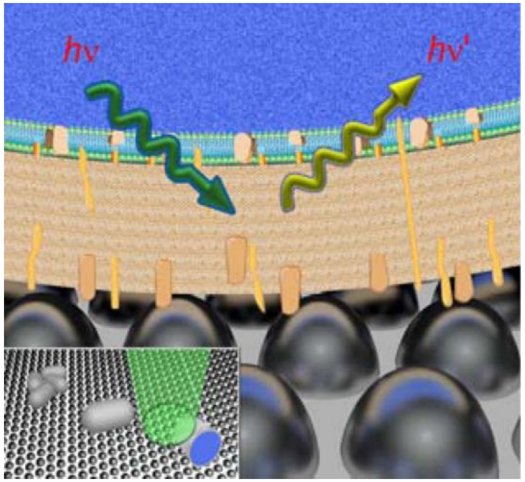


Prof. Yuh-Lin Wang 王玉麟
IAMS Academia Sinica, Taiwan

SERS detection of bacterial cell wall



Dr. Juen-Kai Wang, CCMS, NTU



- Sensitive and stable SERS profiles based on our substrates readily reflect different bacterial cell walls found in Gram-positive, Gram-negative, and mycobacteria group.
- Characteristic changes in SERS profile are recognized in the drug-sensitive bacteria of antibiotic exposure, which could be used to differentiate them from the drug-resistant ones.

H.-H. Wang et al., Adv. Mater. 18, 491 (2006); T.-T. Liu et al., PLoS ONE 4, e5470 (2009).

Papers to read

- "Observation of a Magnetic Antiphase Domain Structure with Long-Range Order in a Synthetic Gd-Y Superlattice", C. F. Majkrzak, J. W. Cable, J. Kwo, M. Hong, D. B. McWhan, Y. Yafet, J. V. Waszczak, and C. Vettier, Phys. Rev. Lett. **56**, 2700, (1986).

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

- "High k gate dielectrics Gd_2O_3 and Y_2O_3 for Si", J. Kwo*, M. Hong, A.R. Kortan, K. T. Queeney, Y. J. Chabal, J. P. Mannaerts, T. Boone, J. J. Krajewski, A. M. Sergent, and J. M. Rosamilia, Appl. Phys. Lett, **77**, 130, (2000).

- "Epitaxial Cubic Gd_2O_3 as a Dielectric for GaAs Passivation", M. Hong, J. Kwo, A. R. Kortan, J. P. Mannaerts, and A. M. Sergent, Science, **283**, 1897, (1999).

- "Observation of the Spin Hall Effect in Semiconductors", Y. K. Kato, R. C. Myers, A. C. Gossard, D. D. Awschalom*, Science **306**, 1910 (2004).

- "Tunnel field-effect transistors as energy-efficient electronic switches", A. M. Ionescu, and H. Riel, Nature, **479**, 329 (2011).