# New direction in science and technology: two-dimensional crystals

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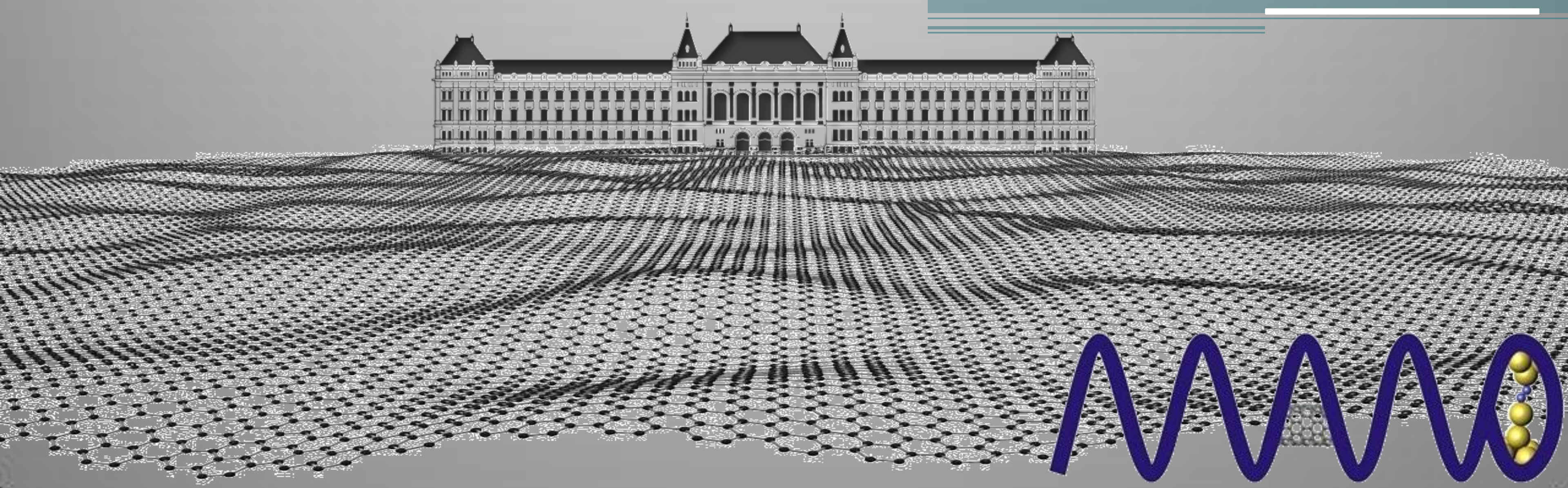

# Graphene

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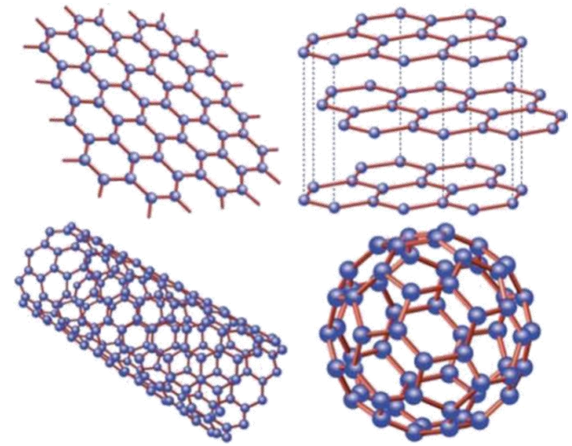


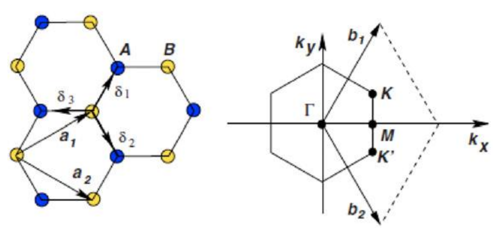
**A H Castro Neto[1,3] and K Novoselov[2]**

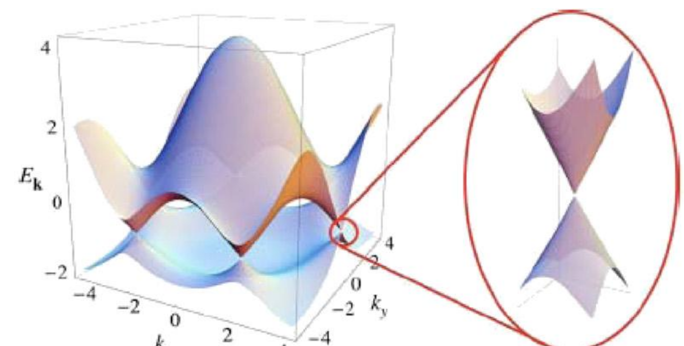
[1] Graphene Research Centre, National University of Singapore, 2 Science Drive 3, Singapore 117542, Singapore

[2] School of Physics and Astronomy, University of Manchester, Oxford Road, Manchester, M13 9PL, UK

## Graphene:

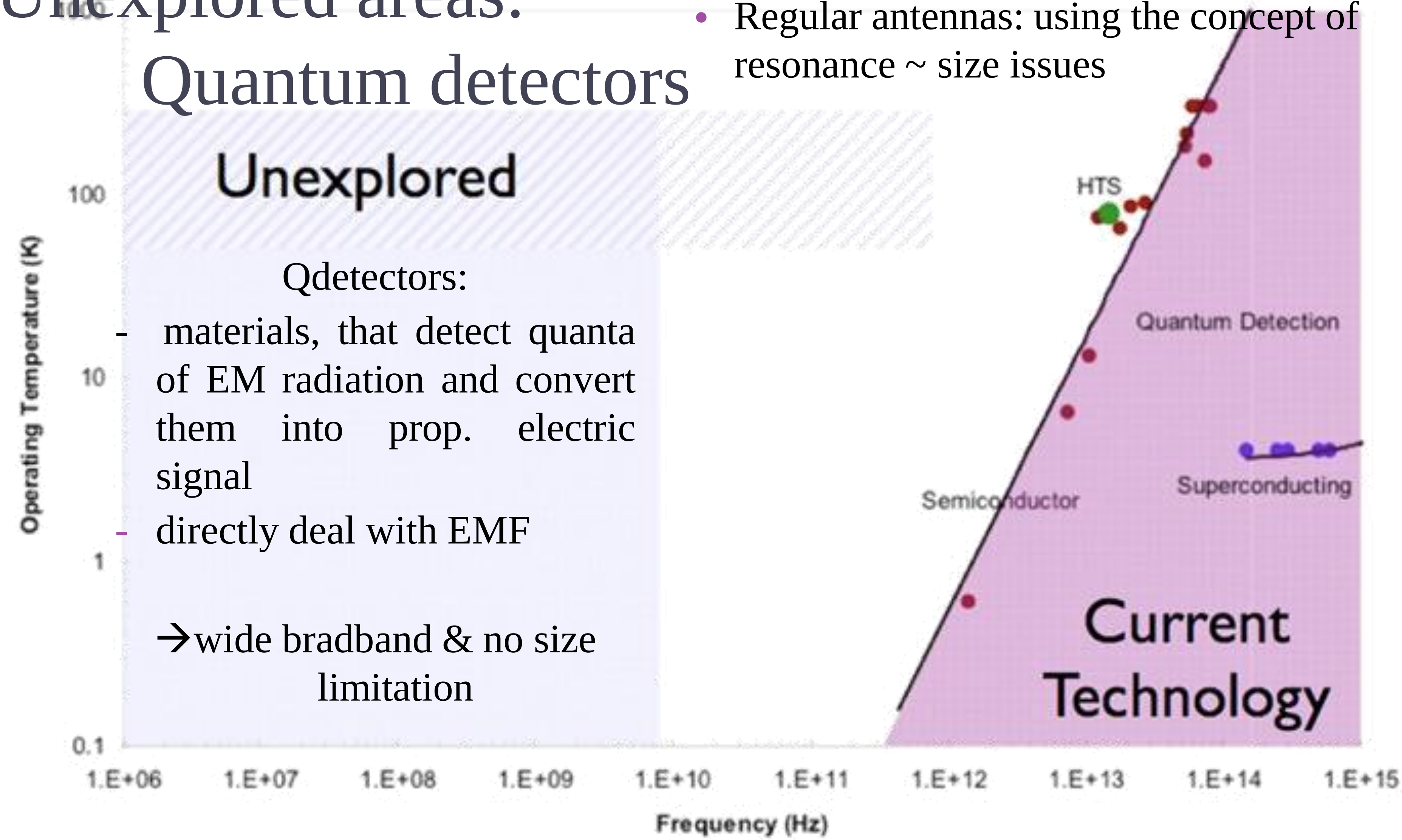
- founded 2004-2005, rapid evolution, (graphite, fullerenes, CNT), NP-2010 →application 2013?
- fabrication: exfoliation, SiC-, CVD growth ($\eta$>5000cm$^2$/Vs) →mass production
- extraordinary properties



# Unexplored areas: Quantum detectors

- Regular antennas: using the concept of resonance ~ size issues




Qdetectors:

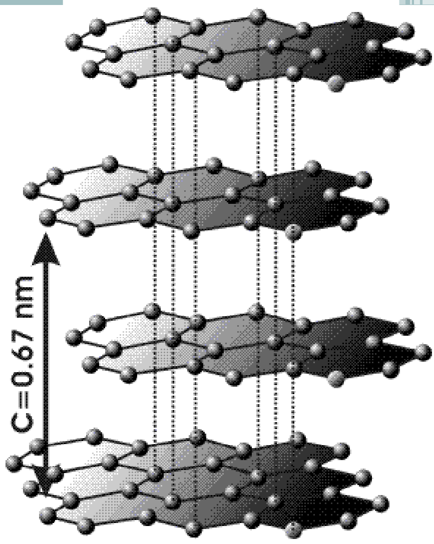
- materials, that detect quanta of EM radiation and convert them into prop. electric signal
- directly deal with EMF

→wide bradband & no size limitation

- huge demand for operating Qdetectors operating @ low frequencies and high (gapless spectrum, large electronical mean free path, high mobility)

[1] de Andrade M C 2011 SPARWAR Systems Center Pacific,CERF Lab. private communication

# Outlook




- Graphene literature explode was its extraction from 3D graphite…

... enormous number of layered materials!!!

→Layered, weak interaction between them, no idea how they act when layers are decoupled

→They present correlated e- states where charge, spin, orbital, valley, lattice etc. play an important role

- High-Tc – $CuO_2$ planes – SC???
- CDW
- $MoS_2$
- Layered manganites, layered titanates, layered cobaltates
- Site exchanges – C ←→BN , molecular doping
- BN

# High-$T_c$ – $CuO_2$ planes

• weakly coupled $CuO_2$ layers – exotic electronic properties!!!

→3D coupling serves to stabilze l.r. magnetic and SC order

→essential features come from 2D $CuO_2$ layers

COMMENTARY

What DO we know about high $T_c$? [2]

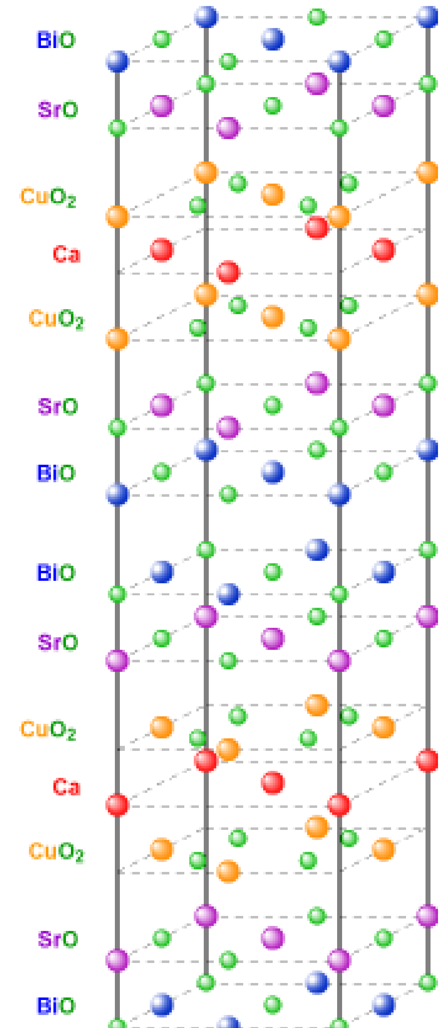
ANTHONY J. LEGGETT

is in the Department of Physics and Center for Advanced Study, University of Illinois at Urbana–Champaign, Urbana, Illinois 61801–3080, USA.

1. SC is a result of CP formation: evidence: flux quantzation, Josephson- effect

   →G-L theory for electric properties
2. $CuO_2$ layer
3. These layers are weakly coupled

   →Lawrence-Doniach model
4. No net saving of ionic kinetic energy by CP formation
5. Spin-singlet state (NMR, spin-lattice relaxation meas.)
6. ...




BSCCO "bisko”

$Bi_2 Sr_2 Ca_{n-1} Cu_n O_{2n+4+x}$

[2] *Nature Phys.* **2 134**

# High-$T_c$ – $CuO_2$ planes

• weakly coupled $CuO_2$ layers – exotic electronic properties!!!

→No signs of SC, not even SC fluctuations (Kosterlitz-Thouless)[3]

→exafoliation is too abrasive, defects induced

→present of the substrate, no SC fluctuations (no imprive since QHE in mobilty, e-h puddles ~ Dirac point)

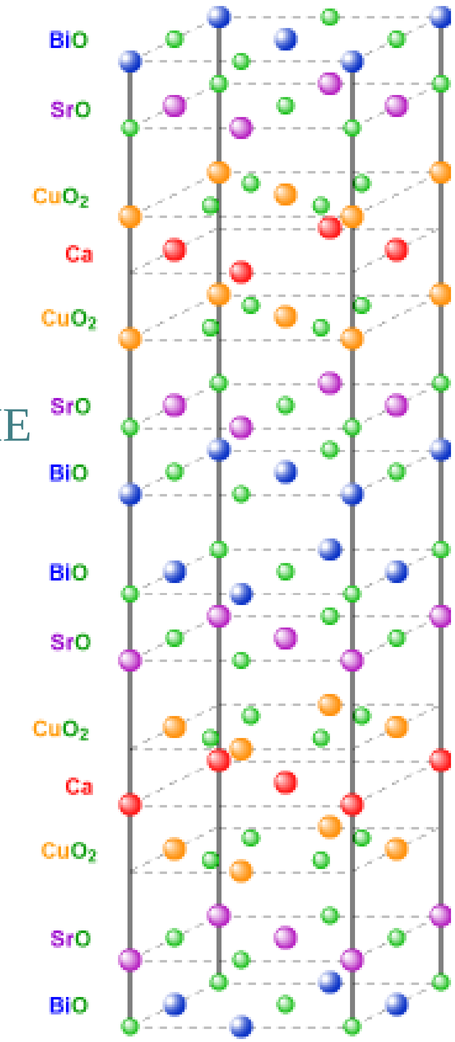
→Recover SC by using other substrate

Boron-nitride (BN)!!![4]

**BN is already use to recover the graphene's intrinsic electronic properties**

Haven't tried yet!

Is the 3D ature of the material is fundamental for SC?

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[3] *J. Phys.C: Solid State Phys.* **6 1181,** [4] *Nature Nanotechnol.* **5** 722

# Graphene – BN substrate

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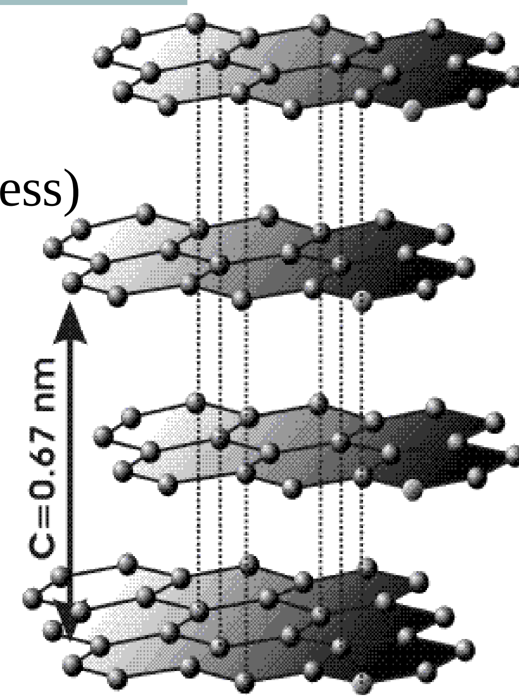




LETTERS
PUBLISHED ONLINE: 22 AUGUST 2010 | DOI: 10.1038/NNANO.2010.172
nature nanotechnology

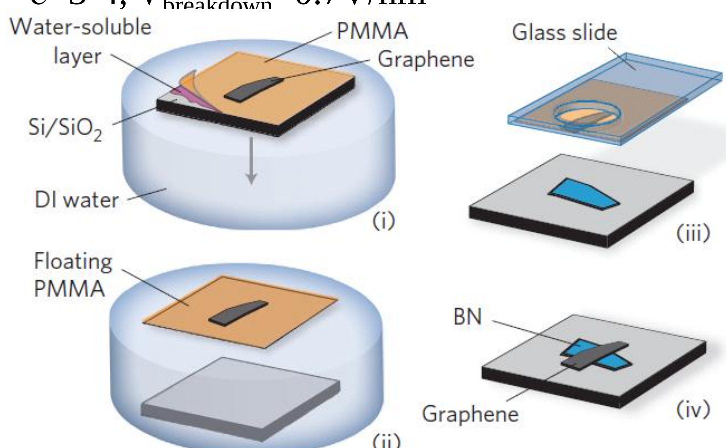
**Boron nitride substrates for high-quality graphene electronics**

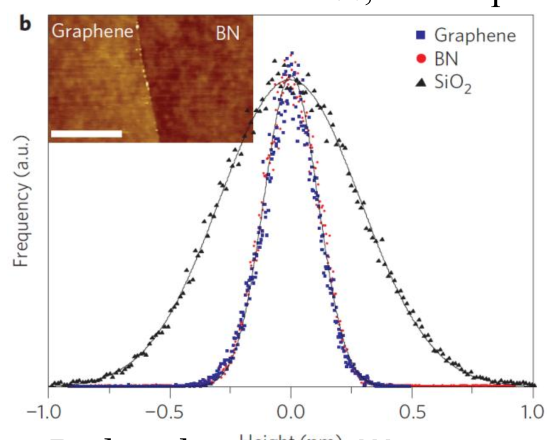
C. R. Dean[1,2*], A. F. Young[3], I. Meric[1], C. Lee[4,5], L. Wang[2], S. Sorgenfrei[1], K. Watanabe[6], T. Taniguchi[6], P. Kim[3], K. L. Shepard[1] and J. Hone[2*]

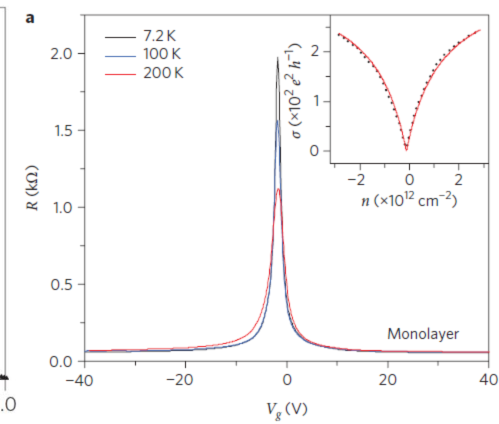
[4]

**→Hexagonal boron-nitride (h-BN):**

- atomically smooth
- free of dangling bonds and trapped charges, inert
- insulator w/ large electrical band gap (~5.97eV)
- similar hexagonal lattice like graphene's @ small lattice mismatch ~1.7%, and surpressed rippling
- €=3-4, $V_{breakdown}$=0.7V/nm




Reduced scattering!!!

$\mu_C$~60 000 $cm^2/Vs$ ←three times bigger seen on $SiO_2$

[4] *Nature Nanotechnol.* **5 722**

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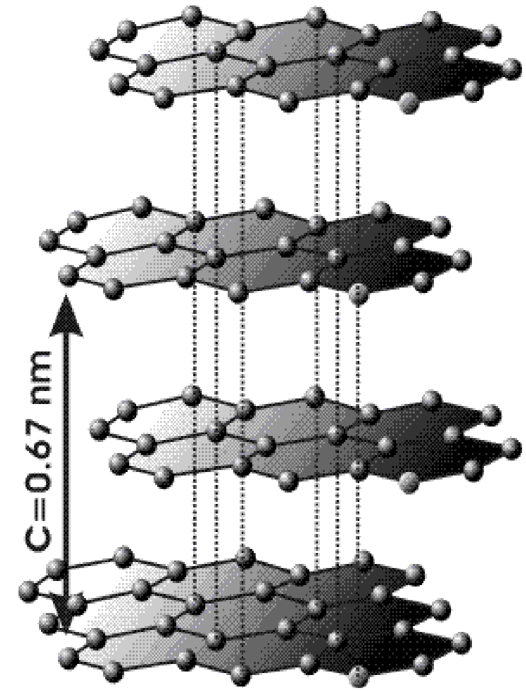


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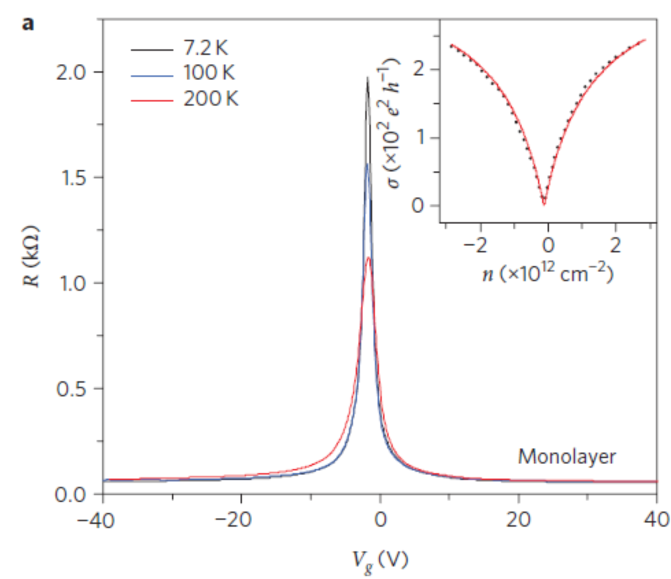
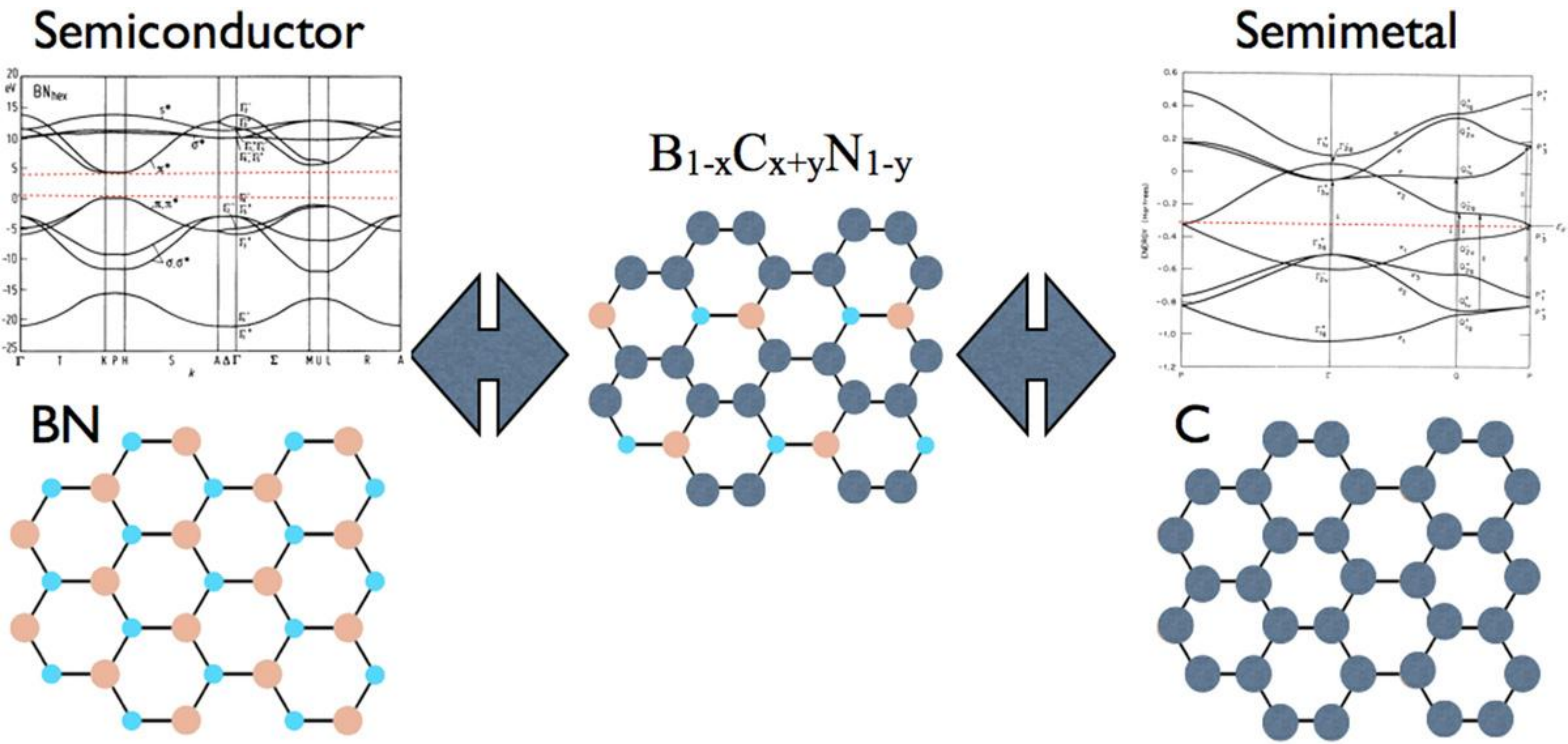
→ Using suspended graphene ~70 000 cm²/Vs [4-2]




[4] *Nature Nanotechnol.* **5 722 ,** [4-2] J. Appl. Phys. **109, 093702 (2011)**

# Incorporating C in BN

- similar hexagonal lattice like graphene's @ small lattice mismatch ~1.7%

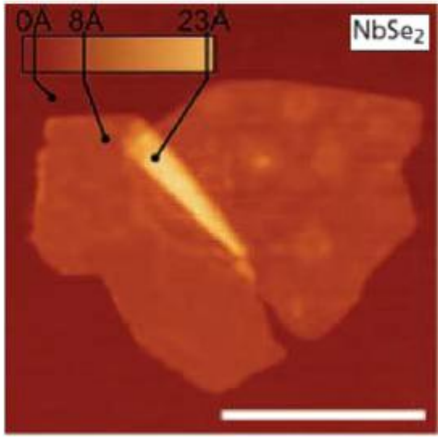



→ stoichiometric compounds $B_{1-x}C_{x+y}N_{1-y}$ semiconductor→semimetal
→ band gap engineering[5]

[5] *Mater. Res. Bull.* **22 399**

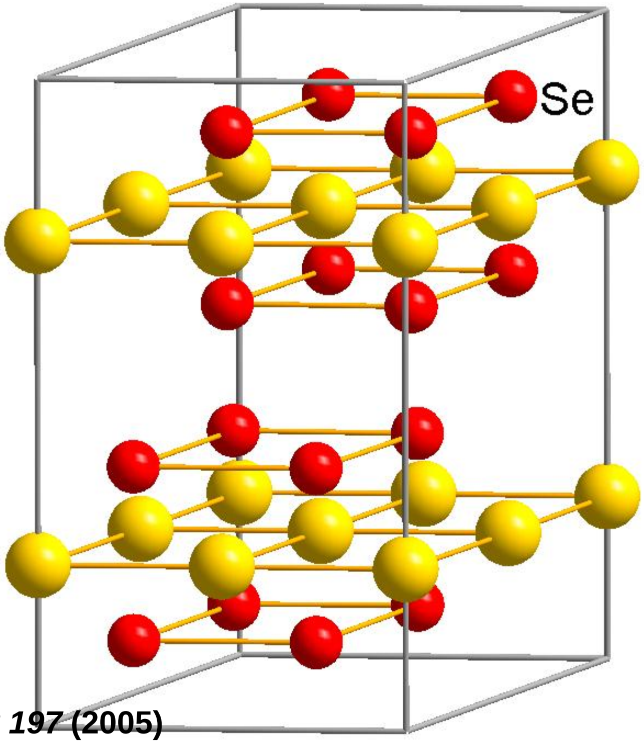
# Charge density waves (CDW)

- modulation of the charge density via $e^-$-$e^-$ $e^-$-ph [6]




→i.e.: transition metal dichalcogenides (TDM): $NbSe_2$, $TaSe_2$, $NbS_2$ or $TaS_2$

- these are also layered materials
- anisotropic physical properties (resistivity, thermal expansion, etc...)
- phenomenological description (McMillan) [7]
  - → CDW @ high T
  - → accompanied SC phase @ low T

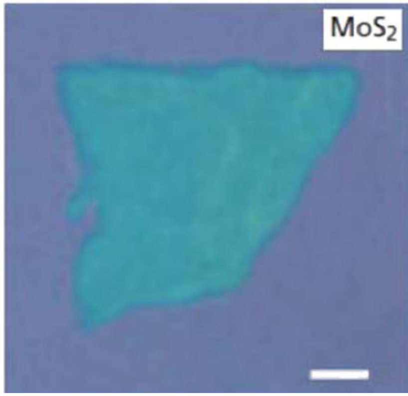



Competition of CDW and SC phase!!!

→No experimental evidence of SC or CDW in these devices [8] → ???

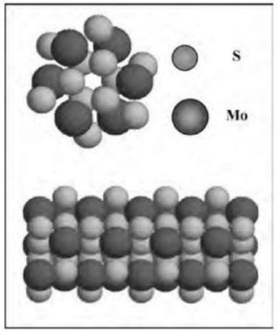
[6]*Phys. Rev. Lett.* **86 4382 (2001),** *[7] Phys. Rev. B.* **12, 1187 (1975),** *[8] Nature* ***438 197*** **(2005)**

# $MoS_2$ FET



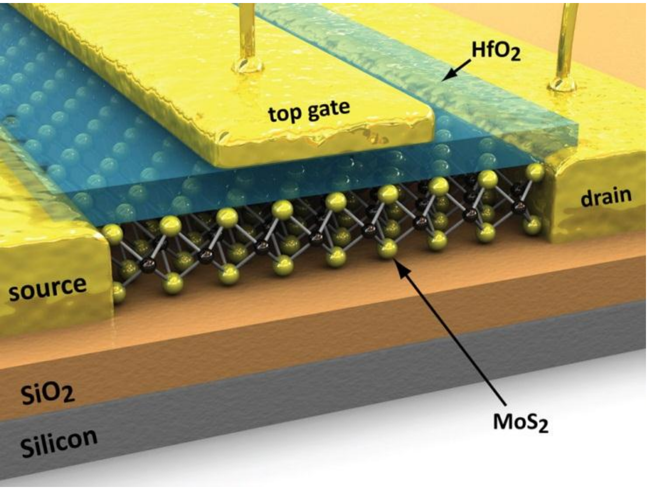

→ $MoS_2$ is also a dichalcogenides[9]

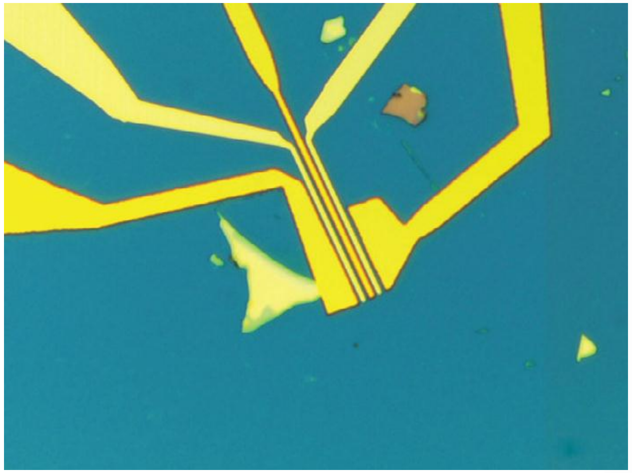
- layered material
- insulator, gap ~1.8-2eV
- low mobility: bulk~200cm$^2$/Vs, layered~0.1-10cm$^2$/Vs
- absence of dangling bonds
- thermal stability up to ~1100°C

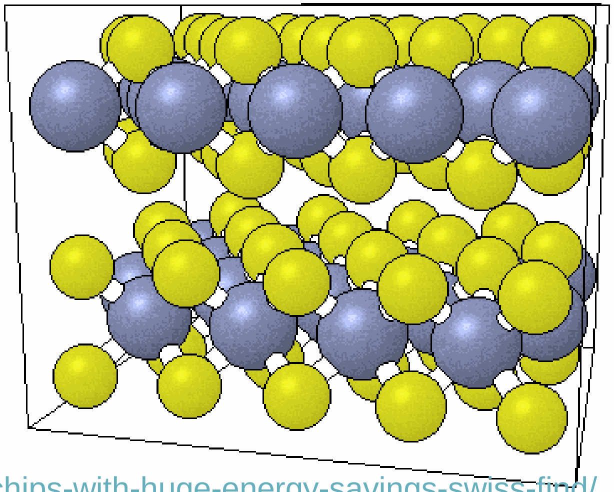



→potential replasement of silicon in CMOS-like logic devices

* induced gap in graphene <400meV (conf., stress, perpendicular electric field by BLG ~100V + μ reduction)





[9] *Nature Nanotechnol.* ***6* 147,** http://genevalunch.com/blog/2011/01/30/mos2-offers-tiny-chips-with-huge-energy-savings-swiss-find/

# $MoS_2$ FET

- →$MoS_2$ is also a dichalcogenides[]
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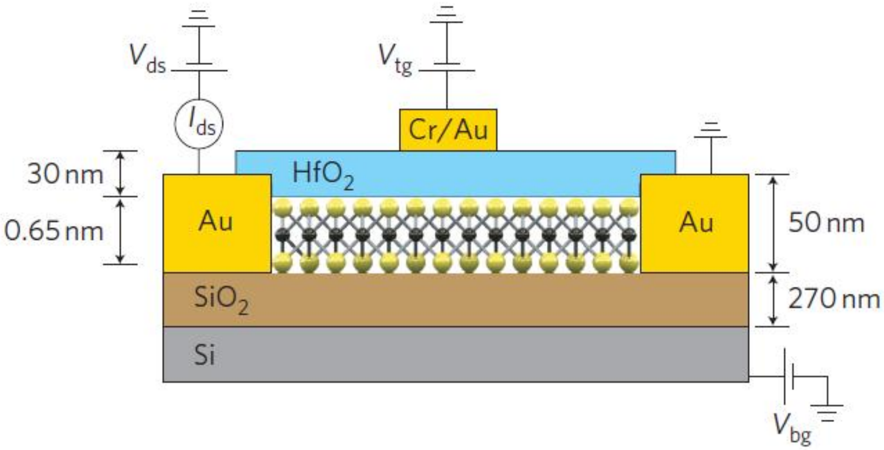
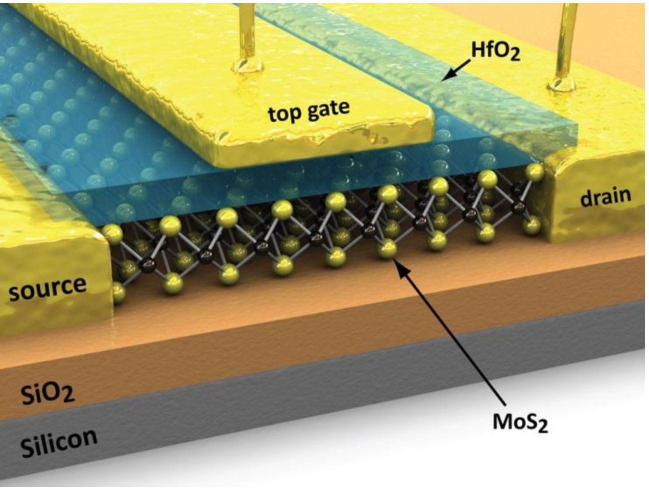
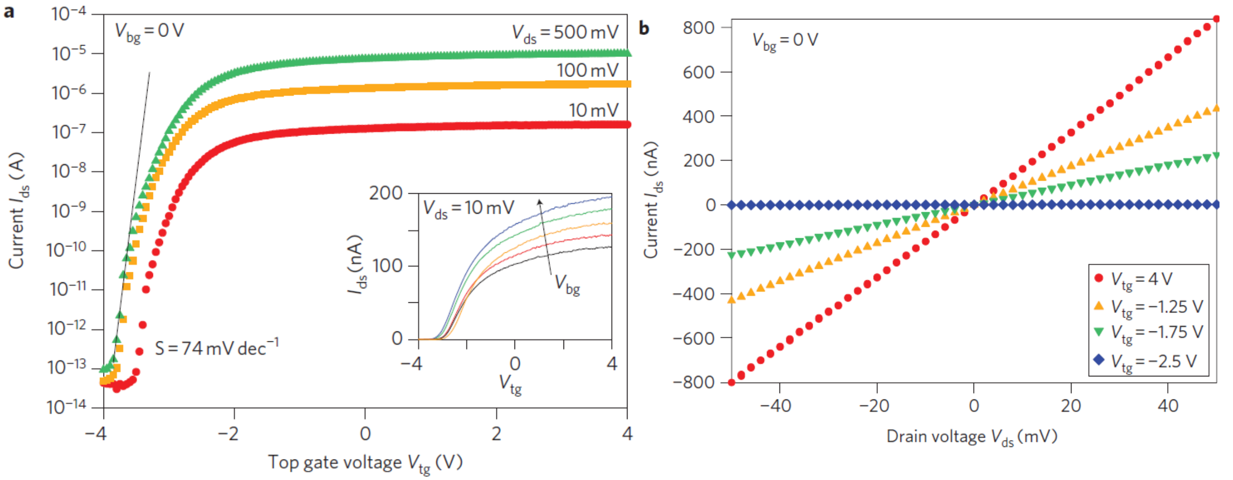



- →FET, 2D layer $MoS_2$ (thickness 6.5A), $HfO_2$ as insulator, on-off ratio: $1x10^8$, mobilty ~200cm²/Vs
- →Improve: BN substrate, increased mobilty by intercalated Li (3D→2D??)




[9] *Nature Nanotechnol.* **6 147**, http://genevalunch.com/blog/2011/01/30/mos2-offers-tiny-chips-with-huge-energy-savings-swiss-find/

# Other materials & methods:

+

- layered magnetites (magnetic, shows CMR and MIT) – $La_{1-x}$Sr1+xMn(2)O4(7)
- layered titanates (strong photoelecttric effects) – $Na_2Ti_3O_7$
- layered cobaltates (magnetic, charge ordering) – $NaCoO_2$

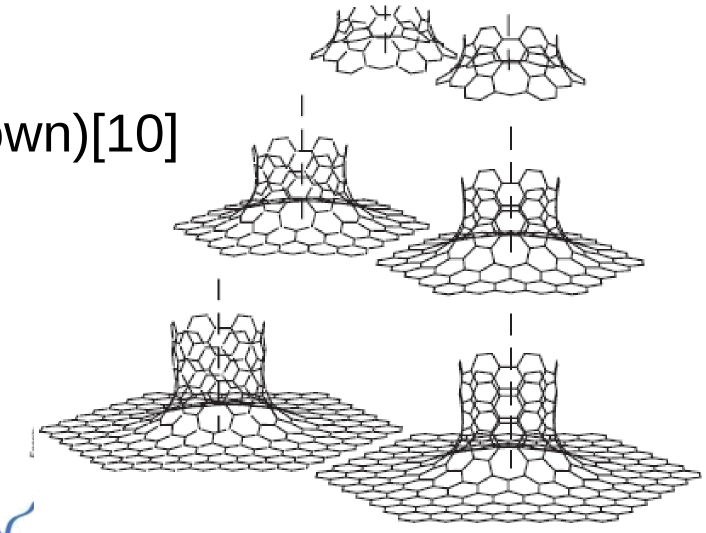
→ All these materials present correlated e- states where charge, spin, orbital, valley, lattice etc. play an important role

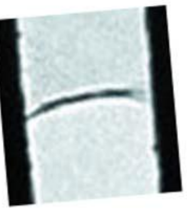
→ Layered, weak interaction between them, no idea how they act when layers are decoupled

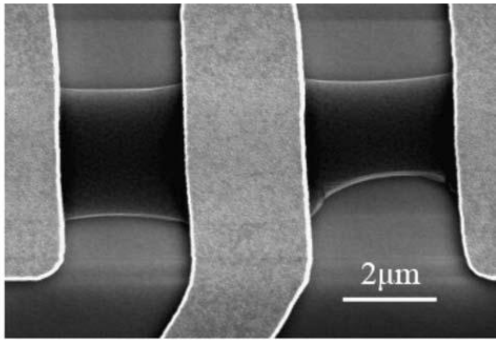
- different growth methods (dynamics unkown)
- origami technic – 3D engineering
- strain engineering
- chemical or molecular doping

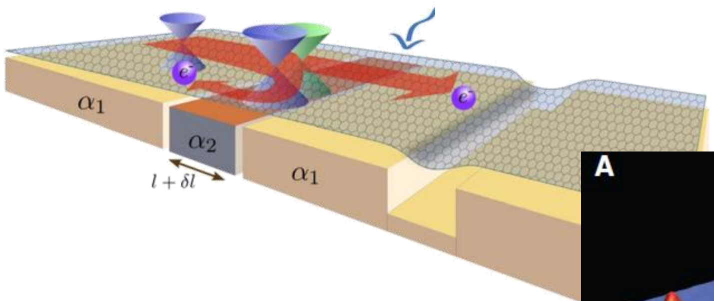
# Other materials & methods:

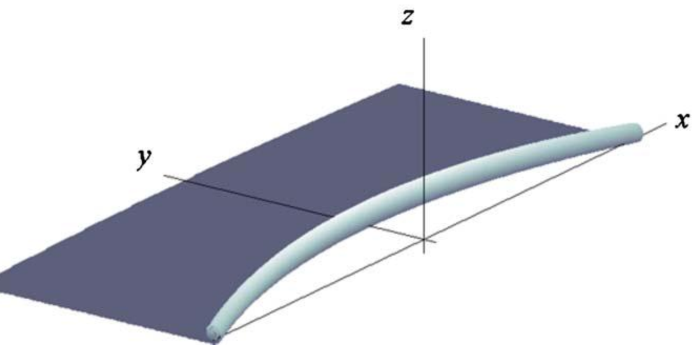
- different growth methods (dynamics unkown)[10]
- chemical or molecular doping
- origami technic – 3D engineering[11]
- strain engineering[12][13][14]

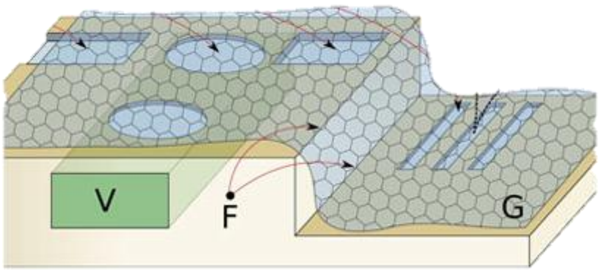


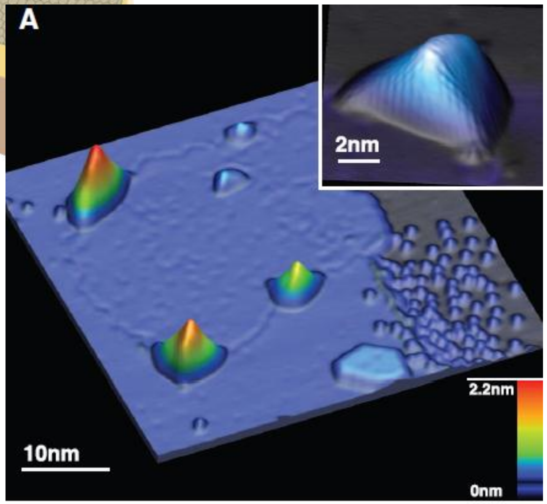





*[10] Nature* **350** 322 , [11] *Phys. Rev.* B **81, 161408**, *[12] J. Phys. Soc. Japan* **71 2765**, *[13] Science* **30 544**, [14] *Phys. Rev.* B **80 045401**

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