Introduction to Nanophysics

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What is the size for a “nano”? 

One (nm) equals to $1/1000000000$ ($10^{-9}$) meter

$10^{-3}$ m, Macro

$10^{-6}$ m, Micro

$10^{-9}$ m, Meso
R. Feymann Already Knew about this!

“ There’s plenty of room at the bottom! ” in 1959.
Physicists noticed the “Nano” as early as …..

• 4th Century, Roman glassmaker: the color of glasses can be changed by mixing in metal particles.
• In 1883, Films containing silver halides for photography were invented by George Eastman, founder of Kodak.
• 1908, Gustay Mie first provided the explanation of the size dependence of color.
• Vision from Feynman in 1959: “There is plenty room at the bottom”, and also recognized there are plenty of nature-given nanostructures in biological systems.
• 1950-1960, small metal particles were investigated by physicists.
• 1957, Ralph Landauer realized the importance of quantum mechanics plays in devices with small scales.
• Before 1997 => mesoscopic (or low dimensional) physics: quantum dots, wells, wires…..are known already.
Major Topics of Nanoscience and Technology
What is the Nano Technology?

- Science and Technology Down scaling to size under 100 nm:
  
  Via “Top-down” lithographic patterning:
  -- Moore’s law!

- Manipulate the atomic and molecular structures:
  “Bottom-up” nano materials, growth and assembly.

  Feymann: There’s plenty of room at the bottom
Major Driving Force pushing for Nano Technology: Due to the bottle neck in Microelectronics

Moore’s Law:
A 30% decrease in the size of printed dimensions in every two years.
Two basic modern electronic technologies in Condensed Matter Physics Field
Metal-Oxide-Field Effect Transistor

1960 Kahng and Atalla, First MOSFET
1970 First IC, 1 kbit, 750 kHz microprocessor
電子科技之基礎--MOSFET
(metal-oxide-semiconductor field-effect transistor)
電子科技之基礎——磁記錄
Bottom-up Nano systems & Self-Assembly

enabling of designing large molecules and nano materials
Five major lessons that we have learned
The First Lesson:

Bulk-to-nano Transition
Ex: size-dependence of melting temperature

Ex: size-dependence of color

powered cadmium selenide

larger

smaller
Ex: size-dependence of magnetism

The Second Lesson: 
The Advent of Nano Era

• The ability of growing the nano scale materials and structures

• The ability of detecting and manipulating on the nano scale.
(I) Advance in thin film growth:
   Such as Molecular Beam Epitaxy, atomic layer deposition, laser MBE, etc…

- For nano electronics in metals, oxides, and semiconductors

(II) Detection at nano scale: STM, AFM, MFM, STEM, Cs-TEM

- In 1982, Binning, and Rohrer in IBM invented scanning tunneling microscope (STM).
- In 1986, Binning, Quate, and Gerber invented the atomic force microscope (AFM).
Integrated MBE Multi-chamber System

Now located in the Nano Technology Center, ITRI, Hsin Chu, Taiwan

For Metal, Oxide and Semiconductor Films On the Nano scale
Scanning Tunneling Microscope (STM)

Figure 1.10 Scanning tunneling microscope. (From C. Julian Chen, *Introduction to Scanning Tunneling Microscopy*, Oxford: Oxford University Press, 1993.)
Scanning Tunneling Microscope (STM) – Physicist used to detect nano structures.

Nature 409, 304 (2001)
Quantum Corral
of 7.13 nm radius, 48 Fe atoms on the Cu (111) surface

This STM image shows the direct observation of standing-wave patterns in the local density of states of the Cu(111) surface. These spatial oscillations are quantum mechanical interference patterns caused by scattering of the 2D electron gas off the Fe adatoms and point defects.

Crommue, Luts, and Eigler, Science 262, 218-220, 1993
Prof. C. H. Chen and Dr. M.-W. Chu
In CCMS/NTU.
Spherical Aberration Corrected (球面相差)
Cs-STEM by C. H. Chen at CCMS, NTU

JEOL 2100;
2009四月底
装機完成
High-Angle ADF: Si dumbbell, 1.36 Å spacing

15s exposure

60s exposure

Drift ~1Å/min !!
InGaAs/InAlAs superlattices on InP Substrate by MBE

- Determining the interface location and sharpness is easy.
- The In-distribution seems to be inhomogeneous in the InAlAs layer (blue arrows).
- Note that InP substrate is In-terminated (red arrow).
Atomic Resolution STEM Imaging: Z-contrast

2-Å Electron Probe

SrTiO$_3$

cubic; $a = 3.905$ Å
Electron Energy-Loss Spectroscopy (EELS)

\[ \Delta E = E_i - E_f \]
\[ q = k_i - k_f \]

Coulomb Interaction

\[ v(r) = \sum_j e^2 / |r - r_j| \]
\[ = \sum_q v_q \rho_q e^{iqr} \]

, where \( \rho_q \) the electron density operator

Inelastic Scattering (\( \Delta E \)) Probability

\[ \frac{d^2 \sigma}{d\Omega d\Delta E} \sim \sum_f \left| \langle \psi_f | v(q) | \psi_i \rangle \right|^2 \delta(E_i - E_f - \Delta E) \]

\[ \sim \frac{1}{q^4} \cdot S(\omega, q) \rightarrow \text{X-ray} \]

\[ \sim \frac{1}{q^2} \cdot \text{Im} \left[ \frac{1}{\varepsilon(\omega, q)} \right] \rightarrow \text{EELS} \]
Spectral Imaging at Ultimate Spatial Resolution

Plasmonic Mapping:
STEM-EELS (2-Å Probe)

Chemical Mapping:
STEM-EDX (1-Å Probe)


The Third Lesson:
The importance of Quantum Physics
The cause for variation of scaling

- Influence of Boundary
  -- Increase of proportion of boundaries
  -- Existence of surface / edge modes
  -- Geometrical reconstruction

- Decrease of the number of particles
  decrease of confinement, increase of perturbation

- Different scaling for different physical entity

Quantum Effect:

=> Most likely to have new breakthrough!
The connection of materials wave with mechanics

\[ h = \text{Planck constant} \]
\[ (6.626 \times 10^{-34} \text{ joule-sec}) \]

DeBroglie wave:
\[ \lambda = \frac{h}{p} \]

Einstein:
\[ E = h\nu = \frac{p^2}{2m} \]

Wave length
- Free electrons
- Semiconductors
- Atoms

自由電子: \[ \lambda_{th}(300K) = 6.2nm \]
(半導體中 \[ 10nm \leq \lambda \leq 100nm \])

原子: \[ \lambda_{th}(300K) \leq 0.2nm \]
Bulk Limit $\iff$ Nano Limit

For bulk materials \( \lambda \ll L \)

For nano materials \( \lambda \sim L \)
Major Quantum Effect at the nano scale

- Interference
- Quantization
- Tunneling
- Quantum Spin
(I) Interference
The wonder of electron in waves

Classical mechanics

Electron source

= ?
The wave property of electrons
Double Slit Interference of Electrons

Electron source
\[ d \sin \theta = m\lambda \]

**constructive interference**

\[ d \sin \theta = (m+1/2)\lambda \]

**distructive interference**

\[ \Delta y = \frac{L}{d} \lambda \]

\[ d \frac{\Delta y}{L} = \lambda \]
\[ \lambda \sim 0.17 \text{nm} \]

\[ \lambda \sim 700 \text{nm} \]

\[ d \sim 10^{-4} \text{mm} = 10^{-4} \text{m} \]

\[ \Delta y = 1.7 \text{mm} \]

\[ \Delta y / \lambda = \frac{1}{\ell} \]
(II) Quantization
Confinement of the materials wave

Standing Wave

Quantizations
The Quantization of Energy

\[ L = \frac{n}{2} \lambda \]

\[ p = \frac{h}{\lambda} = \frac{nh}{2L} \]

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

\[ \delta E \propto 1/L^2 \]
Quantum well: 1D confinement

MOSFET:

AlGaAs

GaAs

2D electron Gas

二維電子氣
Quantum wire: 2 D-Confinement

SEM images of MoO$_x$ nanowires on graphite surfaces
Quantum dot: 3 D - Confinement
Quantum Dots of various shape
Absorption in scattering
From red to yellow

$E = \frac{hc}{\lambda} \propto \frac{1}{L^2}$

powdered Cadmium Selenide
(III) Tunneling and Nano-electronics
in classical physics, the electron is repelled by an electric field as long as energy of electron is below energy level of the field.

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

60 nm

1.2 nm

182 monolayers channel
CMOS scaling, When do we stop?

Reliability: 25 22 18 16 Å
processing and yield issue

Tunneling: 15 Å

Design Issue: chosen for 1A/cm² leakage
\( I_{on}/I_{off} \gg 1 \) 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 SiO₂

and at least 2 of those 5 atoms will be at the interfaces.
Fundamental Materials Selection Guidelines

- Thermodynamic stability in contact with Si to 750°C 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 SiO₂ at \( t_{eq} < 1.5 \) nm
- Low interfacial state density \( D_{it} < 10^{11} \text{ eV}^{-1}\text{cm}^{-2} \)
- Low oxygen diffusivity
- Crystallization temperature >1000°C

\[ t_{eq} : \text{equivalent oxide thickness (EOT) to be under 1.0 nm} \]
\[ t_{eq} = t_{ox} \frac{\kappa_{SiO_2}}{\kappa_{ox}} \]
## Basic Characteristics of Binary Oxide Dielectrics

<table>
<thead>
<tr>
<th>Dielectrics</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Y₂O₃</th>
<th>HfO₂</th>
<th>Ta₂O₅</th>
<th>ZrO₂</th>
<th>La₂O₃</th>
<th>TiO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric constant</td>
<td>3.9</td>
<td>9.0</td>
<td>18</td>
<td>20</td>
<td>25</td>
<td>27</td>
<td>30</td>
<td>80</td>
</tr>
<tr>
<td>Band gap (eV)</td>
<td>9.0</td>
<td>8.8</td>
<td>5.5</td>
<td>5.7</td>
<td>4.5</td>
<td>7.8</td>
<td>4.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Band offset (eV)</td>
<td>3.2</td>
<td>2.5</td>
<td>2.3</td>
<td>1.5</td>
<td>1.0</td>
<td>1.4</td>
<td>2.3</td>
<td>1.2</td>
</tr>
<tr>
<td>Free energy of formation</td>
<td>-</td>
<td>63.4</td>
<td>116.8</td>
<td>47.6</td>
<td>-52.5</td>
<td>42.3</td>
<td>98.5</td>
<td>7.5</td>
</tr>
<tr>
<td>MOₓ+Si₂ → M+ SiO₂</td>
<td></td>
<td>@727°C, Kcal/mole of MOₓ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stability of amorphous phase</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Silicide formation ?</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Hydroxide formation ?</td>
<td>-</td>
<td>Some</td>
<td>Yes</td>
<td>Some</td>
<td>Some</td>
<td>Some</td>
<td>Yes</td>
<td>Some</td>
</tr>
<tr>
<td>Oxygen diffusivity</td>
<td>2x 10⁻¹⁴</td>
<td>5x 10⁻²⁵</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>10⁻¹²</td>
<td>?</td>
<td>10⁻¹³</td>
</tr>
</tbody>
</table>
Integration Issues for High $\kappa$ 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 $\kappa$, Metal gates, and High mobility channel

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

Driving force:
- High speed
- Low power consumption
- High package density

1947 First Transistor
1960 First MOSFET

Metal Gate
High $\kappa$ gate dielectric
Oxide/semiconductor interface
High mobility channel
Integration of Ge, III-V with Si

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

108Å GGG
5nm Ge
High Performance Logic
Low Operating Power Logic

Transistor Scaling and Research Roadmap

- 90nm Node 2003
- 65nm Node 2005
- 45nm Node 2007
- 32nm Node 2009
- 22nm Node 2011
- 20nm Length (Development)
- 30nm Length (Development)
- 30nm Length (Production)
- 50nm Length (Production)
- Uniaxial Strain
- SiGe S/D PMOS
- 1.2nm Ultra-thin SiO2
- High-K & Metal-Gate Options
- Non-planar Tri-Gate Architecture Option

Robert Chau, Intel, ICSICT 2004

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

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

Better performance for ultra low-power applications

Atomic Model Prediction


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

Spintronics ⇔ 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

- 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

Spin structures of heavy rare - earths
Neutron Diffraction Studies of the Gd$_{10}$-Y$_{10}$ Magnetic Superlattice
Antiferromagnetically coupled below 200K
Spin Structure Tailoring in artificial Superlattices

Gd-Y  Dy-Y  Gd-Dy

Year 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.

First Evidence of GMR

$H_s$ corresponds to the field at which all layer magnetizations point along the field direction.
Spin-Valve GMR

- The simple structure of Spin-valve GMR:

- The magnetization of the top permalloy layer is free to rotate as the field is varied. The second permalloy layer is fixed due to its exchange interaction with the FeMn layer.
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!
Can we take the “charge” out of Spintronics?

To generate pure spin current!

Courtesy Claude Chappert, Université Paris-Sud, 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 Quantum 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

- Au NP @ SiO_x NW: Color-selective Optical Switch, SPR-enhanced Sensor
- Pt-Ru NP on CN_x NT: Fuel Cells, Supercapacitors
- GaN Nanobridge: High-gain Photo-detector, Solar Cells, Bio-sensor
- Ag NP on Si NT: 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

Core-shell

Wire/Rod

Nanotip

Tube

Belt

Peapod

Belt

APL 81, 123 (2001)
APL 81, 22 (2002)
JACS 127, 2820 (2005)
APL 88, 241905 (2006)
APL 90, 213104 (2007)
Small 4, 925 (2008)
Analytical Chem. 81, 36 (2009)
APL 79, 3179 (2001)
APL 81, 4189 (2002)
APL 86, 203119 (2005)
JACS 128, 8368 (2006)
PRB 75, 195429 (2007)
JACS 130, 3543 (2008)
Chapter 9, pp. 259-309,
Nanowires and nanobelts, Z.L.
APL 90, 123109 (2007)


APL 83, 1420 (2003)
APL 86, 203119 (2005)
US Patent 6,960,528,B2
APL 89, 143105 (2006)
Nano Lett. 9, 1839 (2009)

APL 81, 1312 (2002)


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)
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

Promising high-density memory: On-going

Nano Letters 9 (2009) 1839
• 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.

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)

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)

- 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/cm$^2$
- Stable at high scan rate
- 10 fold increase in charge-discharge rate
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.
On-chip Fabrication of Well Aligned and Contact Barrier-Free GaN Nanobridge Devices with Ultrahigh Photocurrent Responsivity


- 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
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.

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 with Surface Enhanced Raman Scattering (SERS)

Prof. Yuh-Lin Wang 王玉麟
IAMS Academia Sinica, Taiwan
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 to antibiotic exposure, which could be used to differentiate them from the drug-resistant ones.

The Advent of Carbon Era?

The Physics of Graphene:
- Possibility of relativistic electronics and spintronics
Background for search new platform

Scaling limit of Si MOSFET & superparamagnetism

Carbon era?

Thompson and Parthasarathy, Materialstoday 9, 20, 2006
Carbon Nanotube

Structure of carbon nanotubes

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

$sp^1$, $sp^2$, $sp^3$

Diamond

$C_{60}$ Buckyball

Graphite

Nanotube
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 SiO₂
Papers to read


