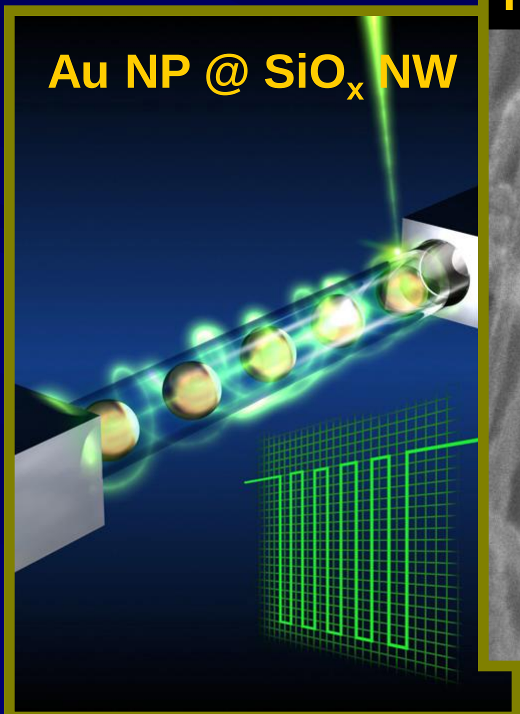
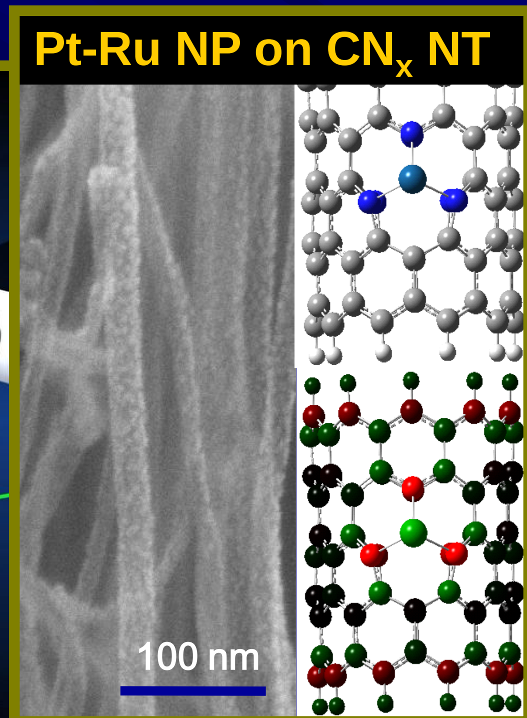
The Fourth Lesson:

Innovations of nano structures and nano materials for various applications

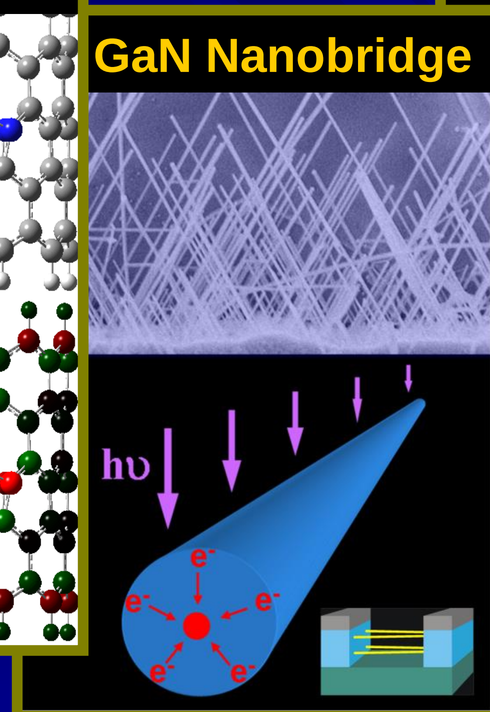
Overview of Advanced Materials Laboratory



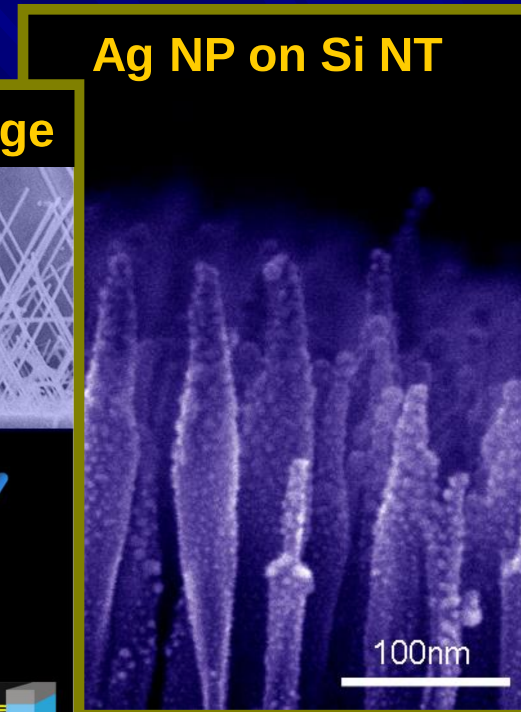
Color-selective Optical Switch, SPR-enhanced Sensor



Fuel Cells, Supercapacitors



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



SERS: Molecule/Bio-sensing

Li-Chyong Chen

Center for Condensed Matter Sciences

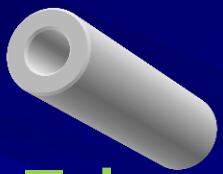
National Taiwan University

The Nano-world at CCMS-AML:
a Fruitful Research Field with Technology Implications

JACS 123, 2791 (2001)
APL 81, 22 (2002)
JACS 127, 2820 (2005)
APL 88, 241905 (2006)
APL 90, 213104 (2007)
Adv. Func. Mater. 18, 938 (2008)
Small 4, 925 (2008)
Analytical Chem. 81, 36 (2009)

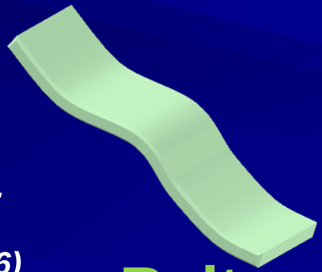
Wire/Rod

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)

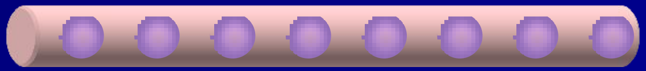


Tube

Chapter 9, pp. 259-309, Nanowires and nanobelts, Z.L. Wang Ed., Kluwer (2004)
Adv. Func. Mater. 16, 537 (2006)
APL 90, 123109 (2007)
Adv. Mater. 19, 4524 (2007)

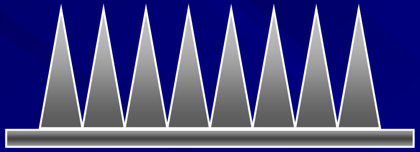


Belt



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

Peapod



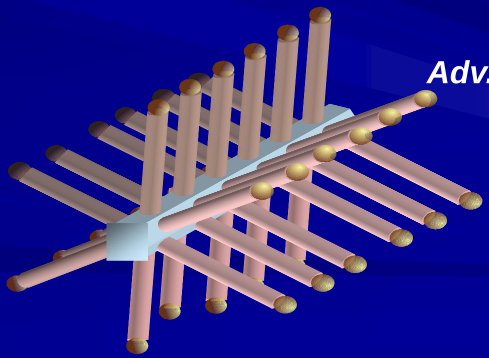
Nanotip

APL 83, 1420 (2003)
Nano. Lett. 4, 471 (2004)
Chem. Mater. 17, 553 (2005)
Adv. Func. Mater. 15, 783 (2005)
APL 86, 203119 (2005)
US Patent 6,960,528,B2
APL 89, 143105 (2006)
Nature Nanotech. 2, 170 (2007)
Nano Lett. 9, 1839 (2009

Core-shell

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

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



Brush

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)

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

* Antireflection:

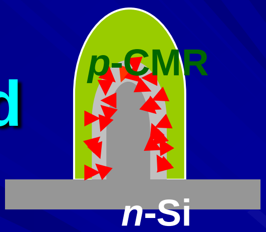
  Broadband (uv-terahertz), Omnidirectional (>70°)

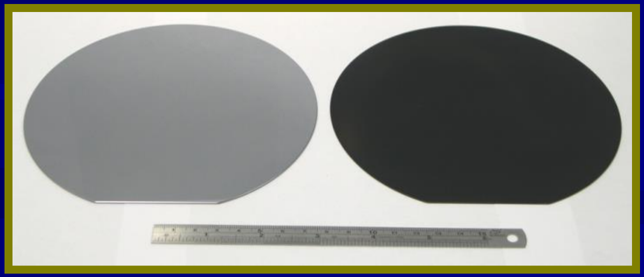
* Electroluminescence in ZnO/SiNTs:

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

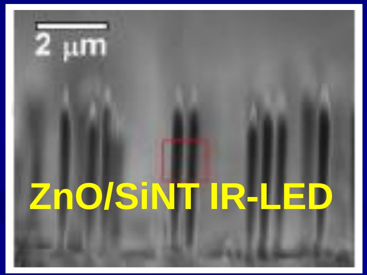
* Magneto-resistance in LSMO/SiNTs:

  Room-temp. MR at lower bias and magnetic field

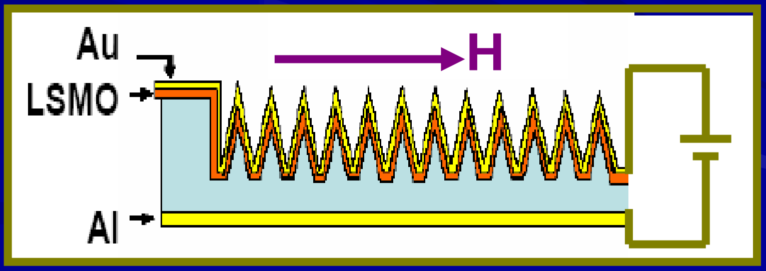




Nature-Nanotechnology 2 (2007) 770



Nano Letters 9 (2009) 1839



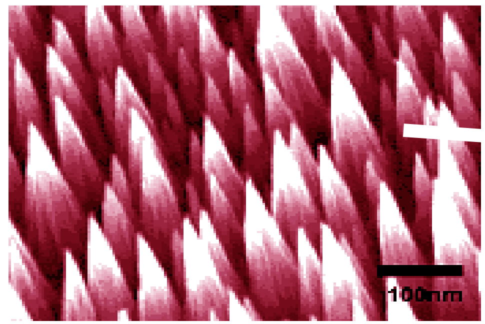
Promising high-density memory: On-going

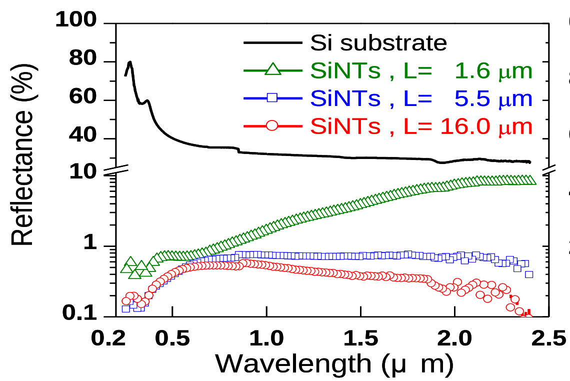
A Man-made Moth Eye

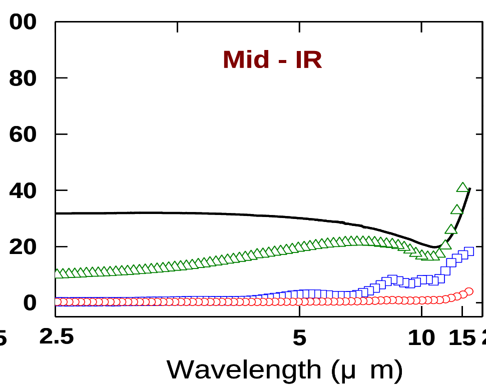
Broadband and Quasi-omni-directional Anti-reflection Properties with Biomimetic Silicon Nanostructure

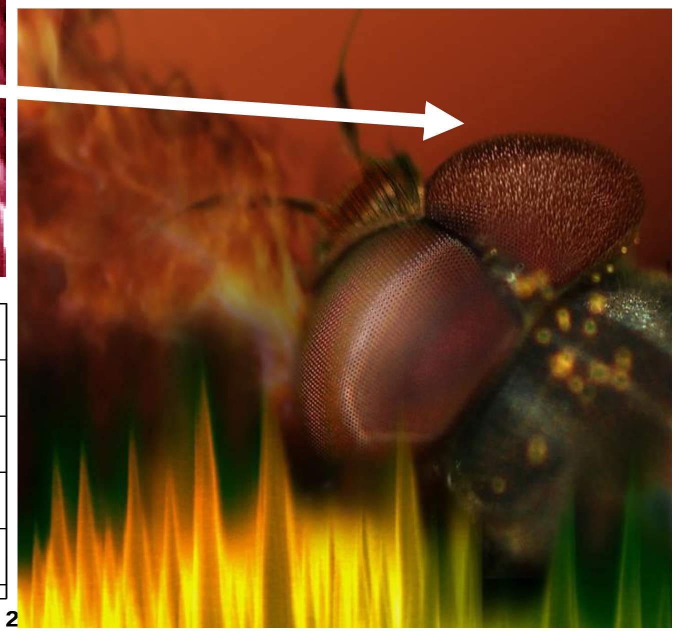
Y. F. Huang, et al., Nature Nanotechnology ***2****, 770-774 (2007), & US Patent 2005*

Featured by NPG Asia Materials, March 2008









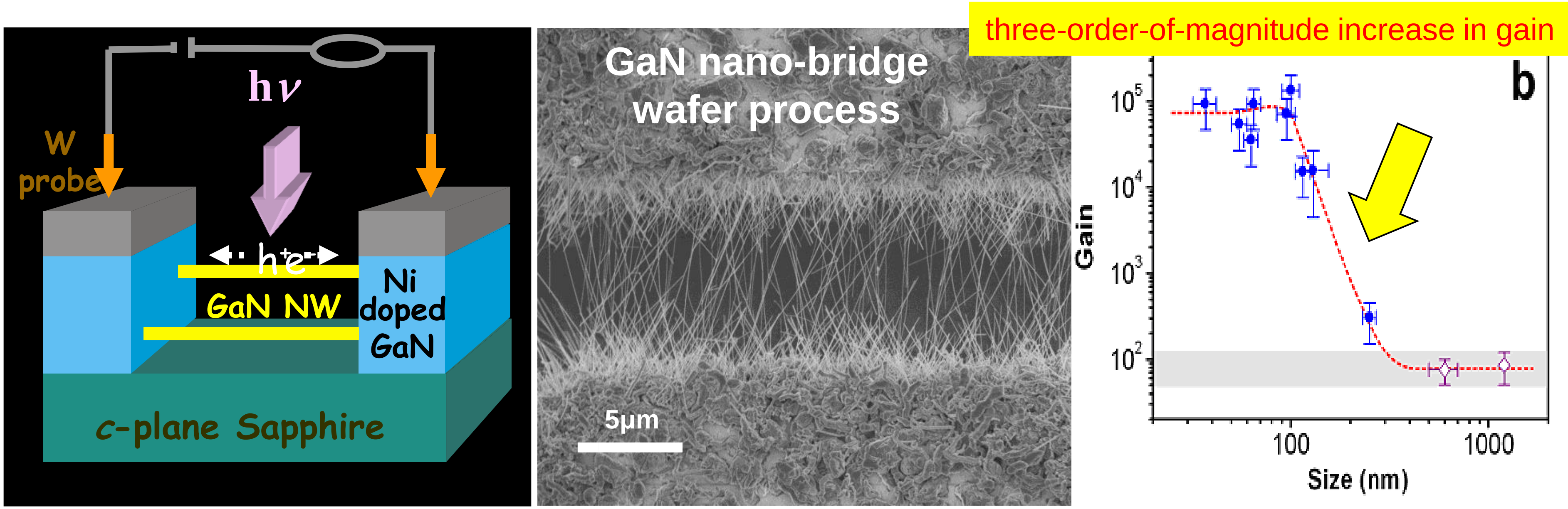
Many plants and animals have tiny surface structures that absorb certain wavelengths of light. These naturally formed nanostructures provide the colors in butterfly wings, camouflage for cicadas and enable moths to capture as much light as possible when flying at night.

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

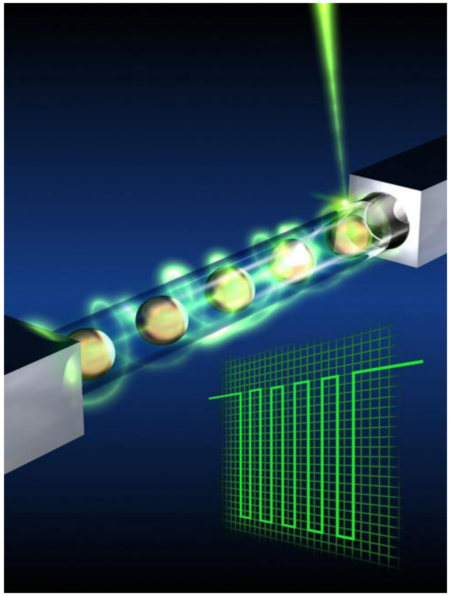
A Color-selective Nanoswitch

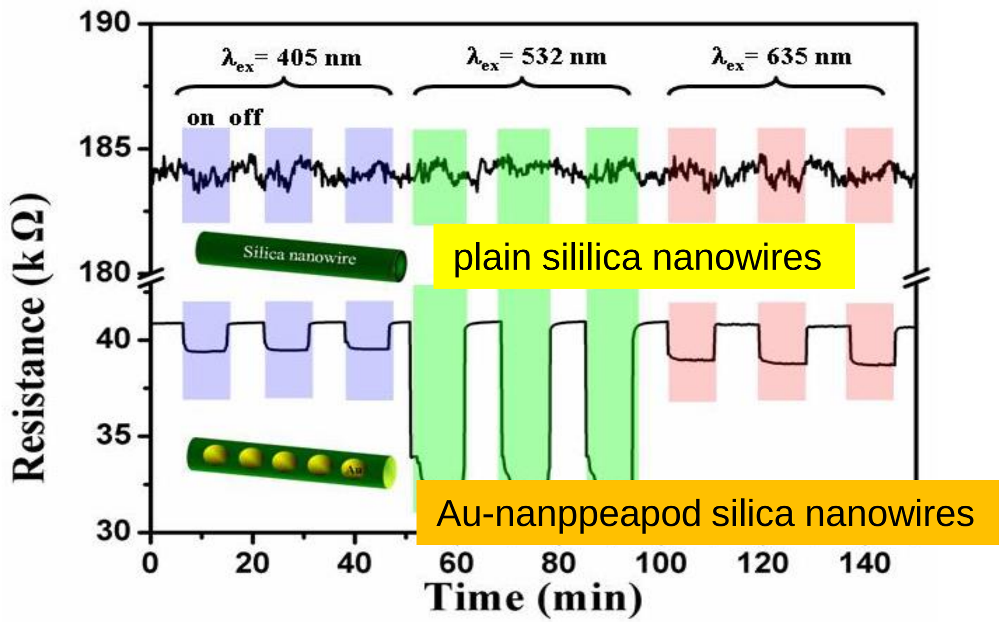
Photosensitive Gold Nanoparticle-embedded Dielectric Nanowires

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)





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".

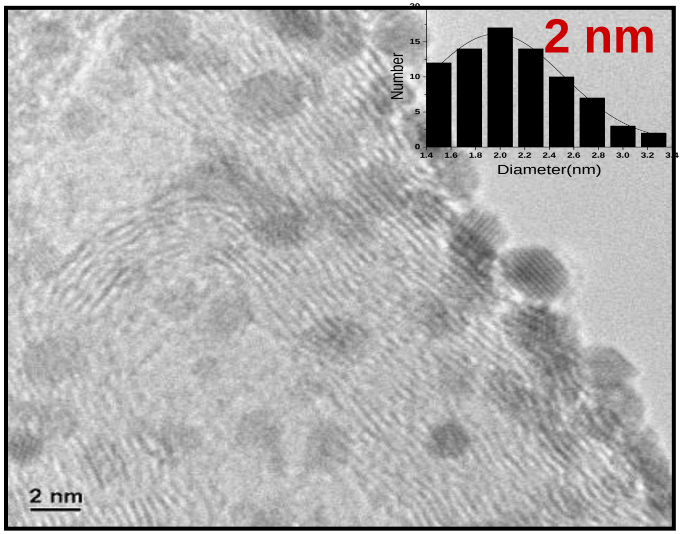
The nanopeapod (i.e., gold nanoparticle-embedded dielectric nanowire) will open up to **green** light, but shut off for lights of other colors.

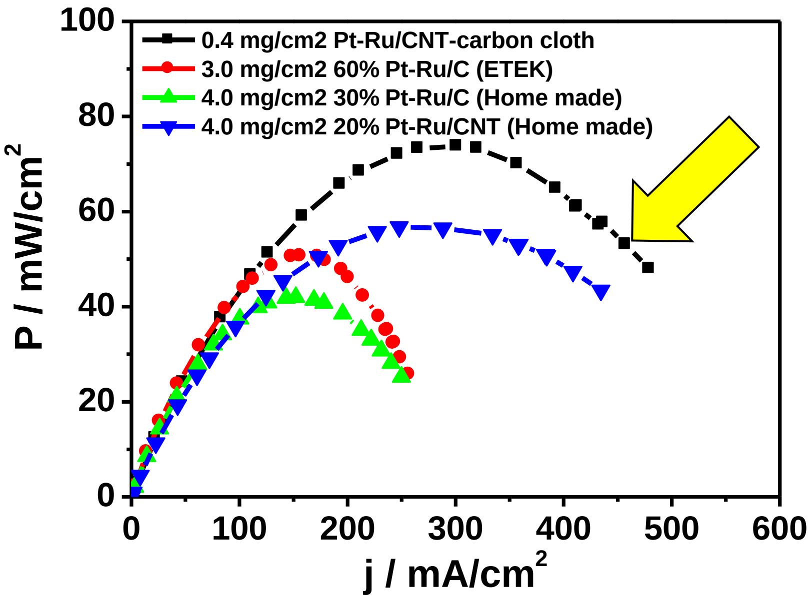
Next-generation Energy Solution (I): Fuel Cell with Low-loading of Precious Metals

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)





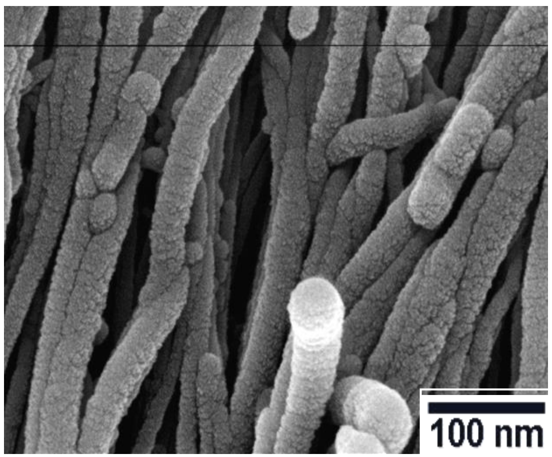
- Direct **methanol fuel cell** is promising power generator with a wide range of applications from portable electronic devices to automobiles.
- **Nanotubes-Pt/Ru composites** are highly efficient in loading precious metals. Only **one tenth** of metal loading, in comparison to the conventional, is needed.

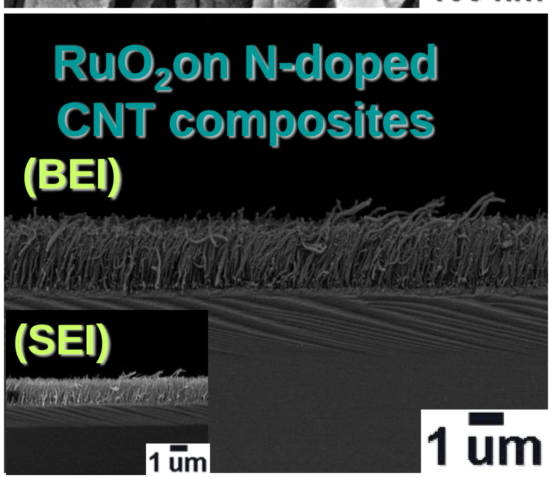
Next-generation Energy Solution (II): High-performance Supercapacitor

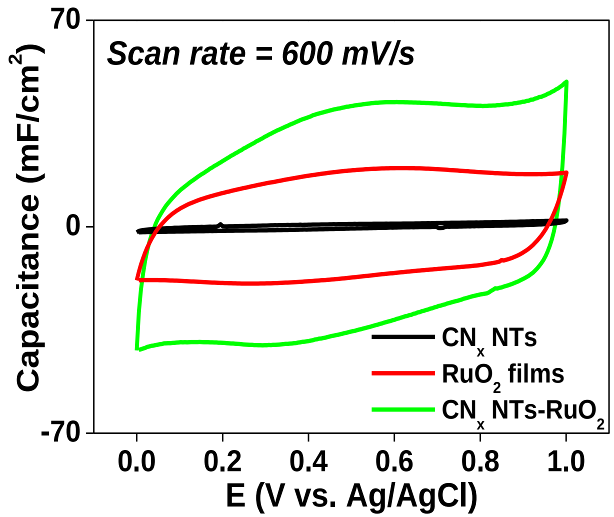
Ultrafast Charging-discharging Capacitive Property of RuO_2 Nanoparticles on Carbon Nanotubes Using Nitrogen Incorporation

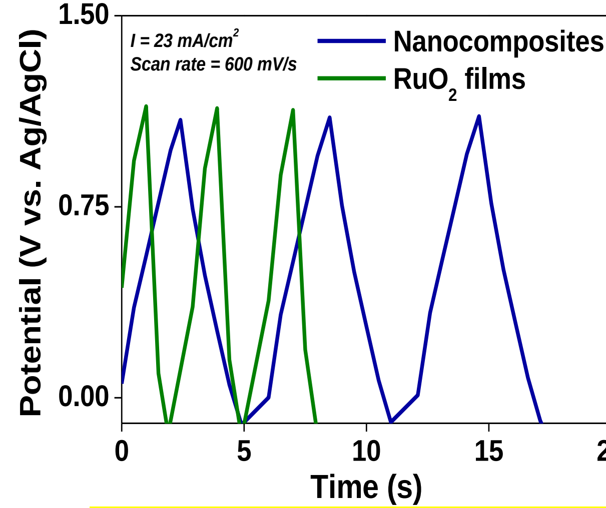
W. C. Fang, et al., Electrochemistry Communications 9, 239-244 (2007)

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









charging-discharging behaviors

- **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

The Fifth Lesson:

Nano photonics

and

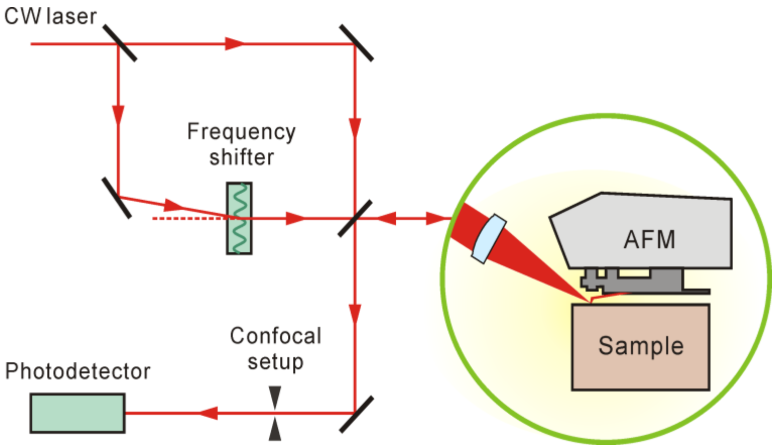
Bio-applications

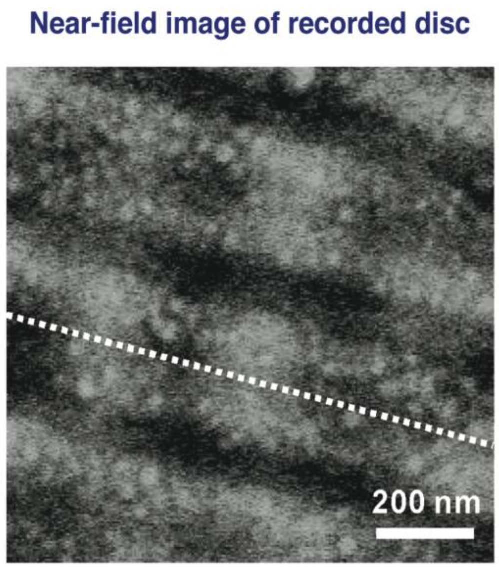
Nano-photonics and Plasmonics

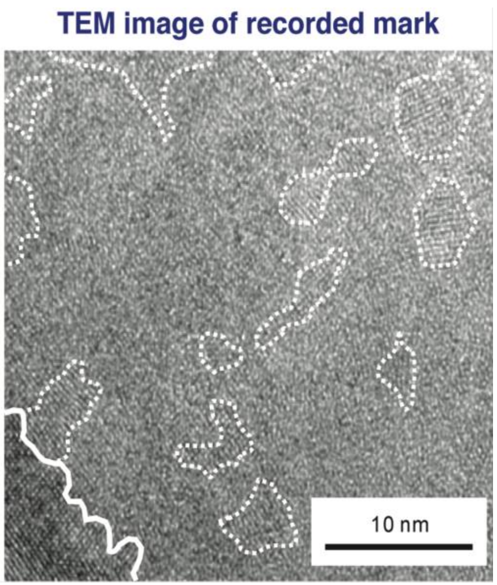
Near-field examination of blue-ray discs

Dr. Juen-Kai Wang, CCMS, NTU

S-SNOM setup



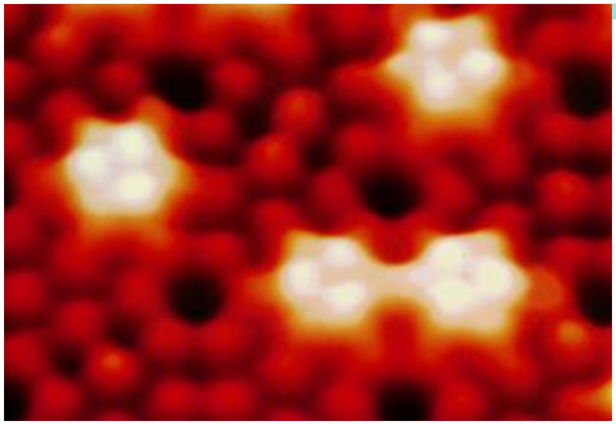


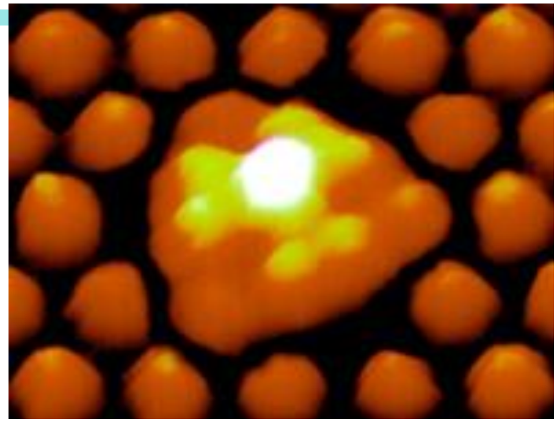


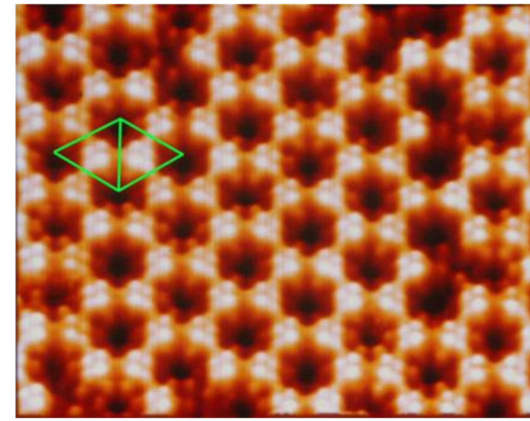
- **Scattering-type SNOM reveals sub-10 nm optical signature**.
- The optical contrasts of the dark and the bright regions in near-field image of phase-change layer correspond to amorphous and polycrystalline AgInSbTe, respectively.
- Small bright spots with a size of ~30 nm emerge within the dark region, 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.**

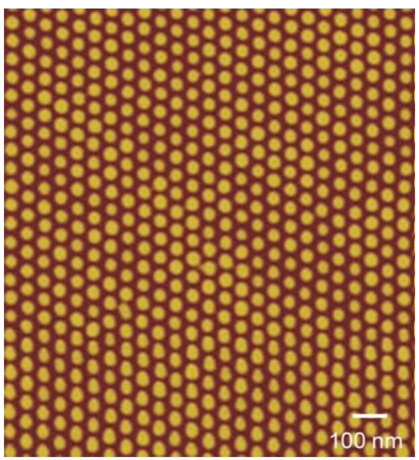
J. Y. Chu et al., Appl. Phys. Lett. 95, 103105 (2009).

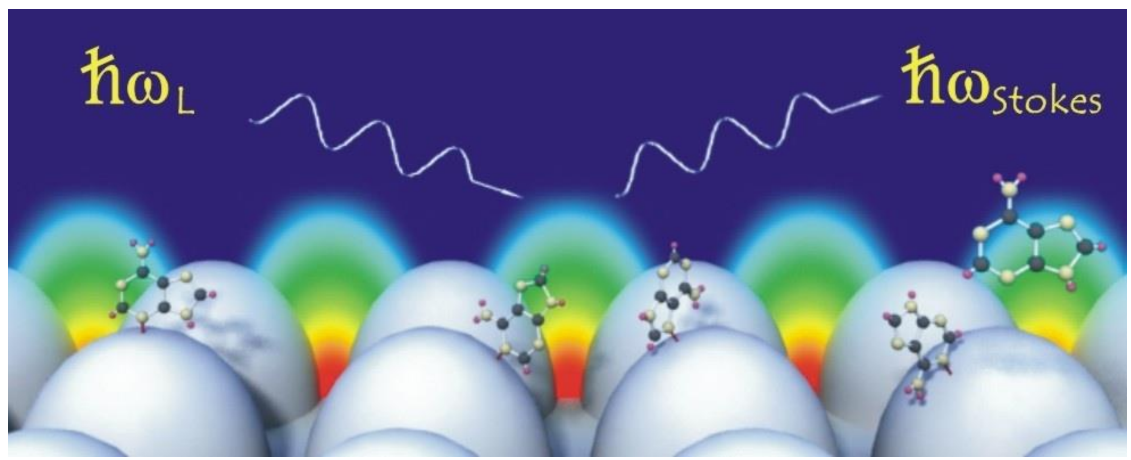
Creating Mono-dispersed Ordered Arrays of Surface-Magic-Clusters and Anodic Alumia Nanochannels by Constrained Self-organization





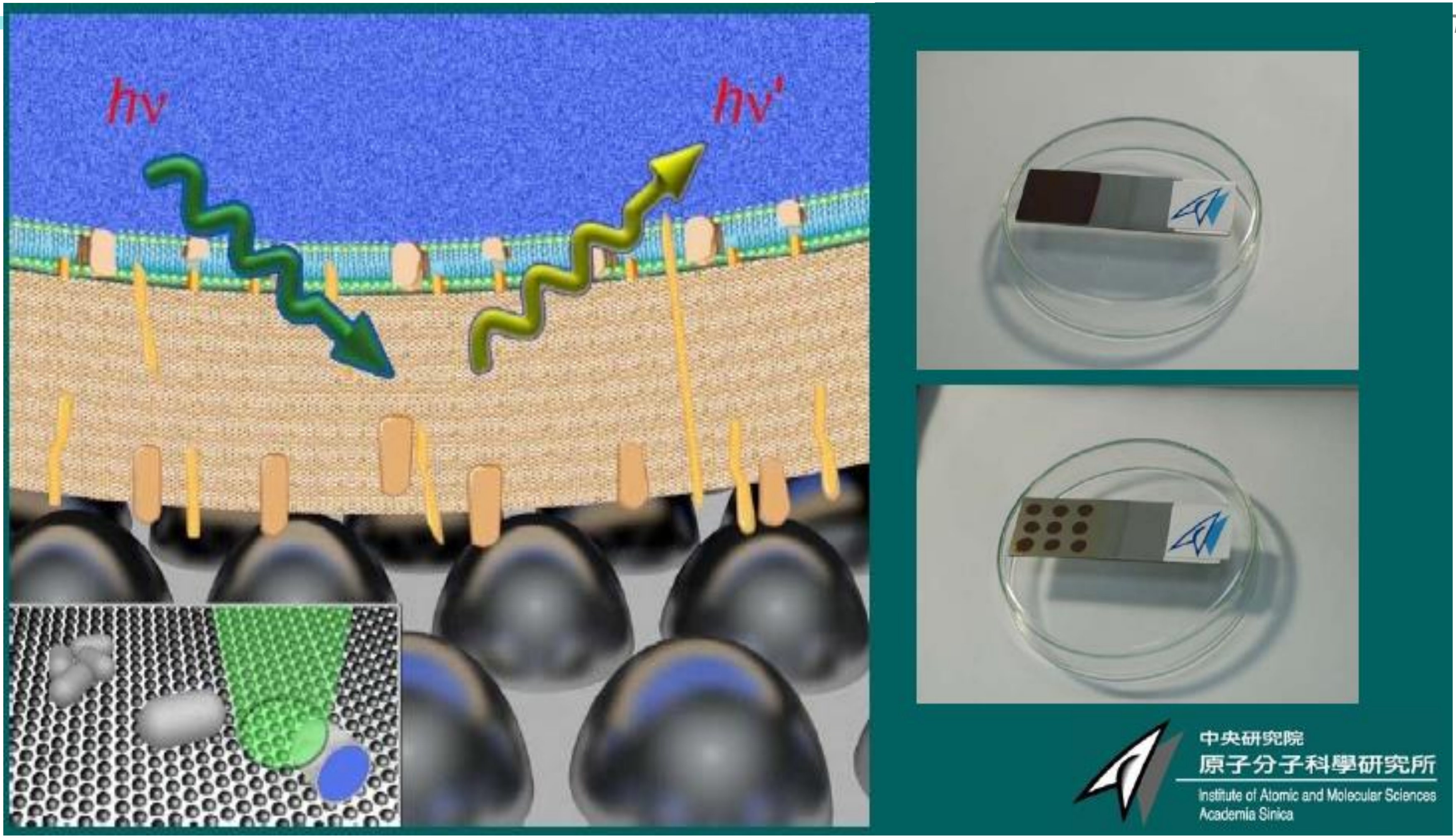






Prof. Yuh-Lin Wang and J. K. Wang
IAMS Academia Sinica, Taiwan

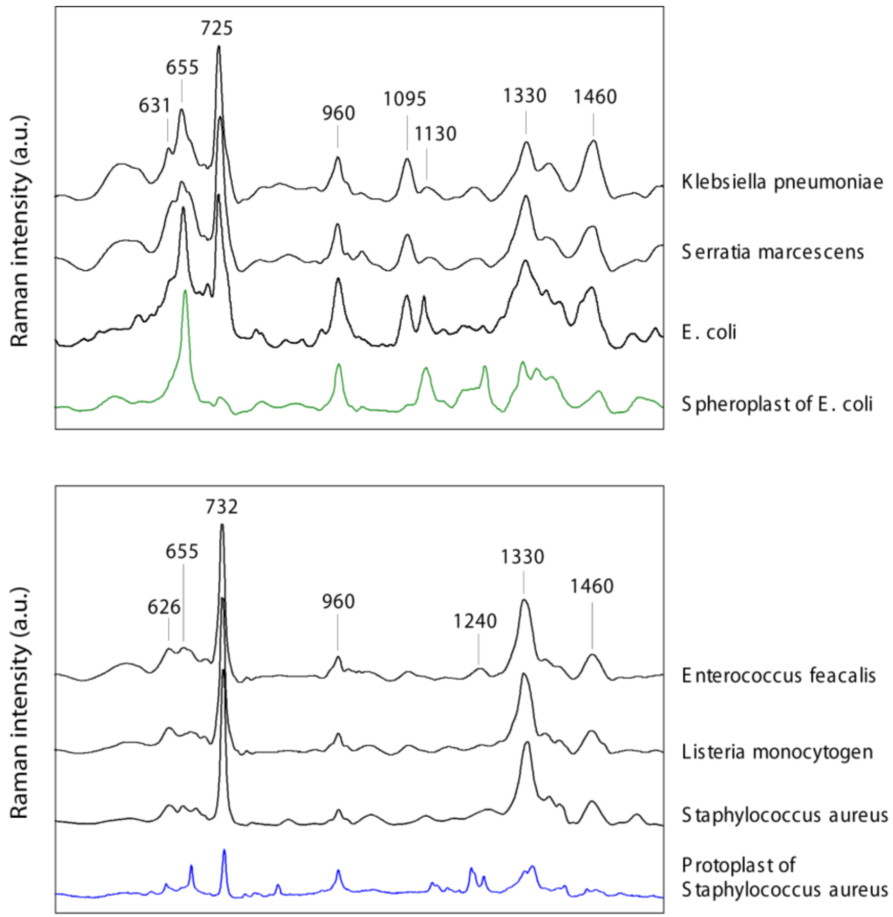
A High Sensitivity and High Speed Biomedical Diagnostic Technology using Surface Enhanced Raman Scattering (SERS)

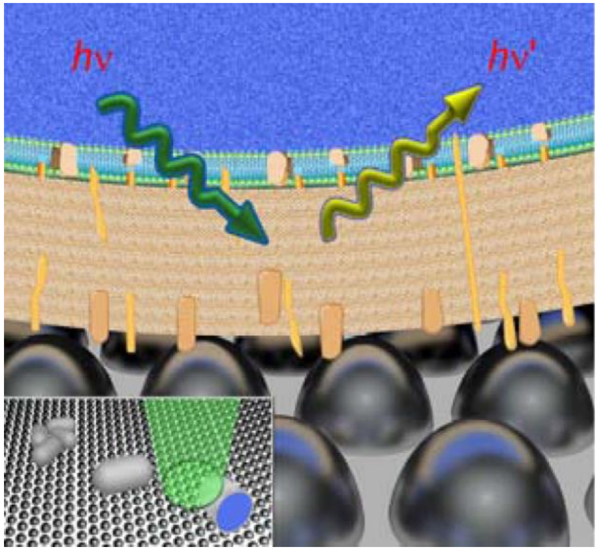


Profs. Yuh-Lin Wang and J. K. Wang
IAMS Academia Sinica, Taiwan

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.

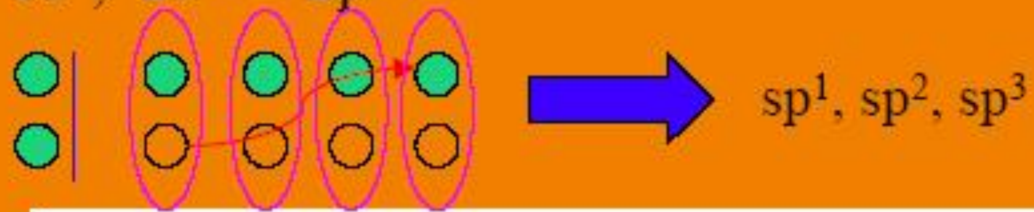
H.-H. Wang et al., Adv. Mater. 18, 491 (2006); T.-T. Liu et al., PLoS ONE 4, e5470 (2009).

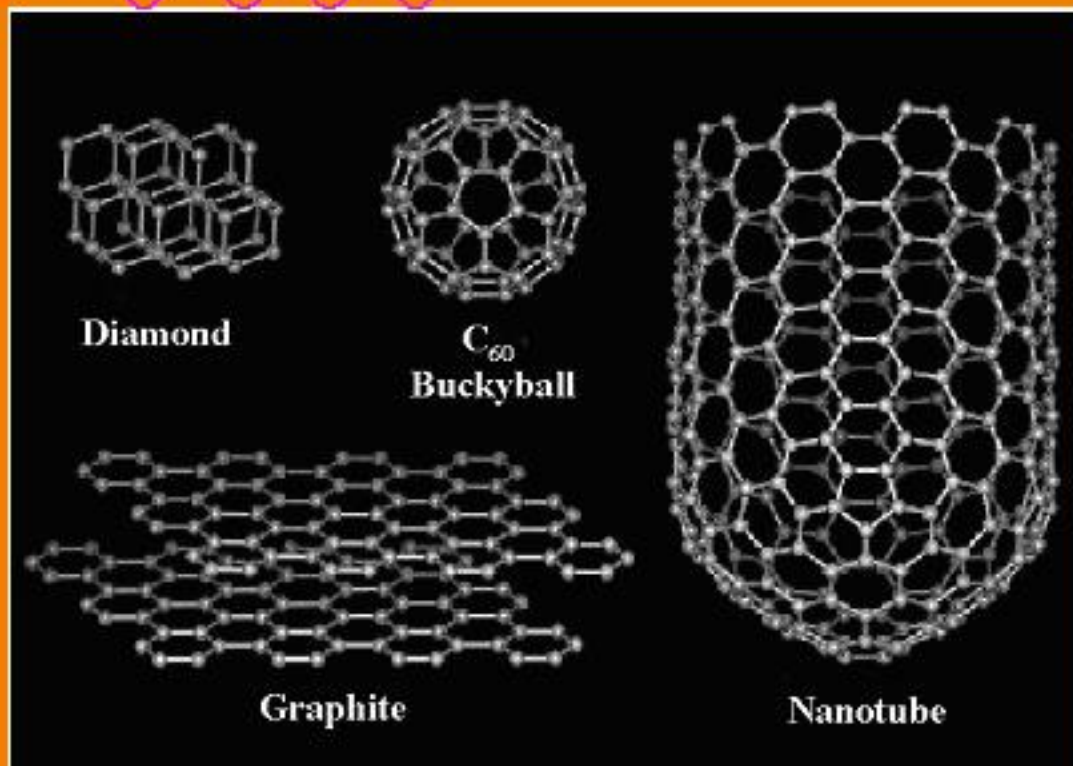
The Advent of Carbon Era ?

Carbon Nanotube

- Structure of carbon nonatubes

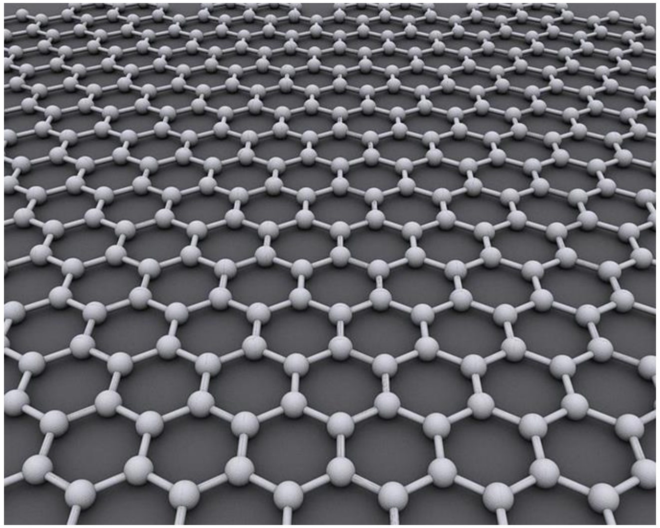
Carbon: $1s^2$, $2s^1$ $2p^3$





Unexpected realization of graphene sheet

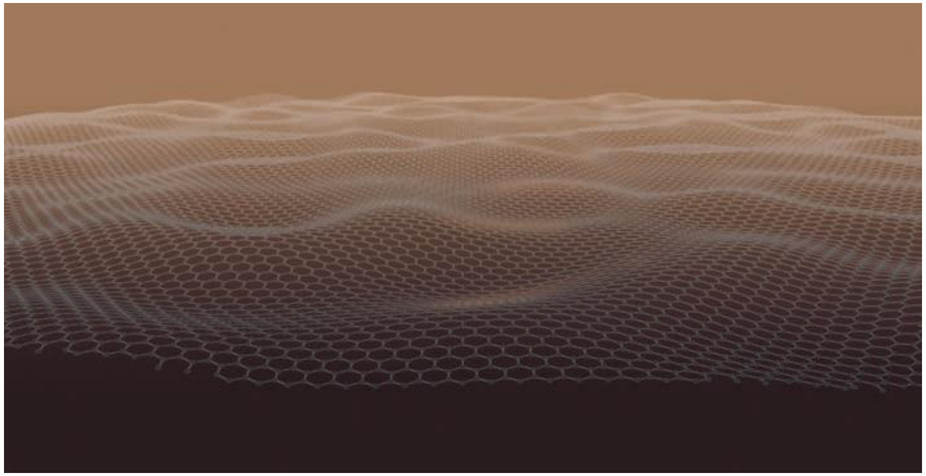
mechanically exfoliated graphene sheets



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

Emergent Properties of Two-Dimensional Materials--

Flatlands beyond Graphene



Outline

- Graphene
- Hexagonal-Boron Nitride (h-BN)
- Transition Metal Dichalcogenides (TMDs)
- Topological Insulator
- Beyond.....

Hot spots of graphene


Andre Geim Konstantin Novoselov

Nobel Prize in Physics for 2010

"for groundbreaking experiments regarding the two-dimensional material graphene"

www.graphene-flagship.eu

GRAPHENE FLAGSHIP

European Commission has chosen graphene as a ten-year, 1 billion euro Future Emerging Technology flagship. (Jan 28, 2013)

Aim to get graphene into industry and product development

http://www.graphene-flagship.eu/GF/index.php

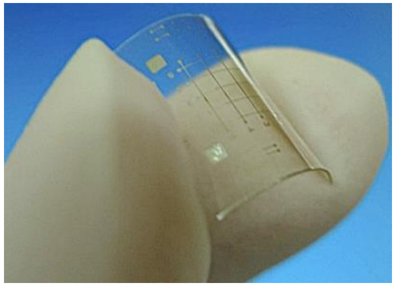
SAMSUNG

SAMSUNG TECHWIN

The South Korean government has invested $200 million, beating the amount actually spent on graphene by the UK government so far at least twenty times over. Samsung has added another $200million in South Korean spend.

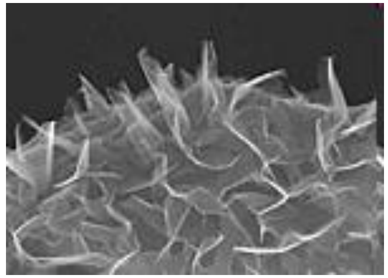
http://www.cambridgenetwork.co.uk/news/is-the-uk-set-to-miss-out-on-the-graphene-revolution/

Graphene's Applications



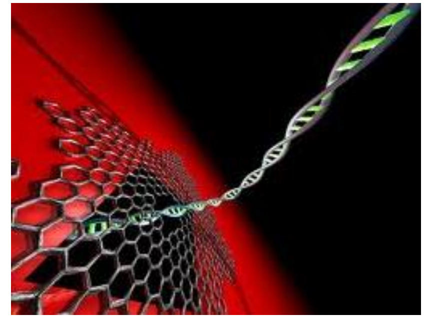
Flexible Memristors

Nano Lett., ***10*** (11), 4381 (2010)



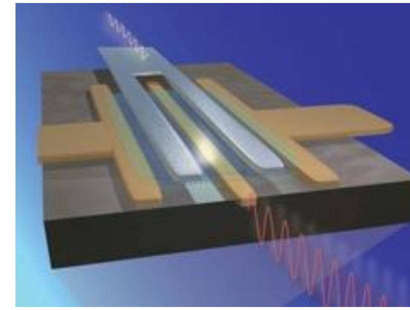
Ultracapacitor

Science **329** (5999) 1637 (2010)



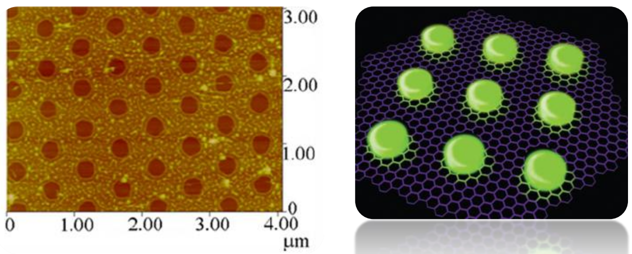
DNA graphene nanopore

Nano Lett.,, ***10*** (8), 2915 (2010)
Nano Lett., ***10*** (8), 3163 (2010)
Nature **467**, 190–193 (2010)



RF transistors

Nano Letters **9** (1), 422 (2009)
Nano Letters, **9** (12), 4474 (2009)
Science, **327**(5966), 662 (2010)
IEEE EDL, **31**(1), 68 (2010)
Nature **467**, 305–308 (2010)



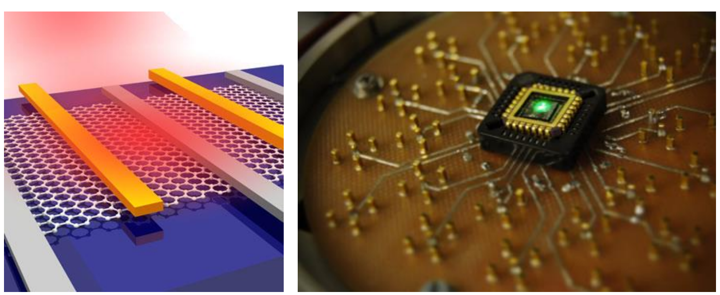
Graphene Transparent Conductors

APL **99**, 023111 (2011) and Adv. Mater. **24**, 71 (2012)

Graphene Commercialization Breakthrough*

- OLED Lighting
- Transparent Conductors
- Logic & Memory
- Printed Electronics Manufacturing
- Catalytic support
- Stretchable and Sensing Electronics
- Solar Opportunities
- Energy Storage
- Advanced carbon based materials for Lithium Ion battery electrodes

*http://www.nanowerk.com/news2/newsid=27702.php

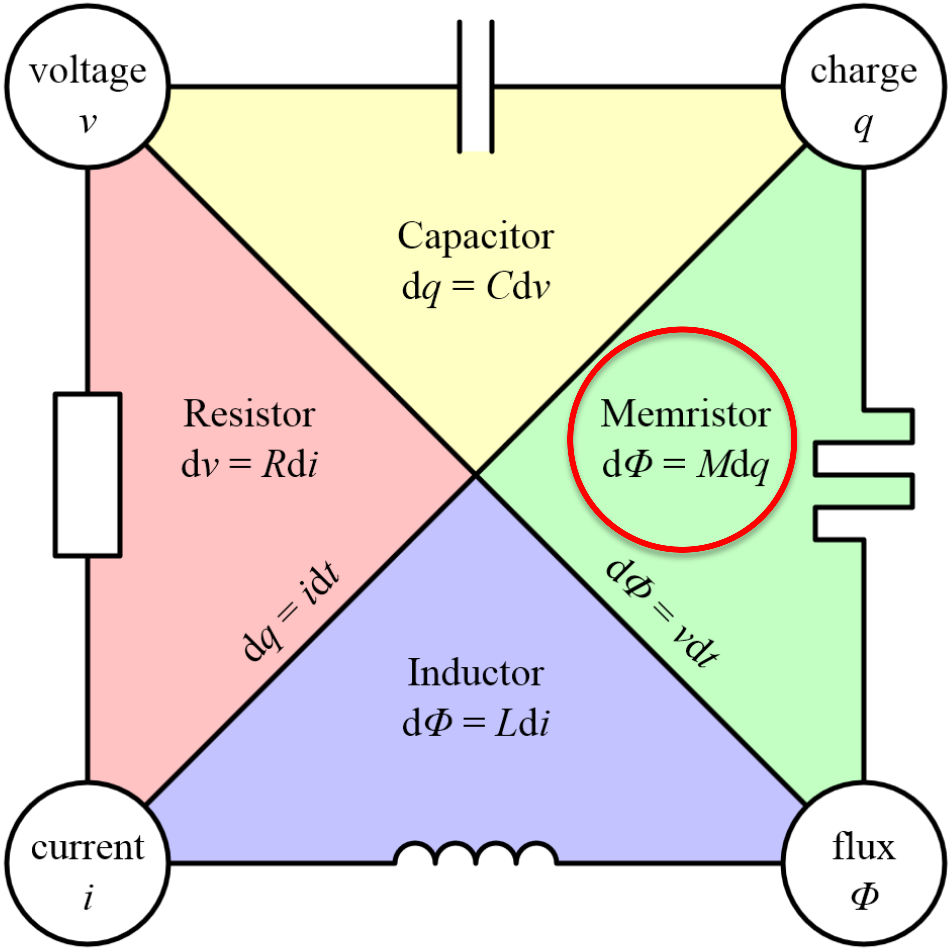


Graphene Photodetector

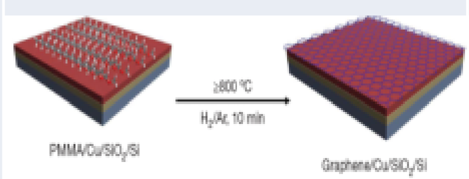
Nature Photonics **4**, 297 - 301 (2010)
Nature Nanotechnology **7**, 363–368 (2012)

Memristors

$$M(q) = \frac{\mathrm{d}\Phi_m}{\mathrm{d}q} \qquad M(q(t)) = \frac{\mathrm{d}\Phi_m/\mathrm{d}t}{\mathrm{d}q/\mathrm{d}t} = \frac{V(t)}{I(t)}$$



Fabrication of graphene

Method	Descriptions	Merits	References
Mechanical cleavage or exfoliation	Scotch Tape 	Minimal defects Intrinsic properties Small sizes	Science 306, 666 (2004)
Chemical oxidized process	Producing GO by the oxidation of graphite with acid	Large scale flakes Composite	Nature 442, 282 (2006)
Epitaxial growth on SiC	Epitaxial growing graphene on SiC	Large area Multilayer High temperature	J. Phys. Chem. B 108, 19912 (2004)
Chemical vapor deposition on Ni	Ambient-pressure CVD on evaporated polycrystalline Ni	Large area multilayer	Nano Lett., Vol. 9, No. 1, 200
Chemical vapor deposition on Cu	Growing graphene on Cu with methane and hydrogen.	Large area, one-layer Defect Mechanism	Science 324, 1312 (2009)
Solid carbon source to graphene		Poly (methyl methacrylate) One step to doped graphene	Nature, 468, 549 (2010)

Unique Properties of Graphene

- Room-temperature electron mobility of 2.5×10^5 cm^2V^{-1} s^{-1}

  Nano Lett. 11, 2396–2399 (2011).

- Young’s modulus of 1 TPa and intrinsic strength of 130 GPa

  Cu: 0.117 TPa Phys. Rev. B 76, 064120 (2007).

- High thermal conductivity: above 3,000$Wm^{-1}K^{-1}$;

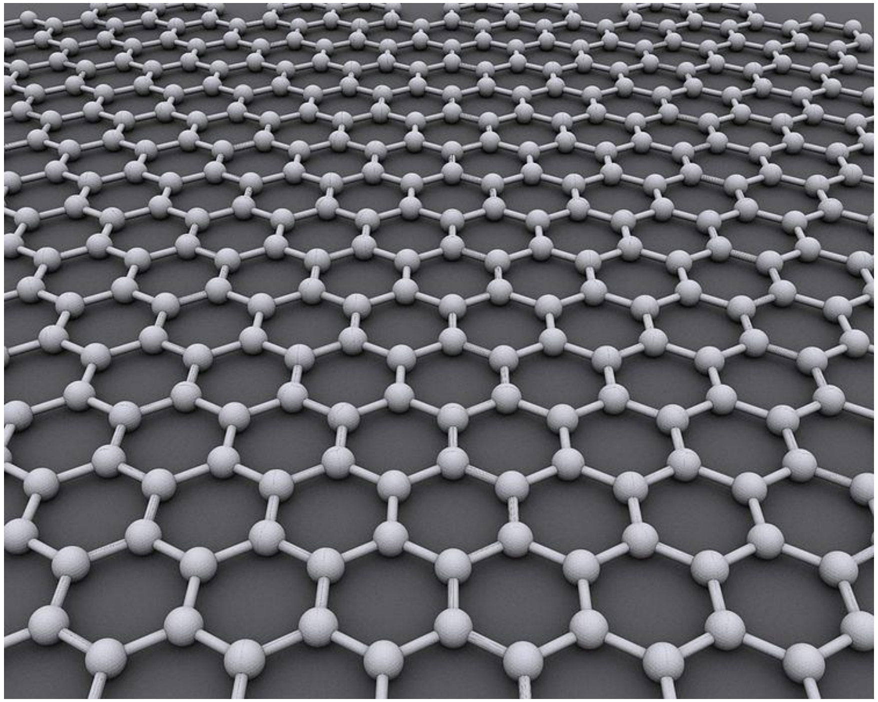
  Cu: 401$Wm^{-1}K^{-1}$ Nature Mater. 10, 569–581 (2011).

- Optical absorption of 2.3%

  Science 320, 1308 (2008).

- No band gap for undoped graphene

Graphene



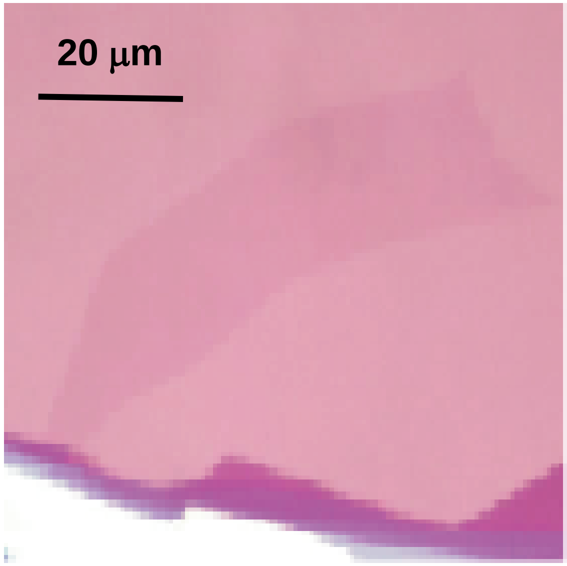
- E–k relation is linear for low energies near the six corners of the two-dimensional hexagonal Brillouin zone, leading to zero effective mass for electrons and holes.
- Due to this linear dispersion relation at low energies, electrons and holes near these six points, two of which are inequivalent, behave like relativistic particles described by the Dirac equation for spin 1/2 particles.
- The electrons and holes are called Dirac fermions, the six corners of the Brillouin zone are called the Dirac points. The equation describing the E–k relation is

$$E = \hbar v_F \sqrt{k_x^2 + k_y^2}$$

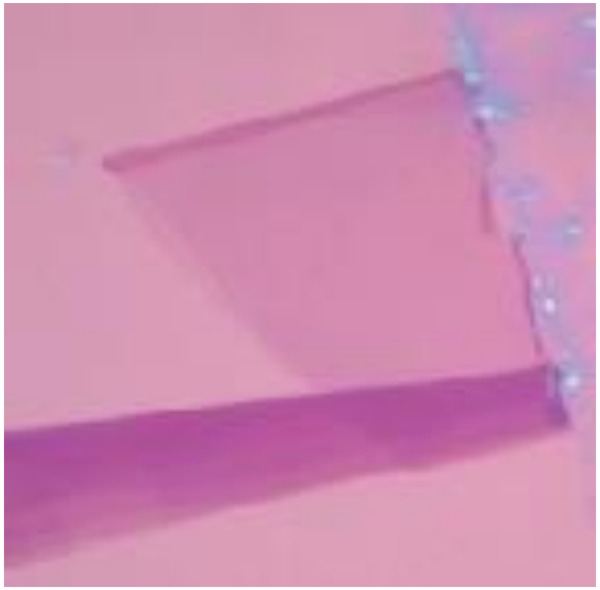
where the Fermi velocity $v_F \sim 10^6$ m/s.

Exfoliated Graphene Monolayers and Bilayers

Reflecting microscope images.



Monolayer



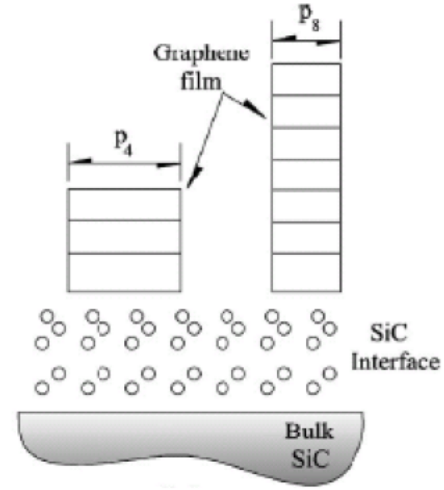
Bilayer

K. S. Novoselov *et al.*, *Science* **306**, 666 (2004).

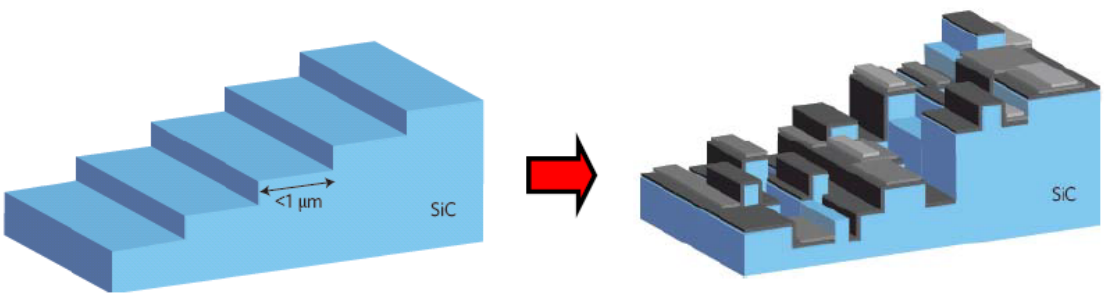
Epitaxial growth of graphene

Epitaxial graphene grown on SiC(0001) surfaces

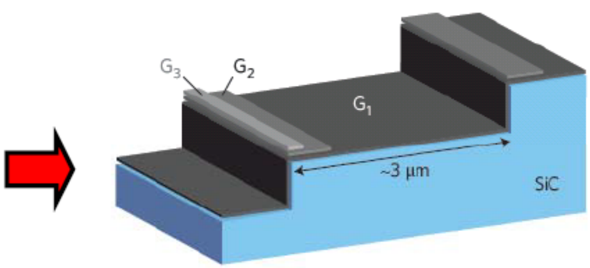
One often ends up with multi-layers of graphene with small grains 30nm-200nm



Recent progress:

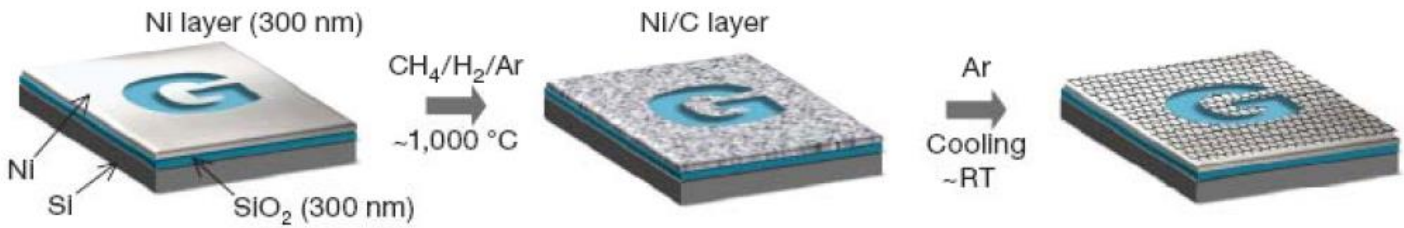


UHV

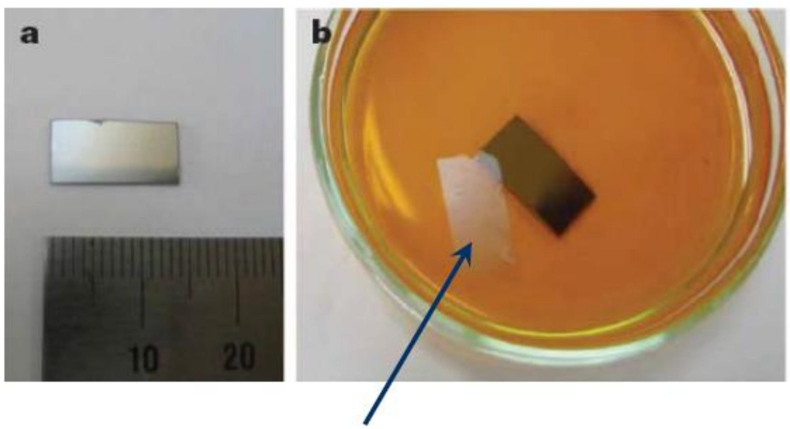


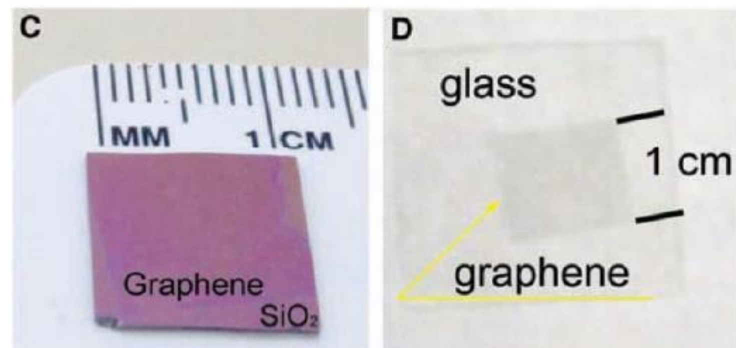
In the presence of pressurized Ar
K.V. Emvsev et al., Nature Materials 8, 203 (2009)

CVD graphene on metal substrates



Etching and transfer

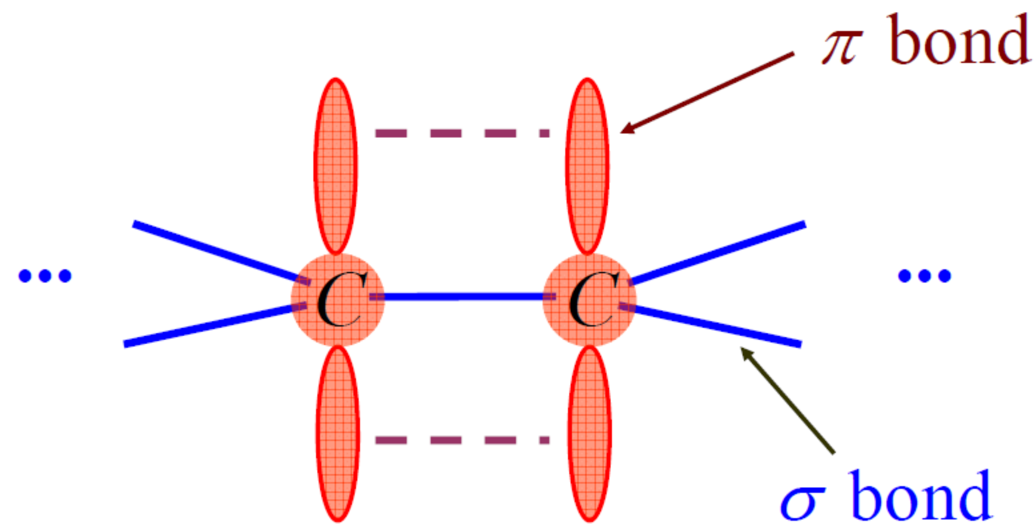




Cu: Li et al., Science 324, 1312 (2009)

Floating graphene after Ni being etched
Ni: Kim et al., Nature 457, 706 (2009)

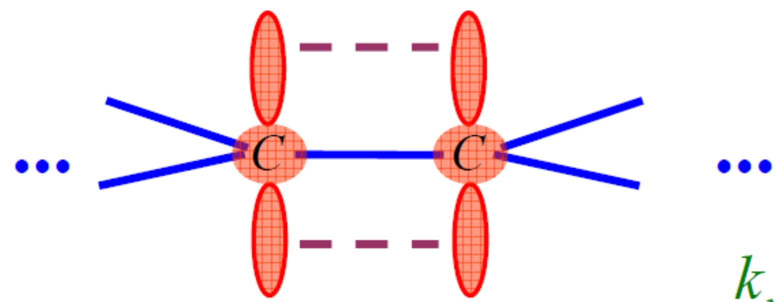
Element of Carbon Network

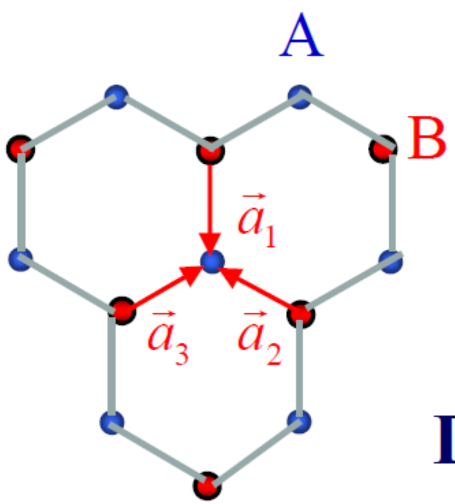


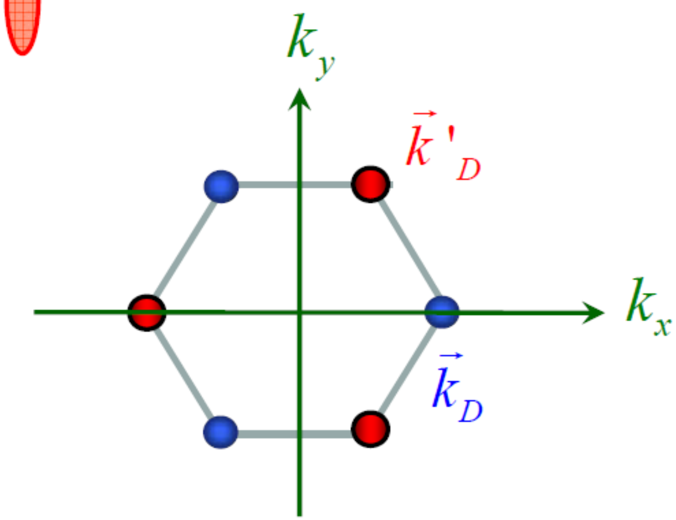
Carbon $1S^2\underbrace{2S^2 2P^2}$

4 electrons in σ bonds $(SP^2) + \pi$ bond or SP^3

Parent spectrum
Two dimensional Dirac Fermions





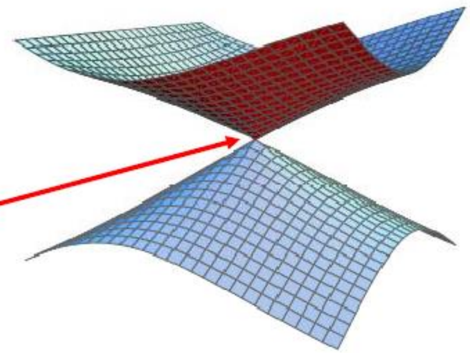


Dirac points

$$e^{i\vec{k}_D\cdot\vec{a}_n} = 1,\ e^{i2\pi/3},\ e^{i4\pi/3} \Leftrightarrow \sum_n e^{i\vec{k}_D\cdot\vec{a}_n} = 0$$

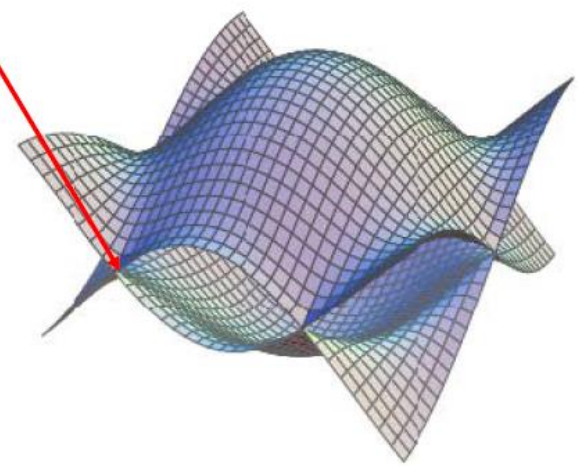
Quasi-Dirac Fermions

$E = \hbar \upsilon k$ with $m = 0$



Dirac points

New playground for testing
relativistic QM and QED!

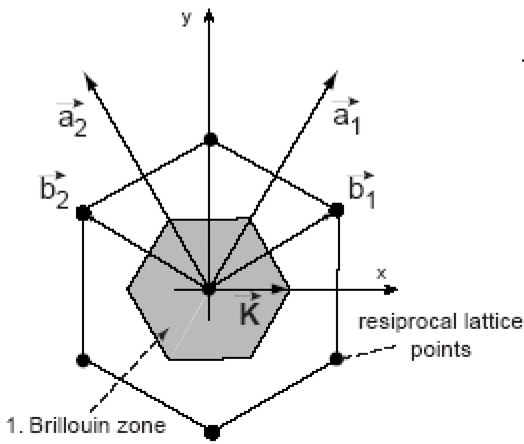


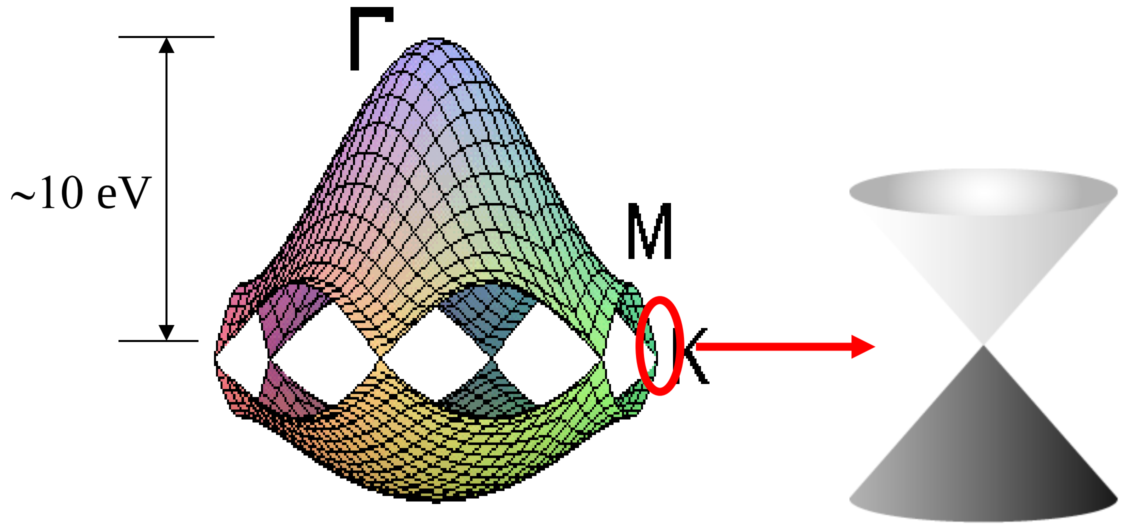
Not exactly Dirac Fermions

$\upsilon \approx c / 300$

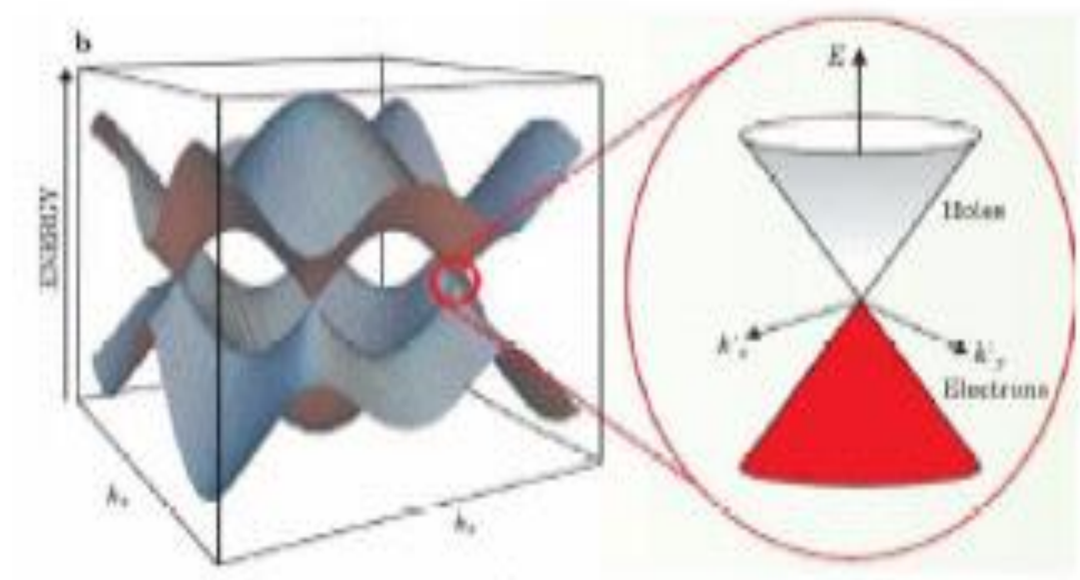
$k_D \neq 0$ and inter-Dirac point scatterings!

Band Structure near K Points





Relativistic Dirac fermion.



General Properties of Graphene

Electrically:

High mobility at room temperature,
Large current carrying capability

Mechanically:

Large Young's modulus.

Thermally:

High thermal conductance.

Super-Qualities

- $m^* = 0$ expect huge mobility

Carrier mobility: 200000 $cm^2/V.s$

(Geim, 2008, 300K, $n \approx 10^{13} cm^{-2}$)

Ballistic transport at micronscale

Epitaxial graphene: 2000 $cm^2/V.s$ **(27K)** $\lambda_\phi \geq 1 \mu m$

CVD graphene: 4050 $cm^2/V.s$ **(room temp)**

Si 1500 $cm^2/V.s$ **high speed GaAs 8500** $cm^2/V.s$

InSb (undoped) 77000 $cm^2/V.s$

- Thermal conductivity (room temp)

$\approx 5 \times 10^3 W m^{-1} K^{-1} \sim 10 \times$ Cu or Al

Exotic Behaviors

--Quantum Hall effect

--Barry Phase

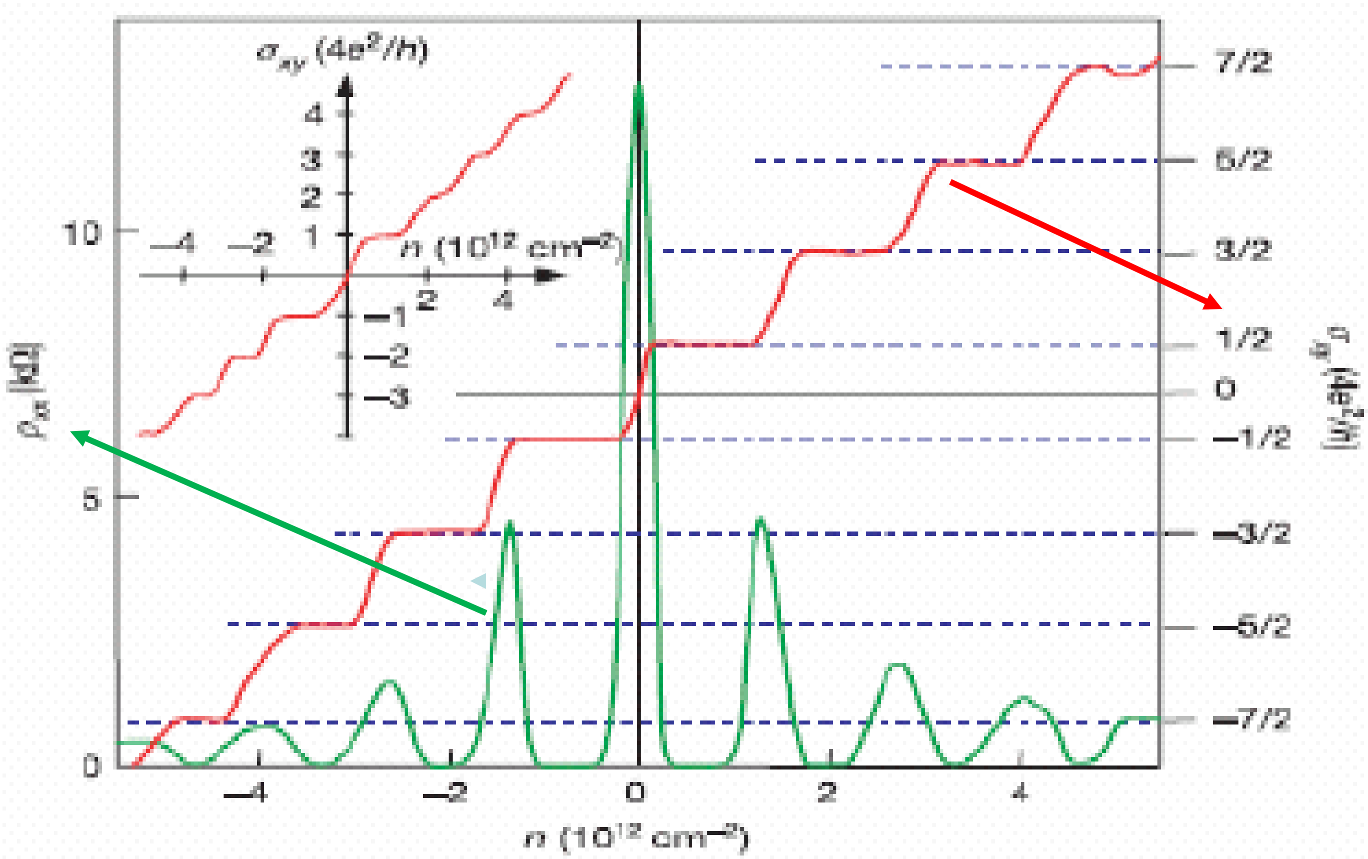
--Ballistic transport

--Klein’s paradox

--Others

-
-

Quantum Hall Effect



$$\sigma_{xy} = \frac{4e^2}{h}\left(N + \frac{1}{2}\right)$$

Y. Zhang et al, *Nature* **438**, 201 (2005)

Berry Phase

- In classical and quantum mechanics, the **geometric phase**, **Pancharatnam–Berry phase** or most commonly **Berry phase**, is a phase acquired over the course of a cycle, when the system is subjected to cyclic adiabatic processes, which results from the geometrical properties of the parameter space of the Hamiltonian. The phenomenon was discovered in 1956, and rediscovered in 1984.
- It can be seen in Aharonov–Bohm effect and the conical intersection of potential energy surfaces. In case of Aharonov–Bohm effect, the adiabatic parameter is the magnetic field enclosed by two interference paths, and it is cyclic in the sense that these two paths form a loop. In the conical intersection, the adiabatic parameters are the molecular coordinates.
- Apart from quantum mechanics, it arises in a variety of other wave systems, such as classical optics. It occurs whenever there are at least two parameters affecting a wave, in the vicinity of some sort of singularity or hole in the topology.
- Waves are characterized by amplitude and phase, and both may vary as a function of those parameters. The Berry phase occurs when both parameters are changed simultaneously, but very slowly (adiabatically), and eventually brought back to the initial configuration. In quantum mechanics, this could involve rotations but also translations of particles, which are apparently undone at the end. However, if the parameter excursions correspond to a cyclic loop instead of a self-retracing back-and-forth variation, then it is possible that the initial and final states differ in their phases. This phase difference is the Berry phase, and its occurrence typically indicates that the system's parameter dependence is singular for some combination of parameters.
- To measure the Berry phase in a wave system, an interference experiment is required. The Foucault pendulum is an example from classical mechanics that is sometimes used to illustrate the Berry phase. This mechanics analog of the Berry phase is known as the Hannay angle.

Berry Phase

Electron subjected to magnetic field B moves on a circular (cyclotron) orbit. Classically, any cyclotron radius R_c is acceptable. Quantum-mechanically, only discrete energy levels (Landau levels) are allowed and since R_c is related to electron's energy, this corresponds to quantized values of R_c.

The energy quantization condition obtained by solving Schrödinger's equation

$E = (n + \alpha)\hbar\omega_c, \alpha = 1/2$ for free electrons (in vacuum)

or $E = v\sqrt{2(n+\alpha)eB\hbar}, \alpha = 0$ for electrons in graphene, where n=0, 1, 2, …

This alternative way is based on the semiclassical Bohr-Sommerfeld quantization condition

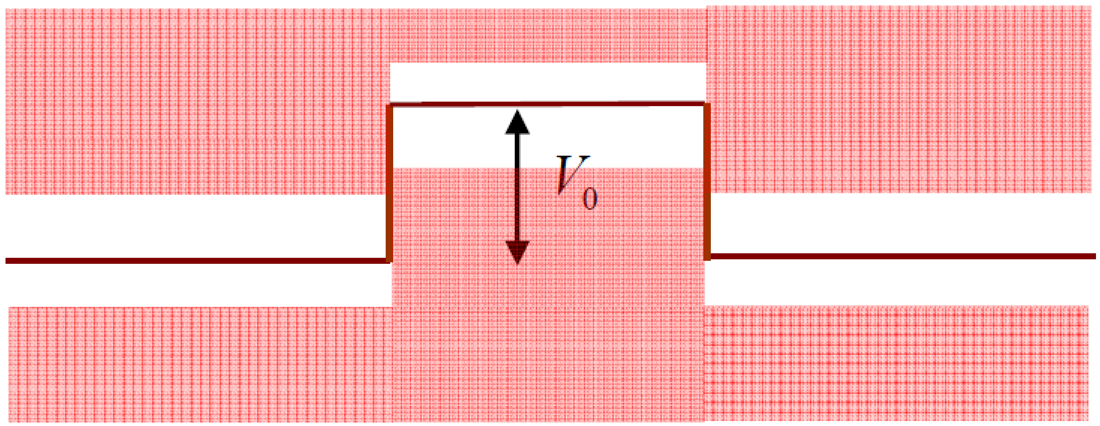
$$\hbar \oint d\mathbf{r} \cdot \mathbf{k} - e \oint d\mathbf{r} \cdot \mathbf{A} + \hbar\gamma = 2\pi\hbar(n + 1/2)$$

which includes the Berry phase Υ picked up by the electron, while it executes its (real-space) motion along the closed loop of the cyclotron orbit.

For free electrons, $\gamma = 0$, while $\gamma = \pi$ for electrons in graphene.

Electron scattering from a potential barrier

Potential complication: Klein Paradox (1929)



$$T \to 1 \text{ as } V_0 \Rightarrow m_0 c^2$$

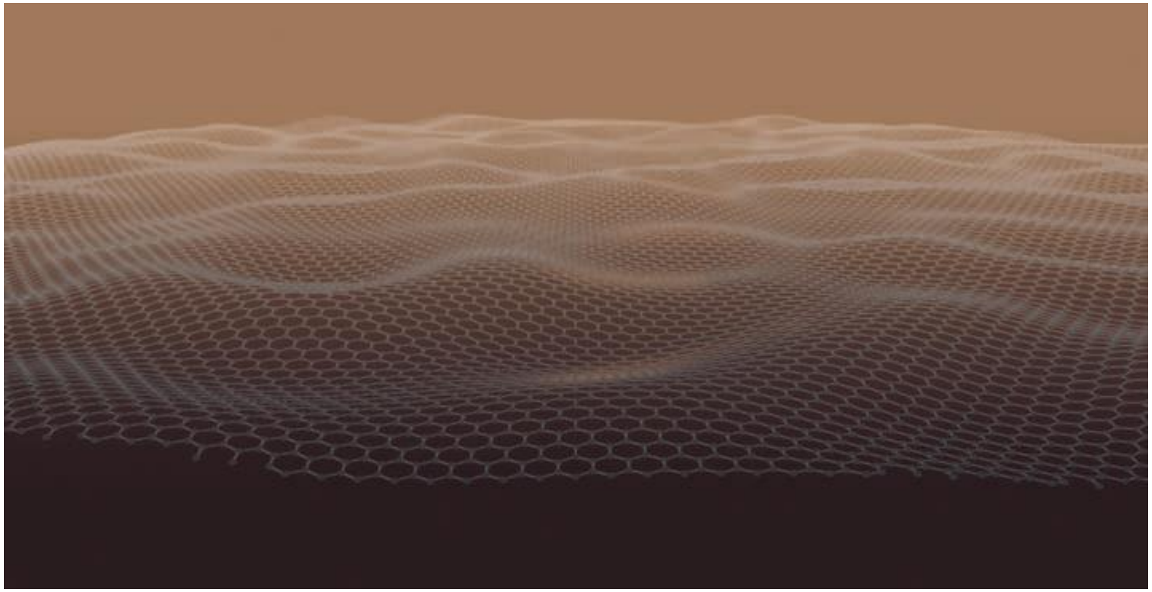
As the potential approaches infinity, the reflection diminishes, and the electron always transmits

No confinement for electrons

On/off ratio is reduced in graphene FET

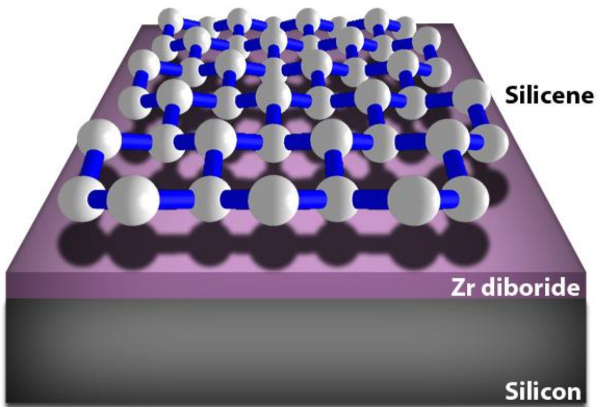
Emergent Properties of Two-Dimensional Materials

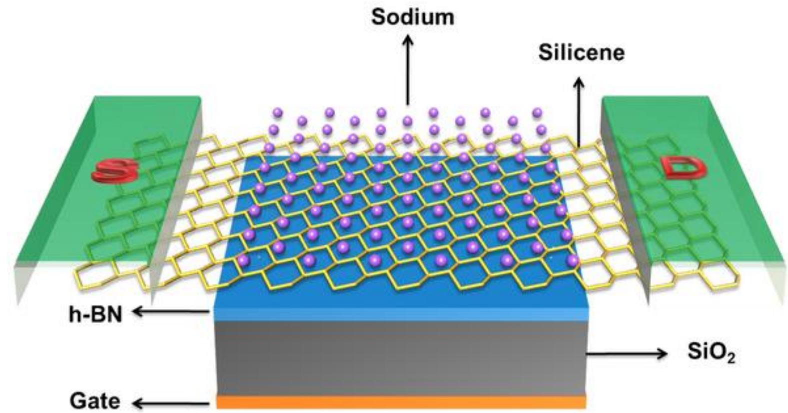
Flatlands beyond Graphene



Another emerging wonder material : Silicene

- Graphene-like two-dimensional silicon
- Could be more compatible with existing silicon-based electronics
- Potential application as a high-performance field effect transistor

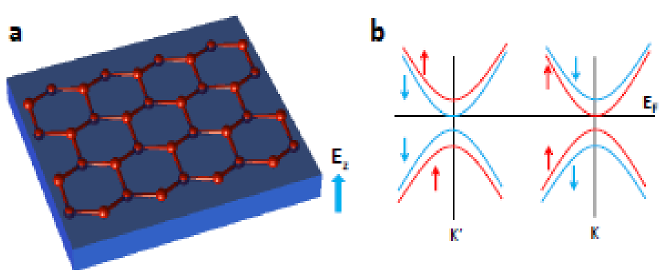


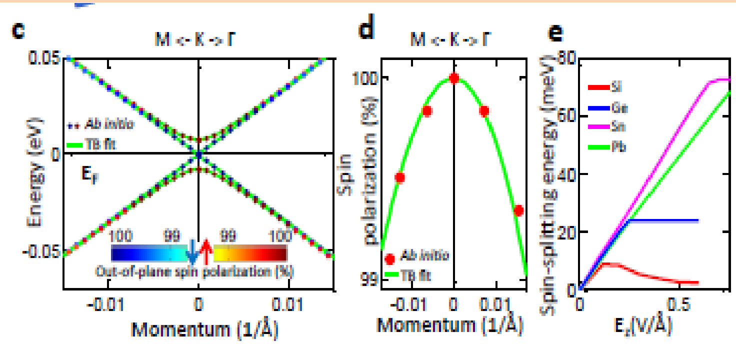


Nature, Scientific Reports **2**, # 853, 2012

To grow Silicene, Germanine, and even Tinene on insulating or semiconducting substrate.

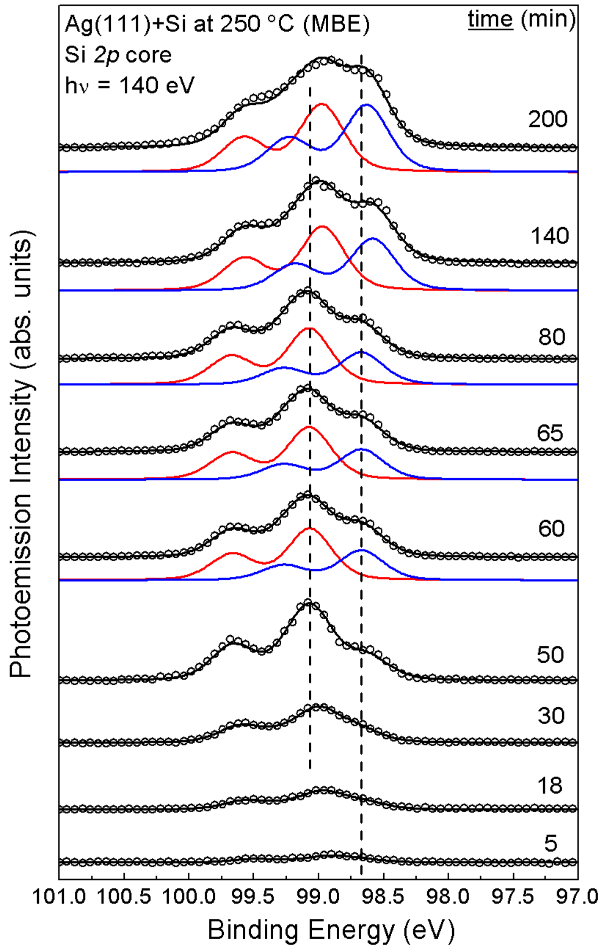
Superconductivity in alkaline or alkaline earth elements doped silicene (CaC_6 T_c = 13K; $CaSi_6$ T_c = ?)





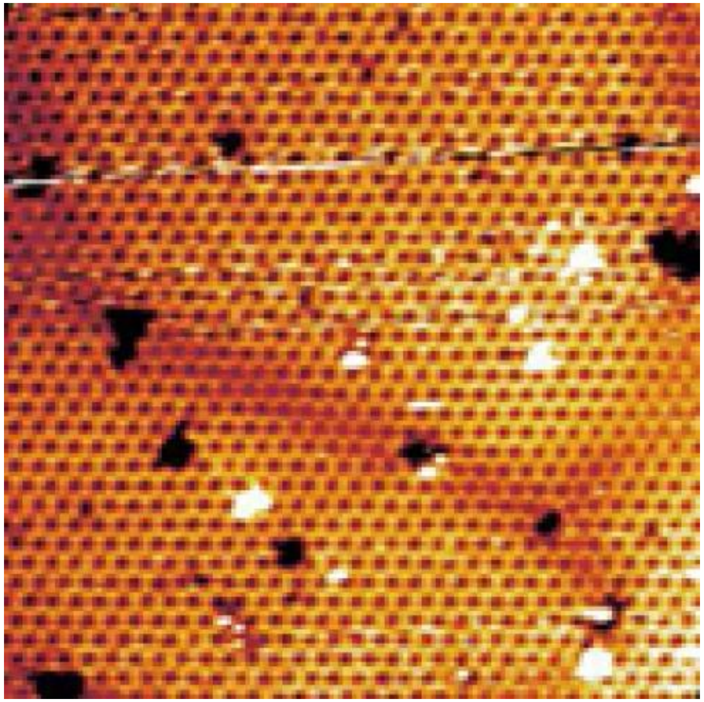
Combined spectroscopic and microscopic study underway

Synchrotron radiation core level photoemission from NSRRC



60s = 1 ML

Scanning Tunneling Microscopy

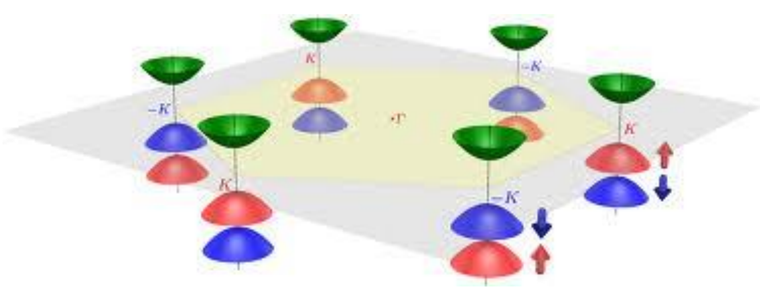


Transition Metal Dichalcogenides (TMDs)

Formula : MX_2 M (transition metals) = Mo, W, Nb, Re, Ti, Ta, etc.
X (chalcogenides) = S, Se, or Te

Semiconducting TMDs

Semi-metal: TiS_2
Charge-density-wave (CDW)
Superconductivity: i.e. MoS_2 Appl. Phys. Lett. 101, 042603 (2012);
Metal-Insulator Transition (http://arxiv.org/abs/1301.4947)
Valleytronics: involves channeling the charge carriers into "valleys" of set momentum in a controlled way.



Valleytronics

- A proposed equivalent of electronics utilizing *valleys* in the valence band or conduction band structure of some semiconductors or insulators, that possess multiple valleys, such as graphene, carbon nanotubes, bismuth, dichalcogenides.
- That is to control electric current is by using the "valley" degree of freedom of electrons. This novel concept is based on utilizing the **wave quantum number** of an electron in a crystalline material.
- In **diamond**, for instance, an electron has its minimum energy for a finite value of momentum along certain directions of high symmetry in the crystal. At low T, electrons will reside in these valleys of minimum energy.
- **The first demonstration of the generation, transport and detection of valley-polarized electrons was in bulk diamond** – a result which opens up new opportunities for quantum control in electronic devices.
- Such **valley-polarized states** have been created in 2D materials, such as graphene or molybdenum disulfide, relatively stable in diamond (~300 nanoseconds at liquid nitrogen temperature, 77 K), making it possible to manipulate them.
- Useful for information processing that the polarized electrons can be transported across macroscopic distances (0.7 mm) during the 300 ns polarization relaxation. "The electron polarization can subsequently be detected in a magnetic field by the Hall effect.

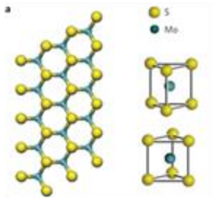
Motivation

1. Why TMDs?
   – A 2D semiconducting transition metal dichalcogenides with potential applications that could complement those of *Graphene*.
     - High on/off ratio, and moderate mobility: *electronics*
     - Direct bandgap (for monolayer): *optoelectronics*
     - *Valleytronics*
   – *Large area vapor phase growth accessible (so far MoS_2)*

2. Bandgap Engineering
   - Layer numbers (quantum confinement)
   - Strain
   - Temperature

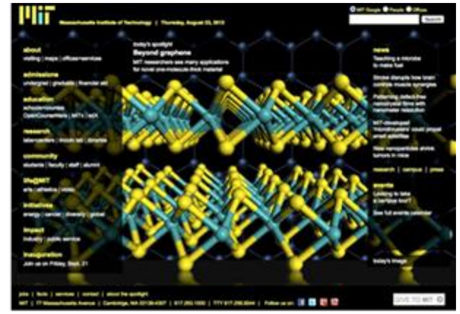
   --Potentially leading to many optoelectronics applications.

Introduction: TMDc Monolayer

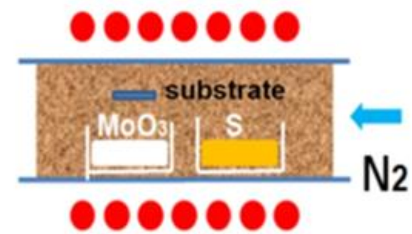


MoS_2 transistor
A. Kis, Nat Nano (2011)

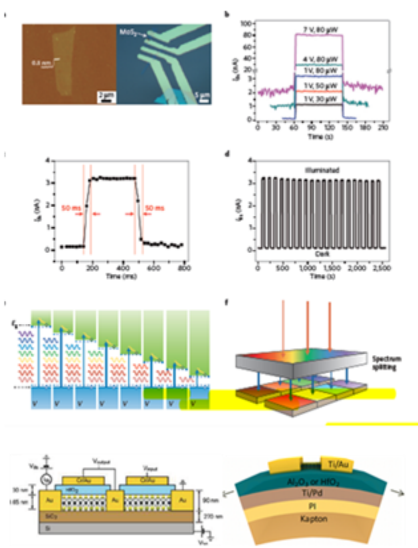
MoS_2 circuit
H Wang, YHLee
MIT Highlighted
Aug. 23, 2012



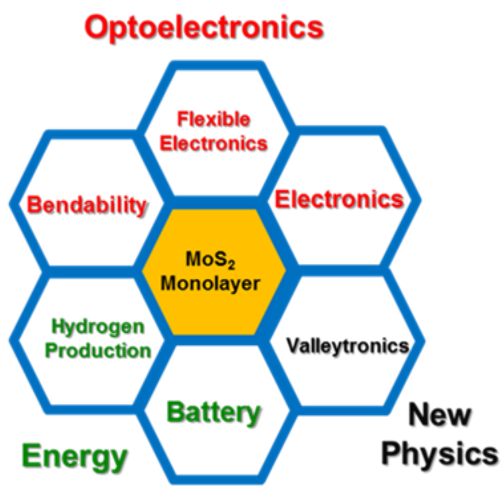
Y.H. **Lee** et al,
Adv Mater, 24, p2320 (2012)
Citation: 145



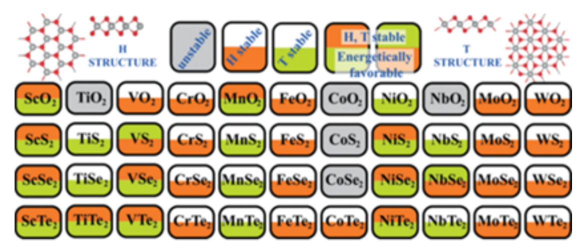
Flexible optoelectronics



QH **Wang** et al,
Nat. Nano, 7, p699 (2012)



Low power consumption
Good SS:
High on/off ratio 10^6~10^8
Enough Mobility: 1~100
Excellent Bendability



Ref: C. Ataca et al, JPCC, 116, p8983 (2012)

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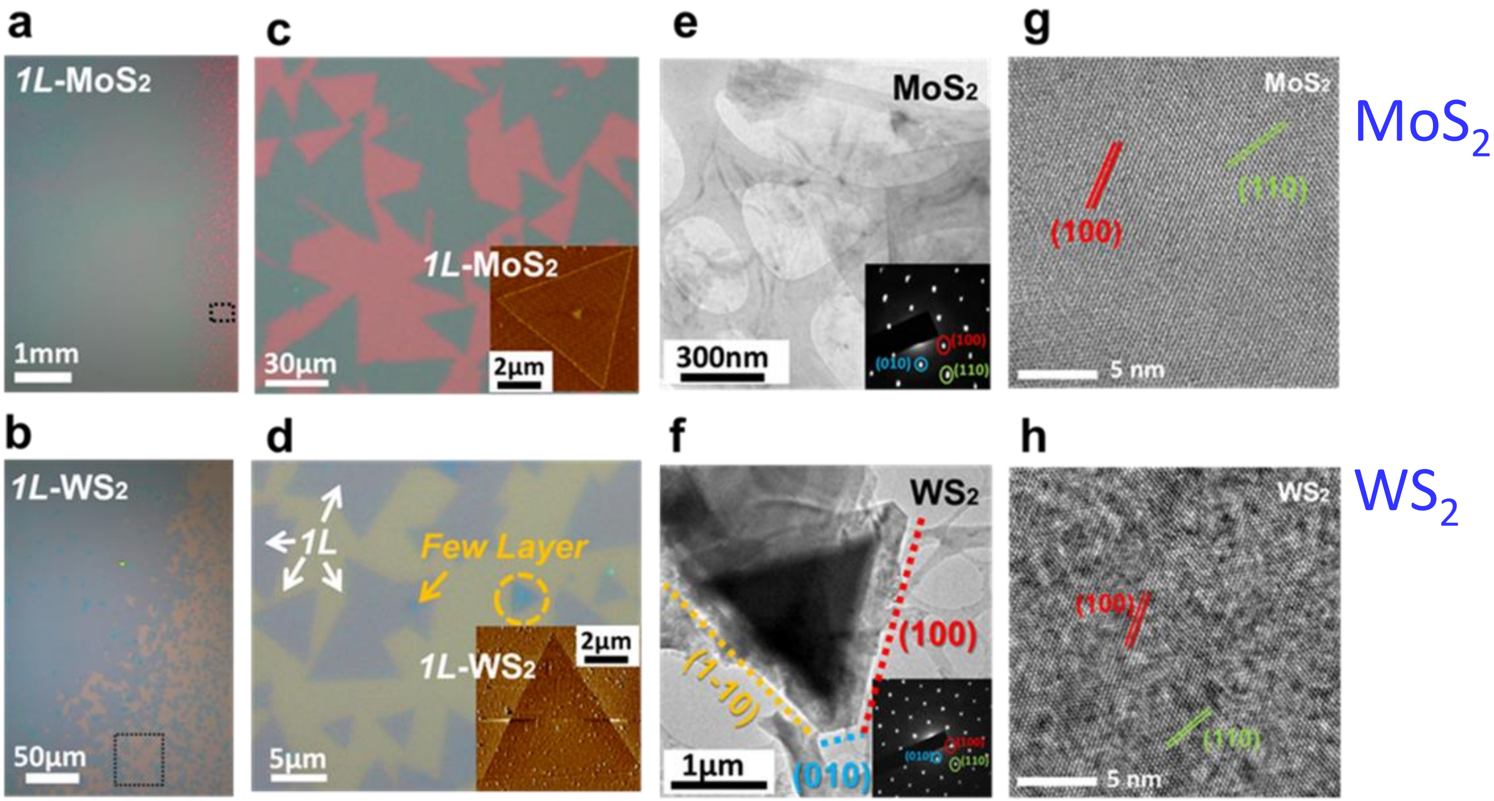
Synthesis: the thinnest semiconductors, TMD Monolayer

- **Scalable,**
- **Single Crystal**
- **Thinnest semiconductors**



Synthesis of Single Layer Transition Metal Disulfides on Diverse Surfaces

YHLee et. al., ***Nano Lett***. 13, 1852–1857 (2013)

YHLee et. al, ***Adv. Mater***. 24, 2320-2325 (2012)

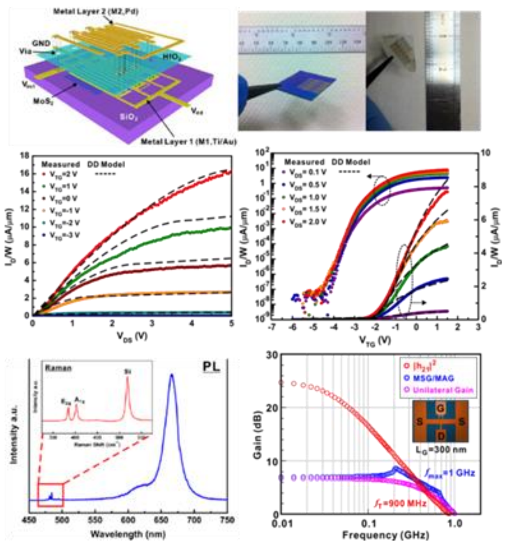
Applications: Electronics

The thinnest transistor, surpassing Si

Large-scale CVD-MoS_2 Monolayer Devices:

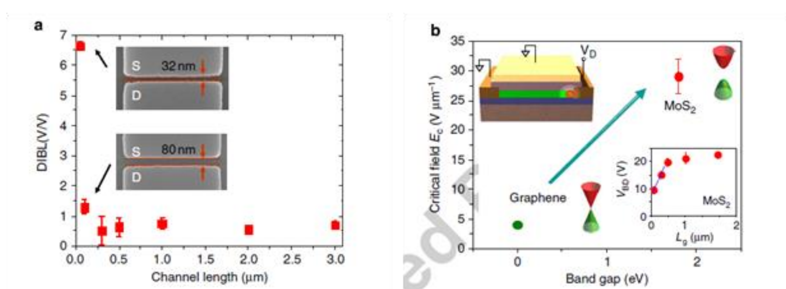
H. Wang, L. Yu, YH Lee et. al., ***IEDM Tech. Digest***, 2012

-the best paper award in IEDM 2012



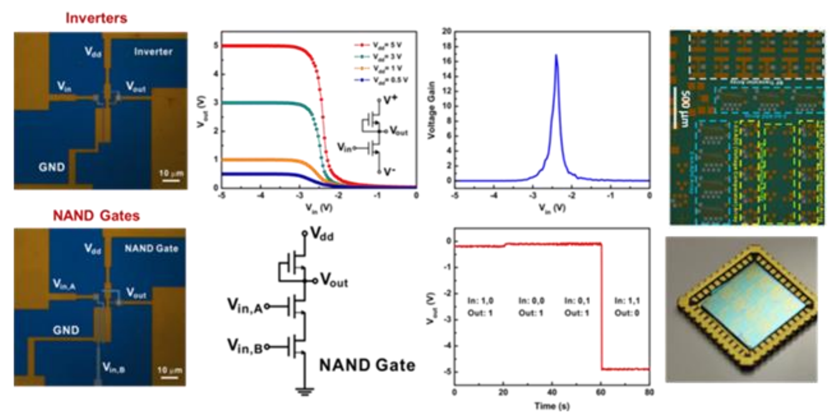
Electronic transport of CVD-MoS_2 Monolayer

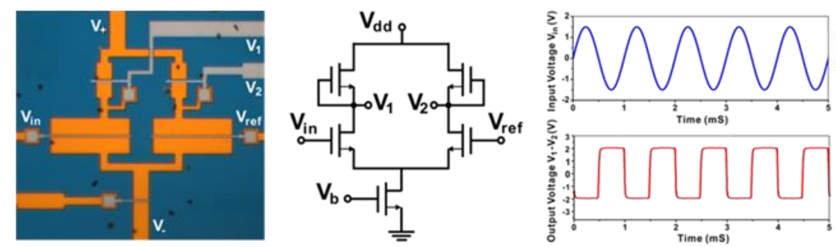
W. Zhu, and YH Lee et. al., **Nat. Comm.** 5,3087 (2014)

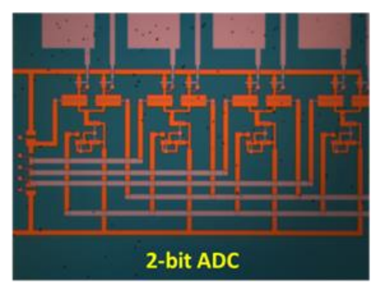


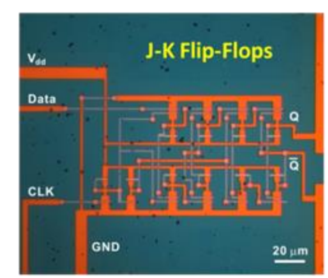
CVD-MoS_2 Monolayer Mixed-signal Circuits

H. Wang, YHLee et. al., (in-preparation)









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Field-Effect Mobility

Monolayer MoS_2

- Room temperature mobility
- Back-gated silicon oxide : **0.1 - 50** $cm^2/V.s$
  SS: $1 cm^2/V.s$
- Dual gate (SiO_2+HfO_2): **15** cm^2/V sec
  Correction: Nat. Nanotechnol **8**, 147 (2013)
  Original : Nat. Nanotechnol **6**, 147 (2011)
- On/off ratio: 10^8

Multilayer MoS_2

- Back-gated Al_2O_3: **100** $cm^2/V.s$
- multilayer MoS_2: 30nm
- On/off ratio: 10^6
  Nature Communications, **3**, 1011 (2012)
- On PMMA: $470 cm^2/V.s$(electrons)
  $480 cm^2/V.s$(holes)
  APL, **102**(4), 042104 (2013)

- Graphene
- Silicene, Germanene, Tinene…..
- Transition Metal Dichalcogenides (TMDs)
- Topological Insulators
- Beyond…..