Nano-carbon structures for electronic applications?

1st Ireland SummerSchool 2011

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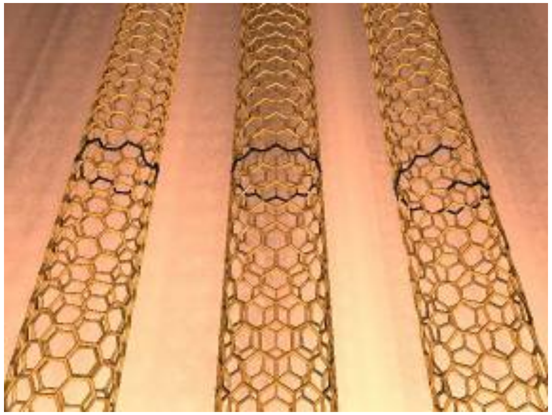
(CRANN)

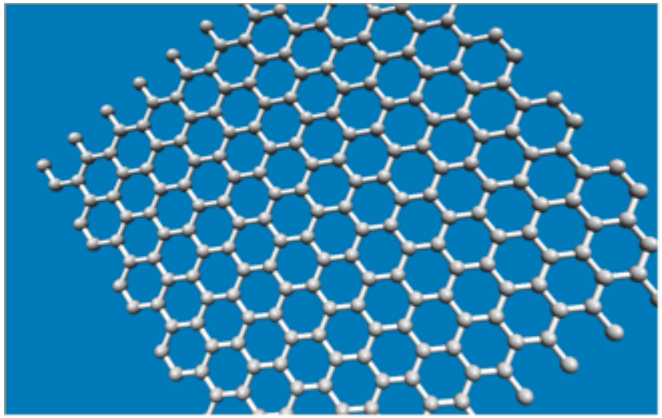
Outline

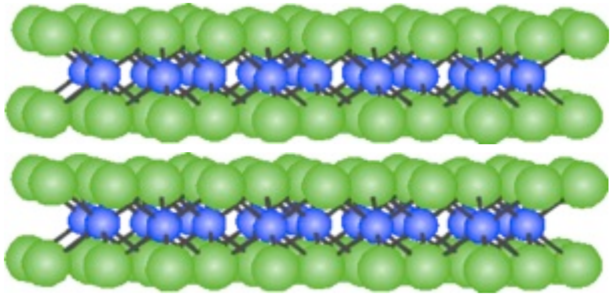
- Carbon Nano-structures: Applications in microelectronics
- Vertical Carbon devices
- Graphene Processing
- Other 2D Materials
- Carbon NEMS?
- Conclusions

Graphene and Nanotubes – Unique Properties

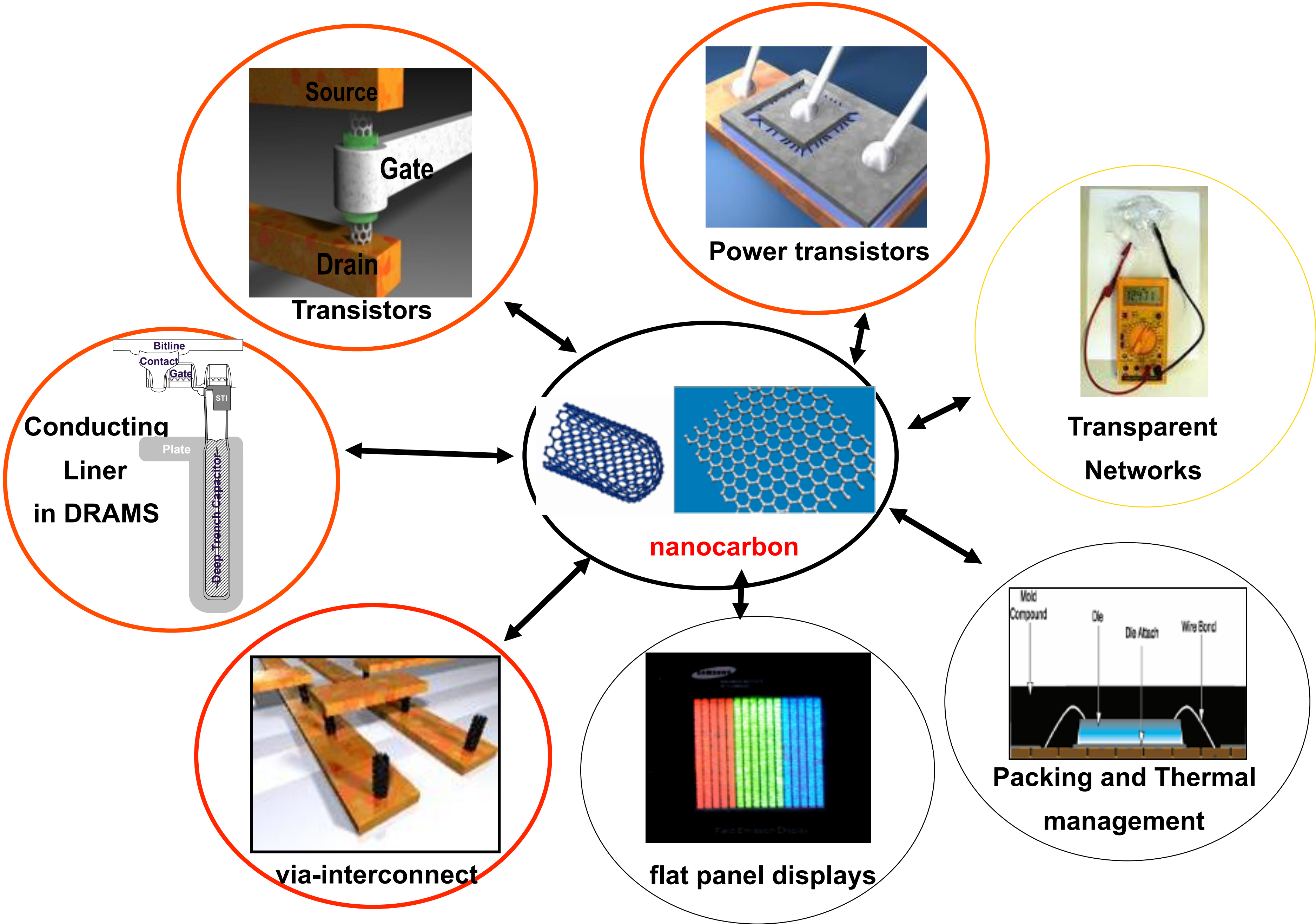
- High Mobilities – Ballistic conductance, massless Dirac fermions in graphene
- High Thermal Conductivity
- Room Temperature Quantum Effects
- Tuneable Band Gaps
- High surface area
- Chemically inert
- Mechanically stable



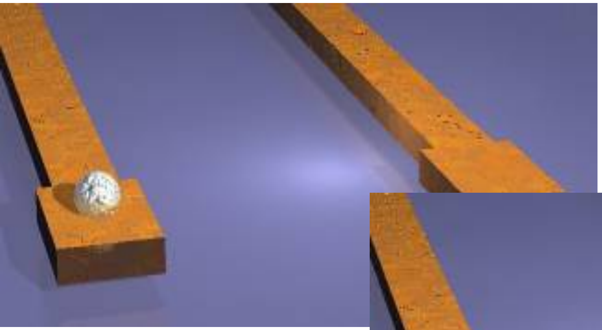




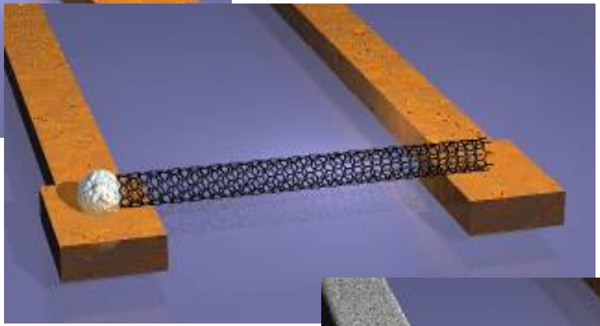
Potential Applications for Carbon Nanostructures in electronics



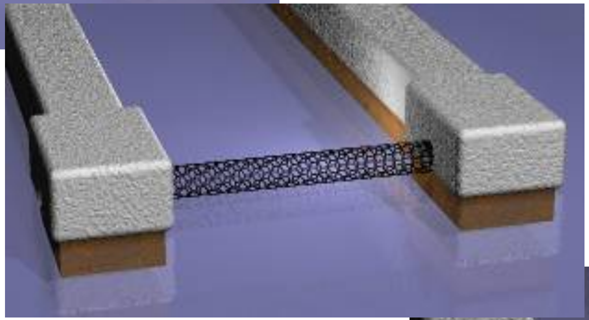
Lateral CNTFETs – process flow



Structure metal contacts and Catalyst on wafer scale

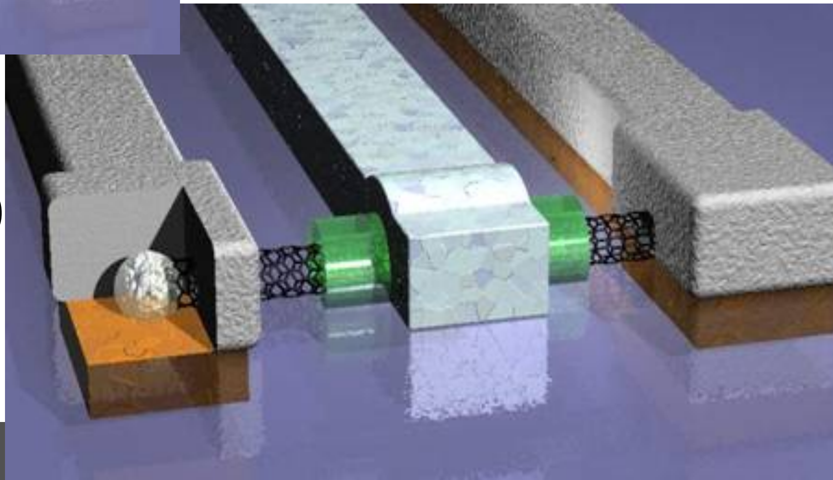


Deposition by drop casting or CVD – random process!

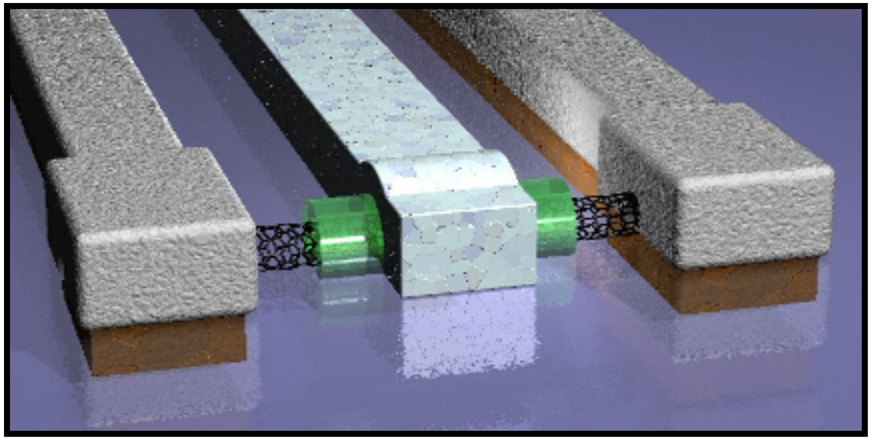


Encapsulate CNT and Contact by electroless deposition

Apply Dielectric (Dip Coat Process!) and Top Gate (E-beam lithography)



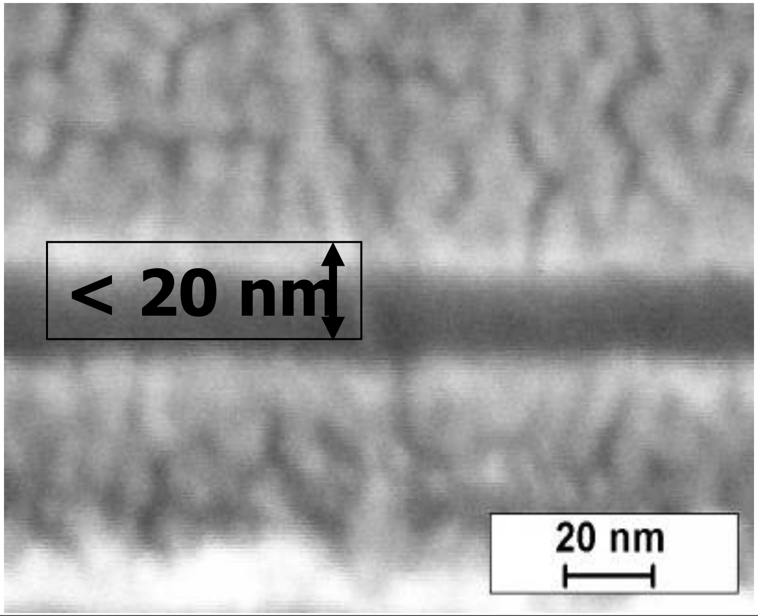
Performance of Carbon Nanotube as Transistors

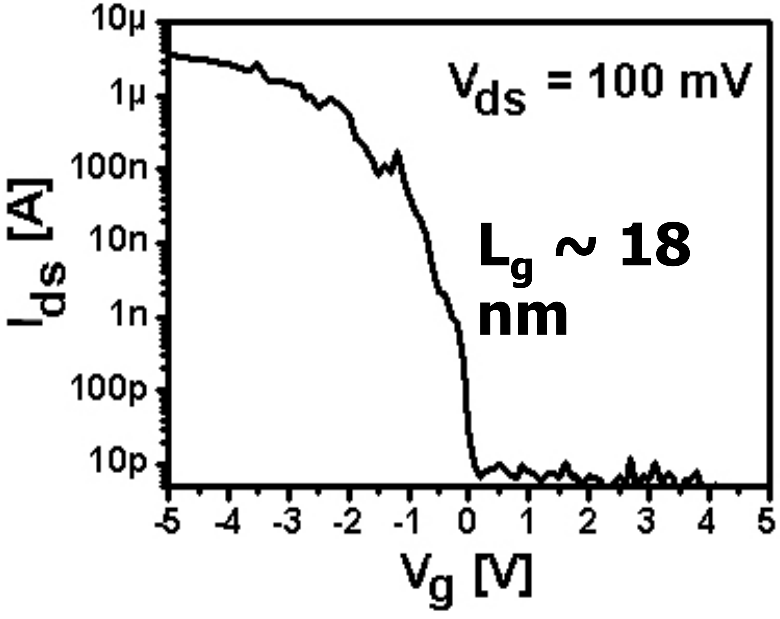


⇒ Works at channels shorter 20 nm! Ballistic regime

⇒ Ultra high currents can be switched (I_{on} > 10 μA/tube)

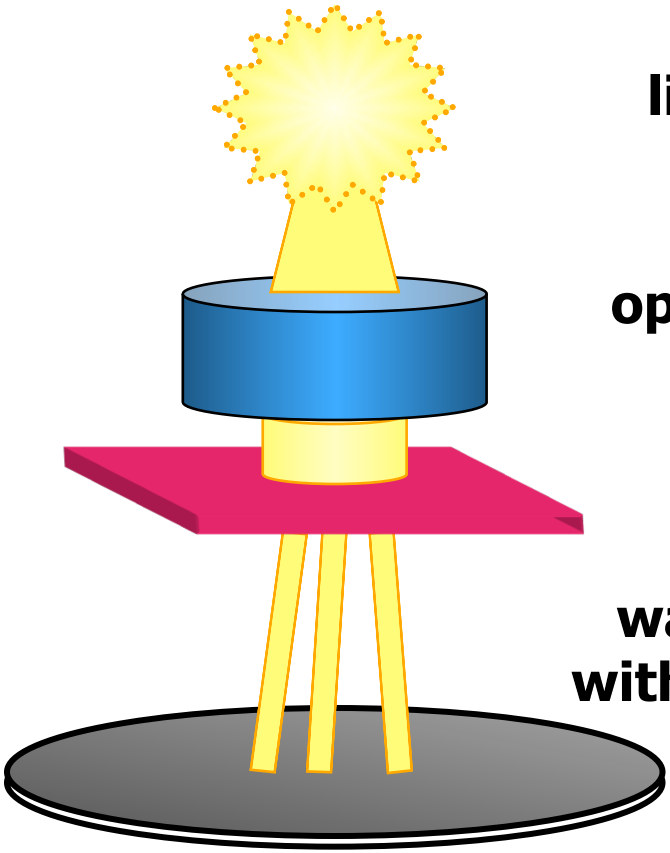
⇒ On/off ratio > 10^5



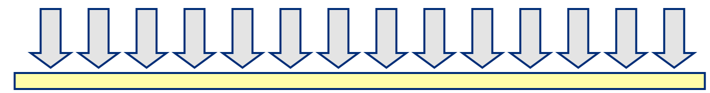


Seidel, Duesberg et al.: Nano Letters, 2004

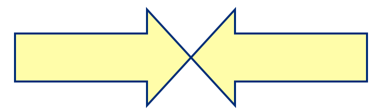
Power of silicon processing and lithography



Parallel Processing

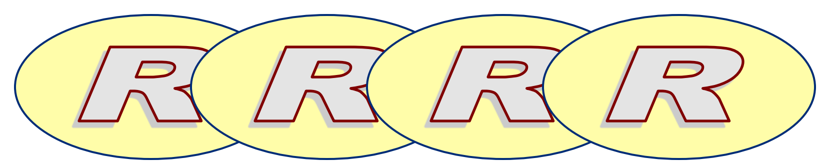


Lateral Scaling



Reproducibility

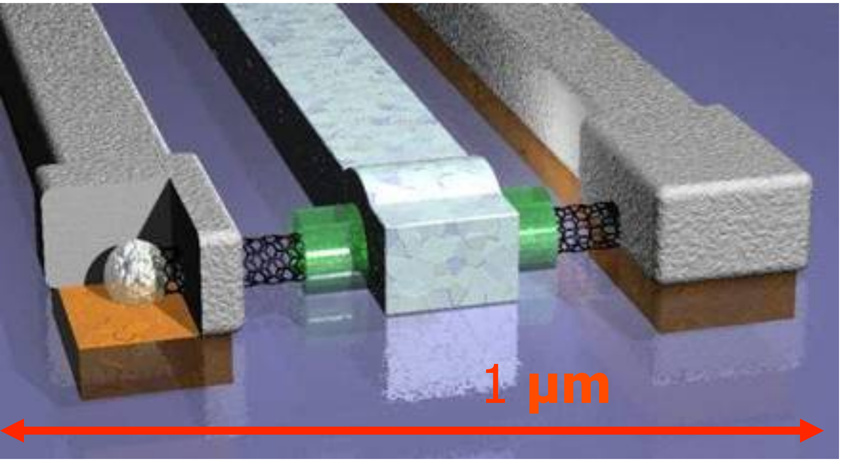
good process control high yield



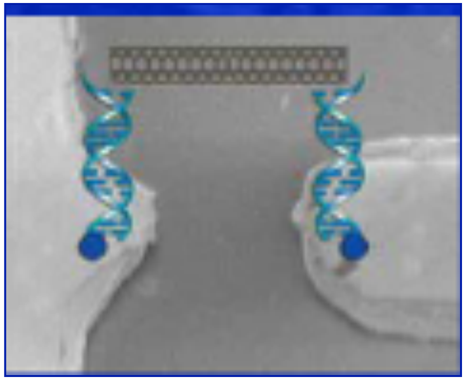
Throughput –
the number of wafers per hour optical lithography → *60* - *90* wafers/hour

Limitations of lateral CNTFET approach

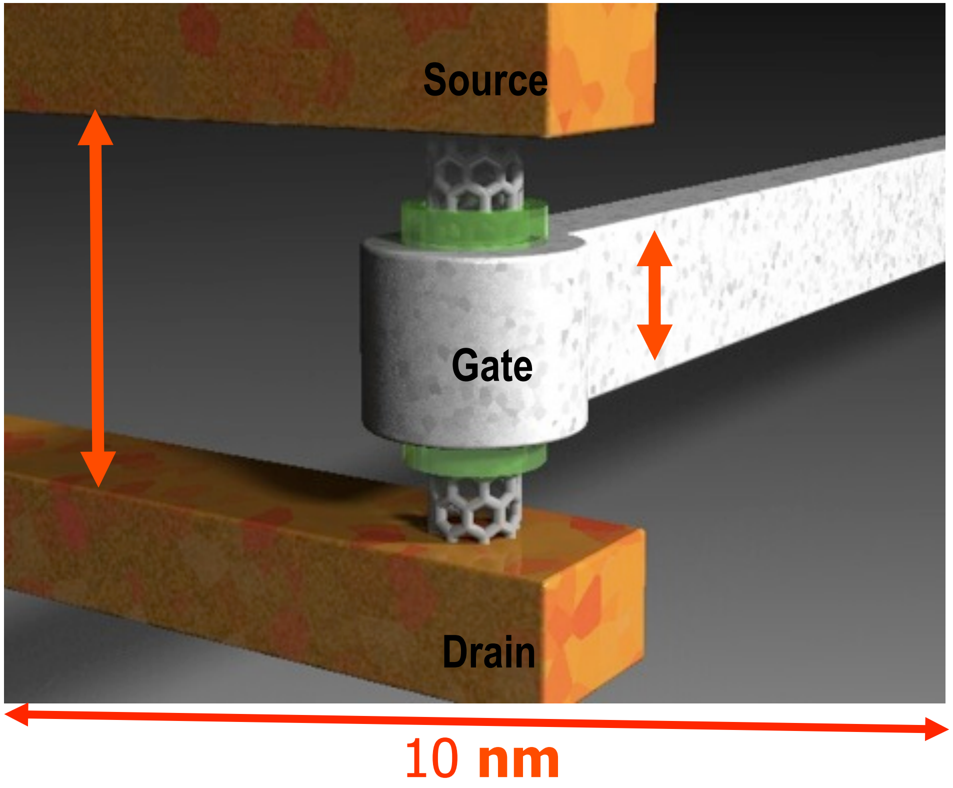
Lateral dimmensions?



Accurate Positioning of CNTs ?

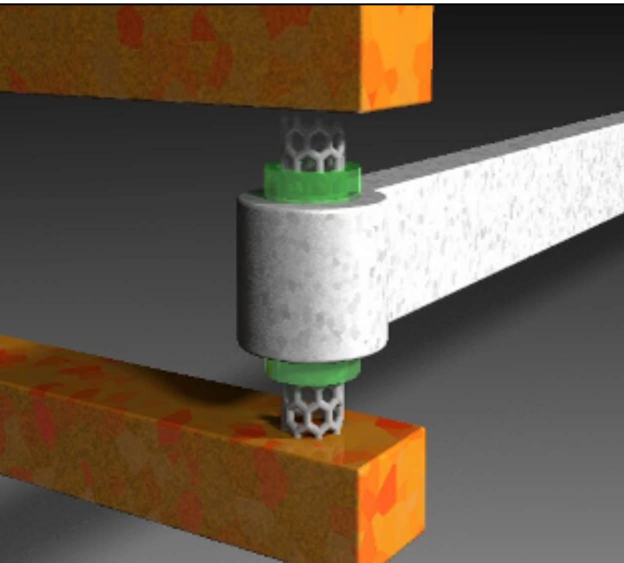


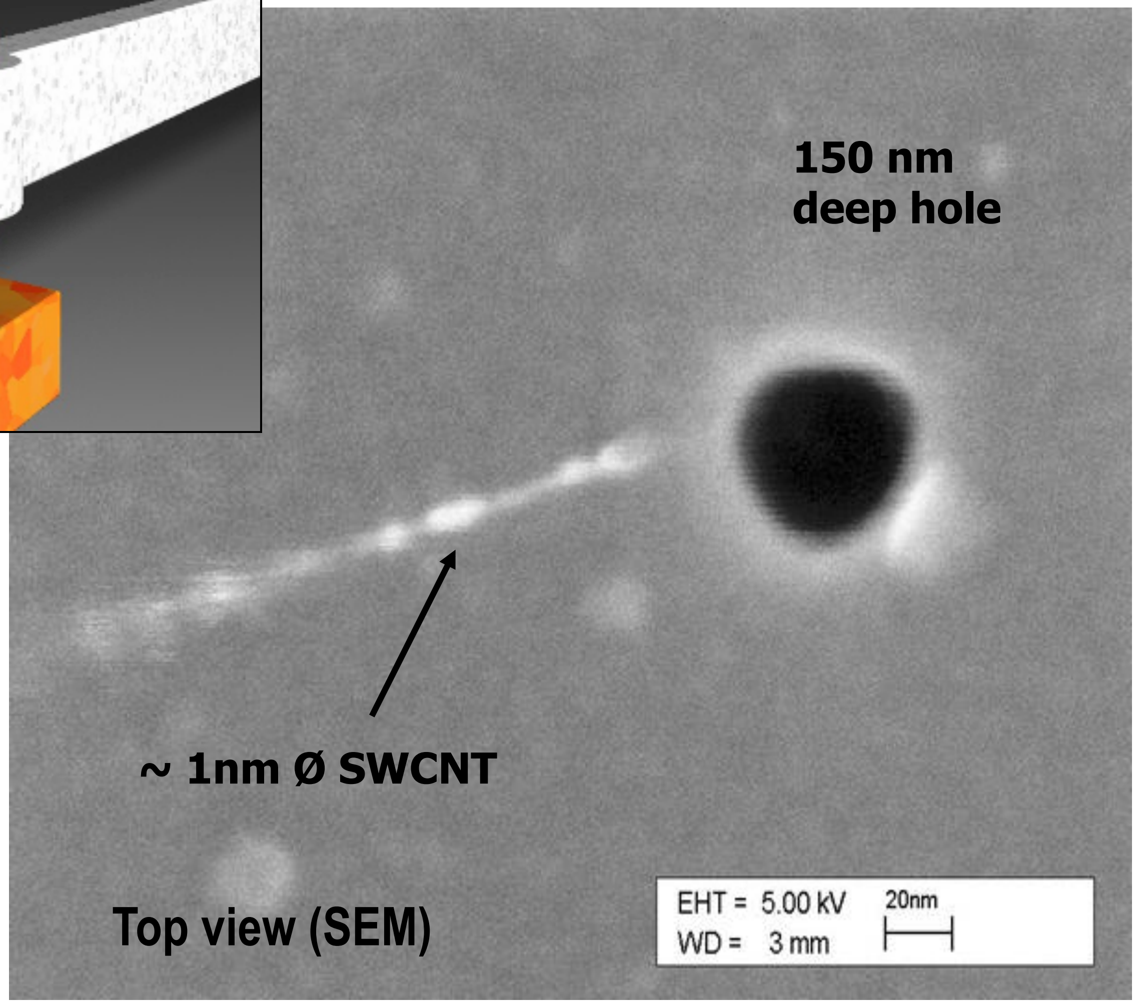
The vertical CNTFET could be the solution – but there is still a long way to go....

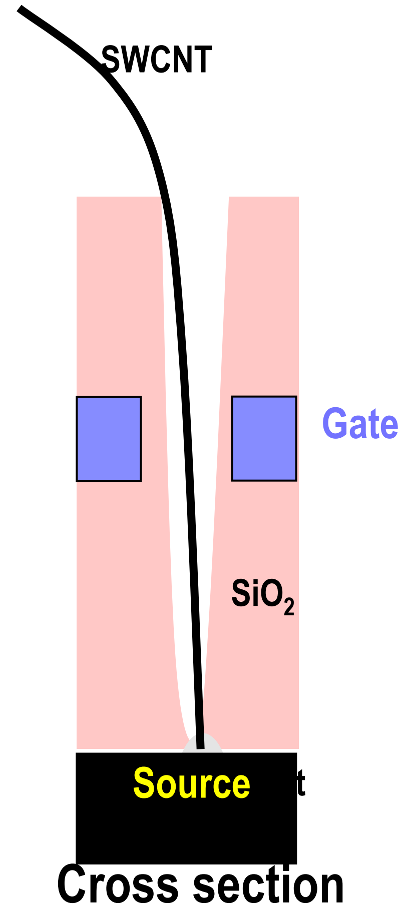


metal gate length can be adjusted to sub-nm accuracy by deposition

The vertical transistor concept



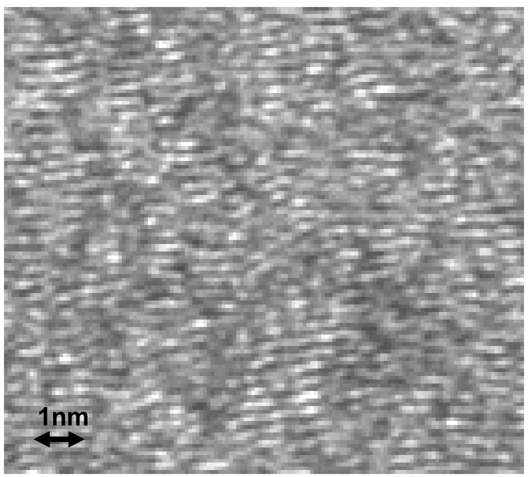




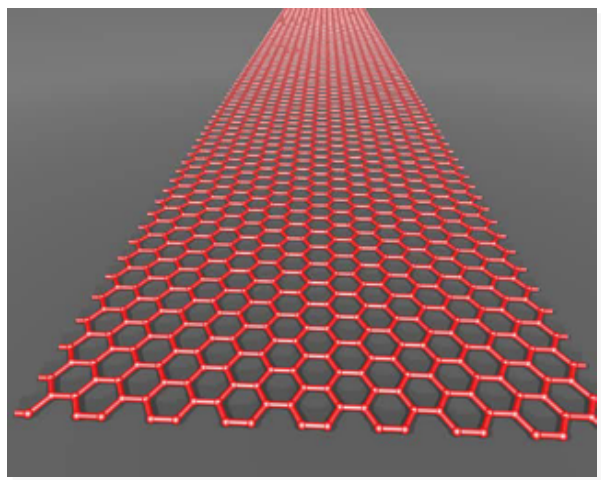
CVD of nano-carbon structures

$$\begin{array}{ccccccccccc} CH_4 & \rightarrow & C_1 & \rightarrow & C_2 & \rightarrow & (C_4) & \rightarrow & C_6 & \rightarrow & C_n \\ & & \downarrow & & \downarrow & & & & \downarrow & & \downarrow \\ & & C_\infty & & C_\infty & & & & C_\infty & & C_\infty \end{array}$$

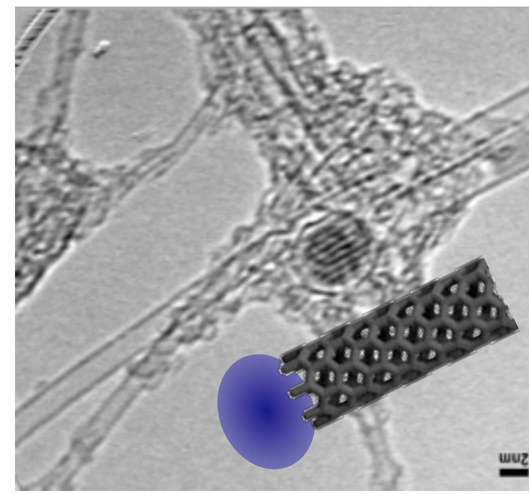
Pyrolysis of hydrocarbons



Pyrolytic Carbon (PyC)



Graphene by CVD

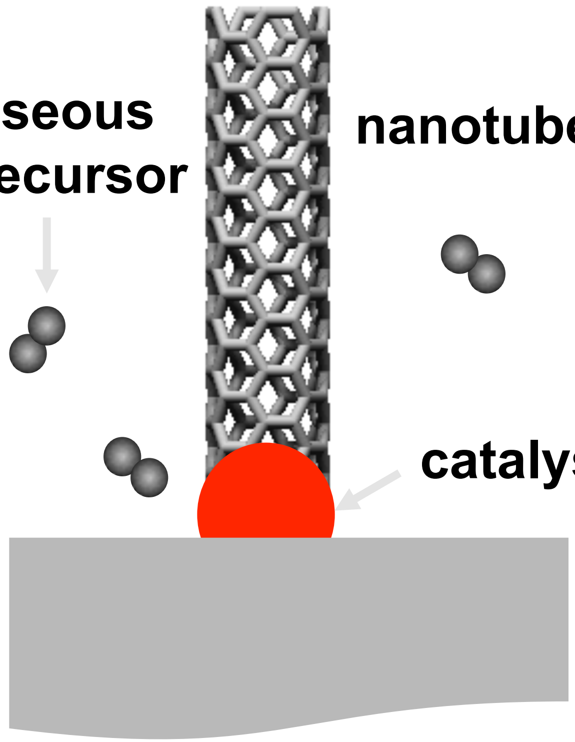


CNTs by CVD

Challenge: Structural homogenity of CVD CNTs

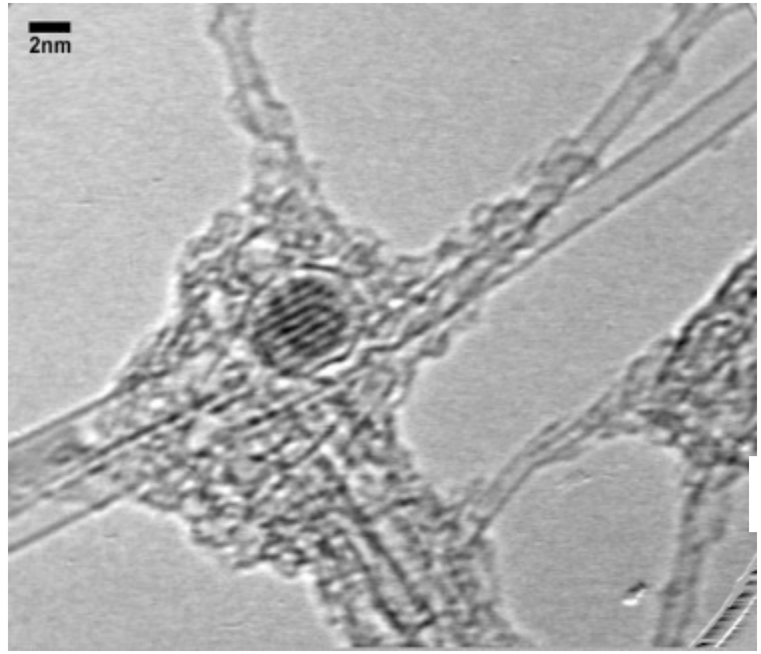
Bottom-up

(nanotubes, nanowires)



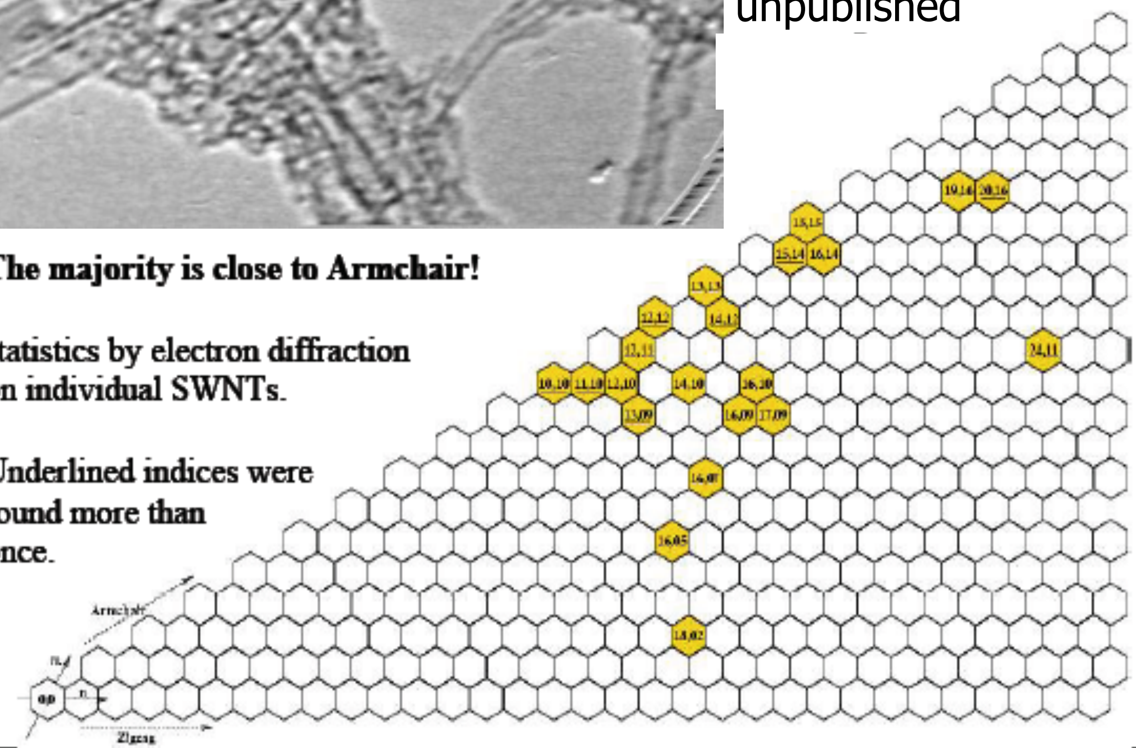
self-organized 1-D structures

high perfection



Lattice fringes match with walls of SWCNT a MoCo-Catalyst

J. C. Meyer, G.S Duesberg et al. , unpublished

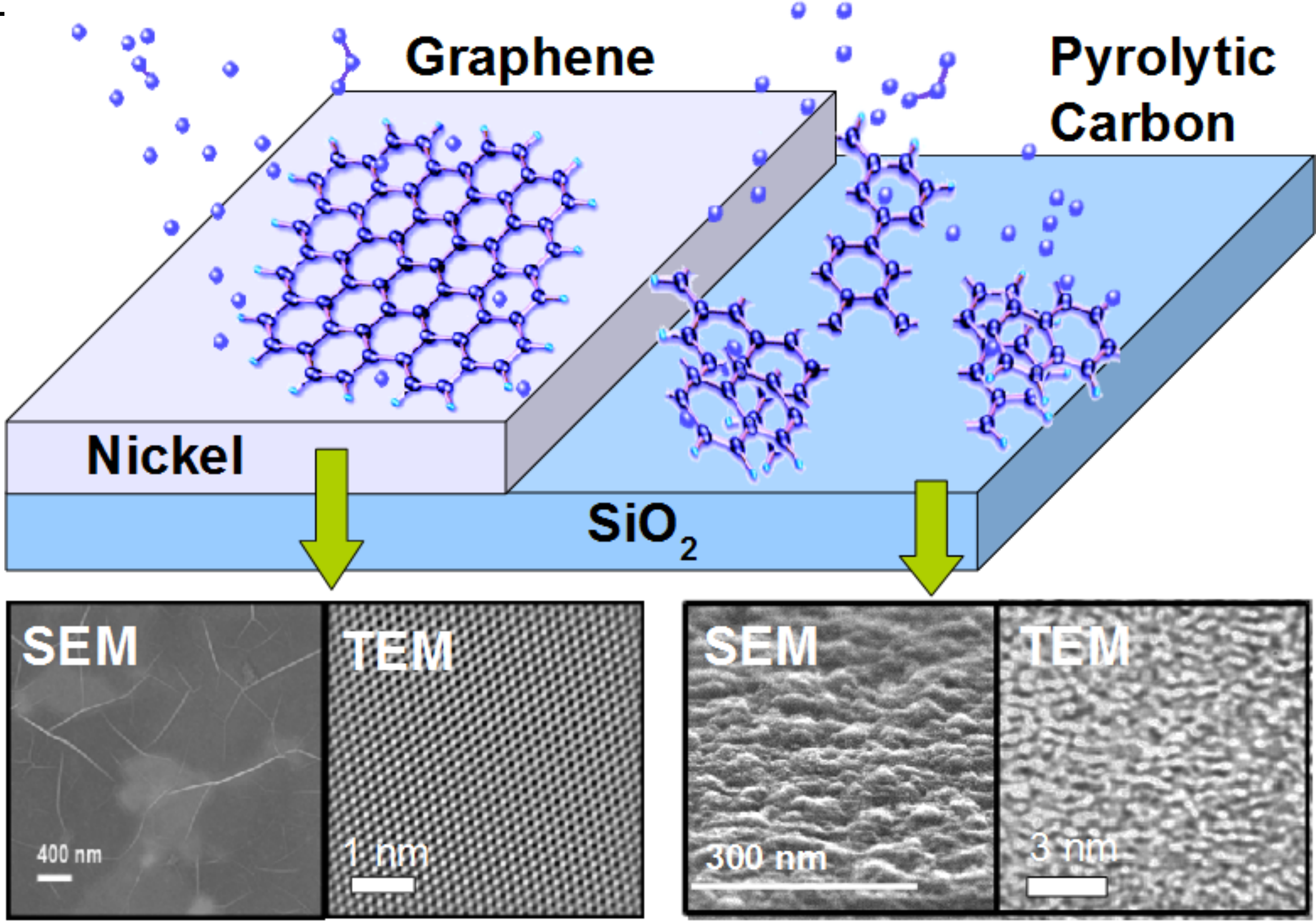


The majority is close to Armchair!

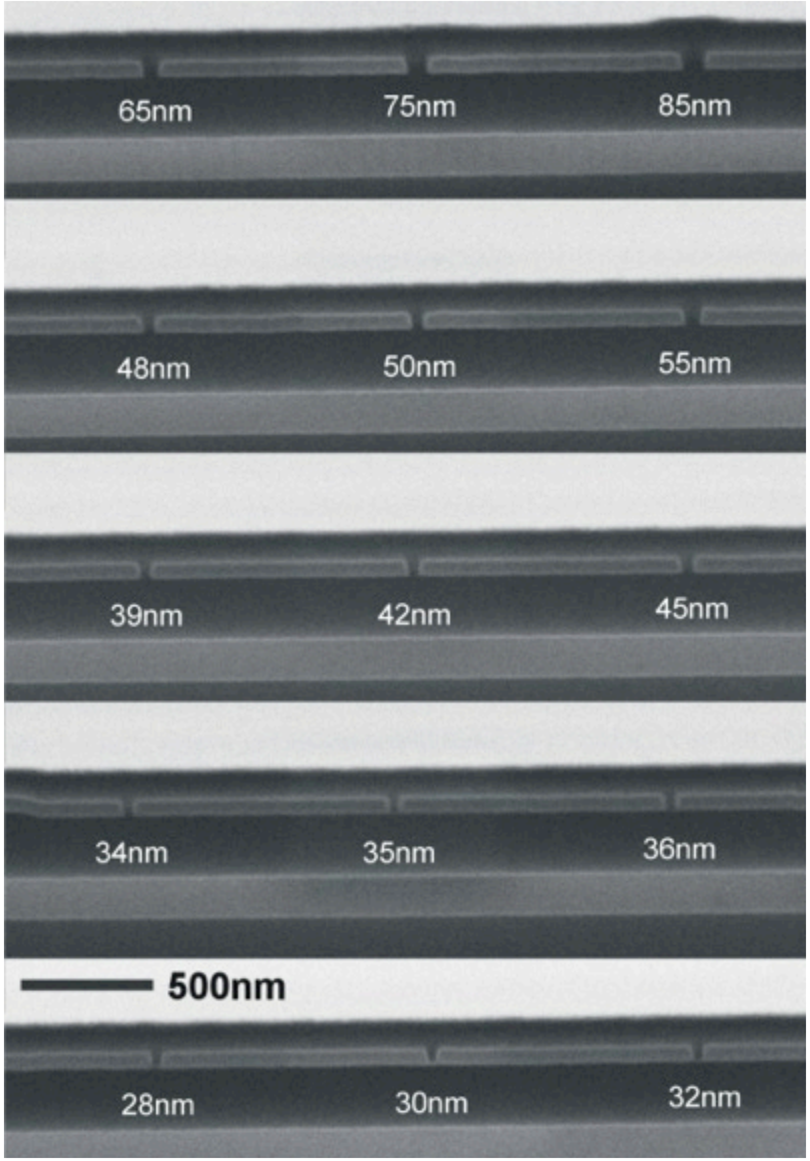
statistics by electron diffraction on individual SWNTs.

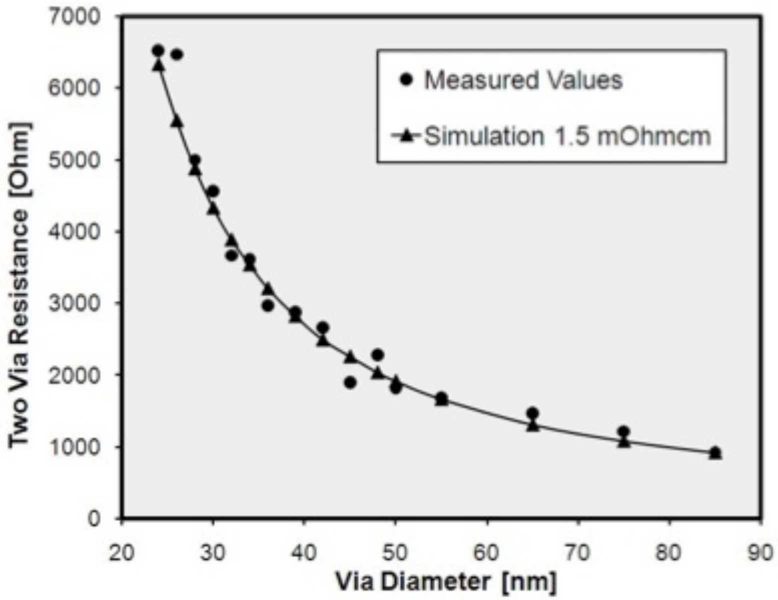
Underlined indices were found more than once.

Hetero-epitaxial CVD



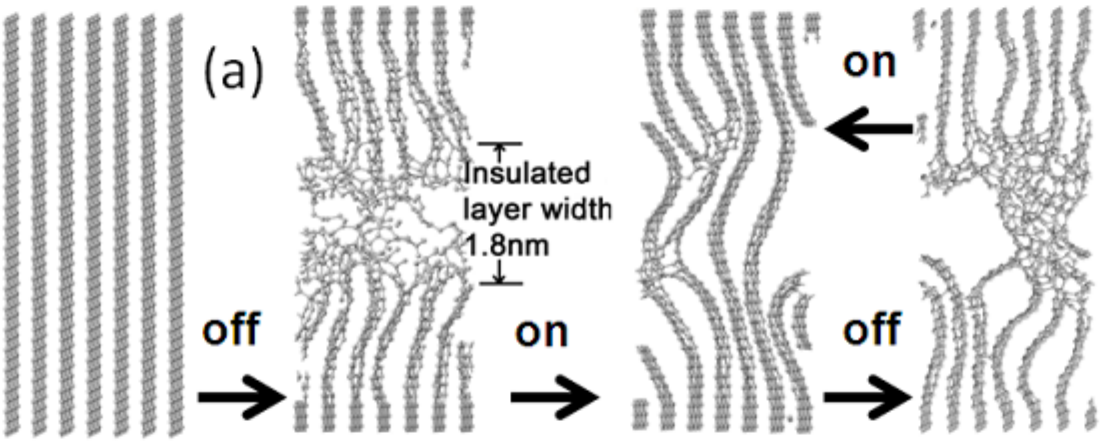
Carbon Interconnects – PyC and CNTs

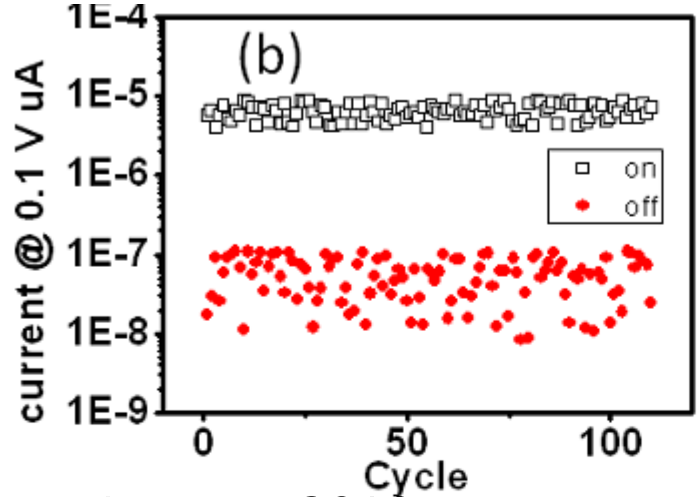




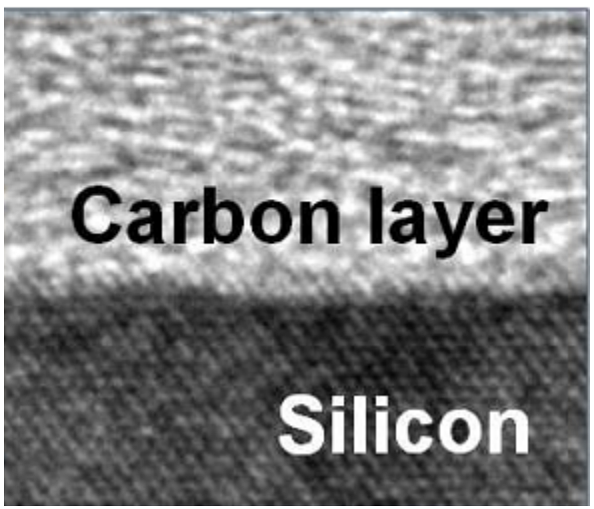
A. Graham, G. Schindler, G. S. Duesberg, T. Lutz, and W. Weber, Journal of Applied Physics, 107 114316.2010.

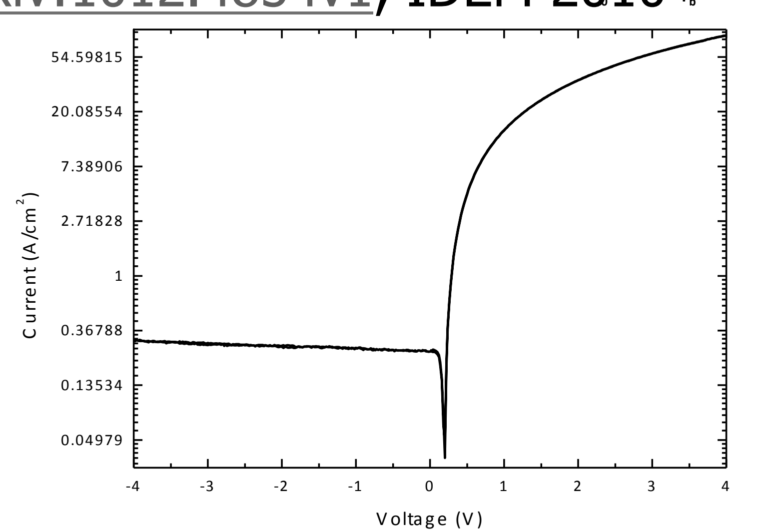
Carbon devices: Memory and diode





Carbon CB Ram: Kreupl et al. arXiv:1012.4854v1, IDEM 2010





Schottky diode: Duesberg, Kreupl, Graham et al.

Outline

CRANN

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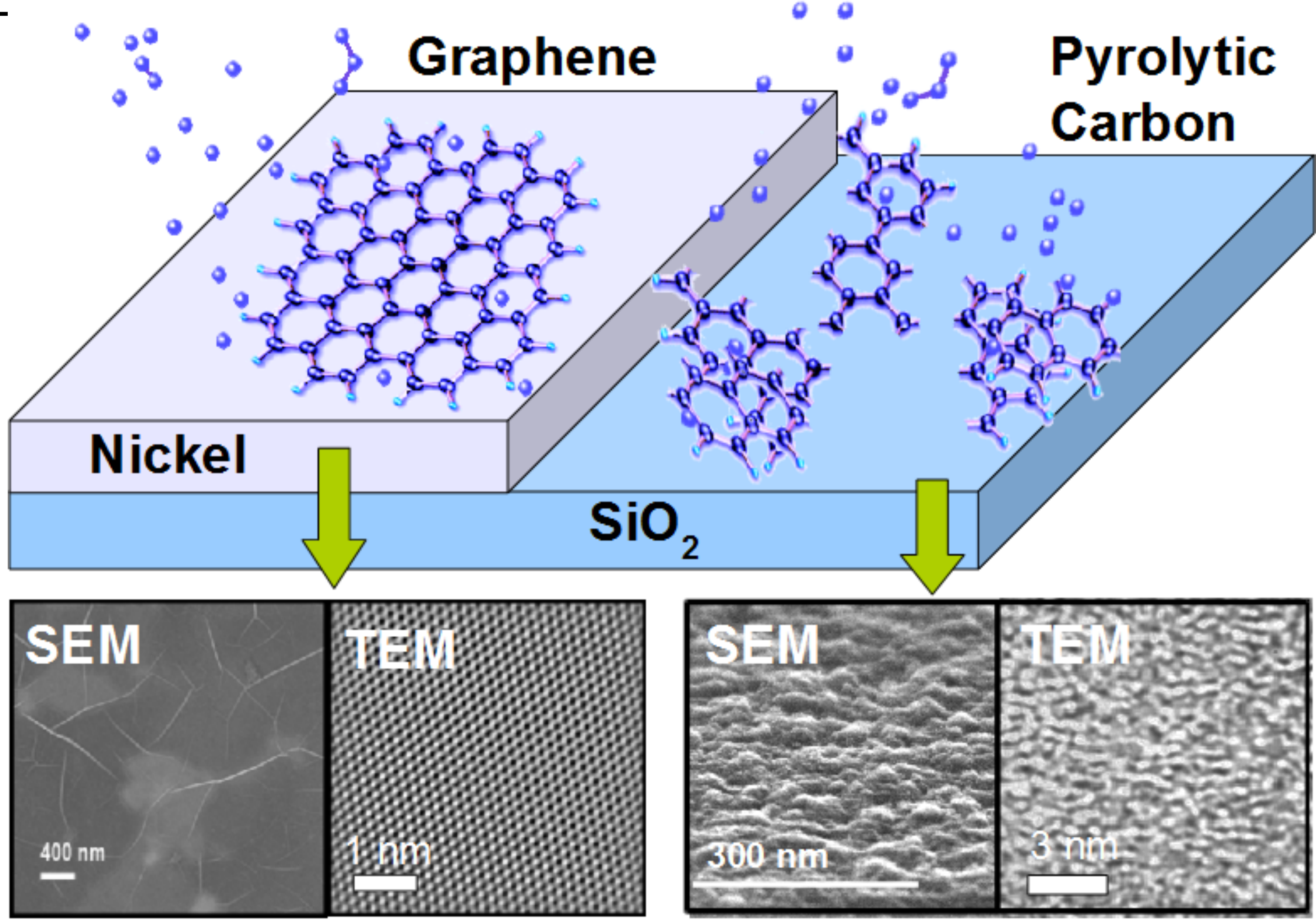
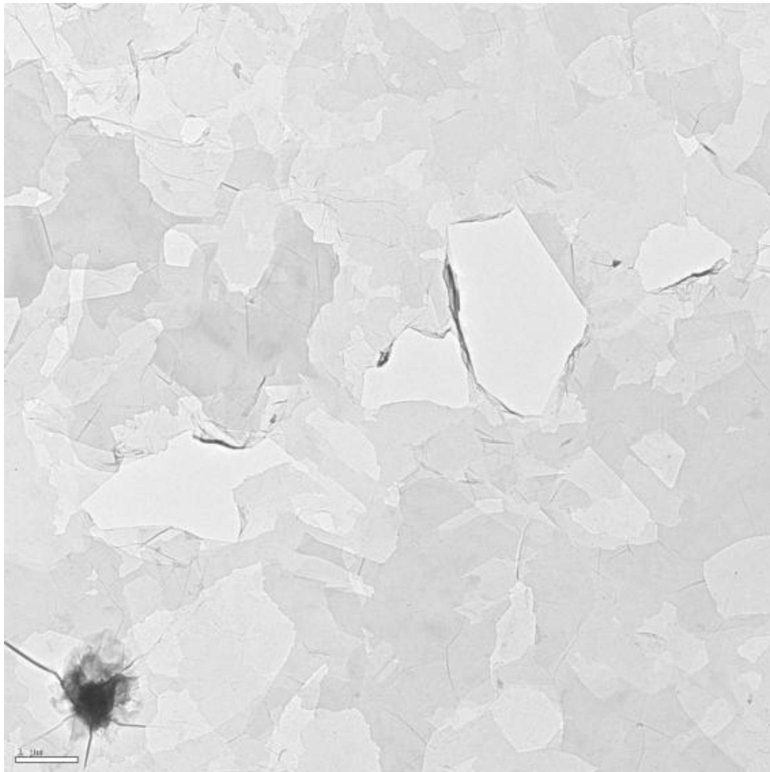
- Vertical Carbon devices
- Graphene Processing
- Other 2D Materials
- Carbon NEMS?
- Conclusions

Hetero-epitaxial CVD

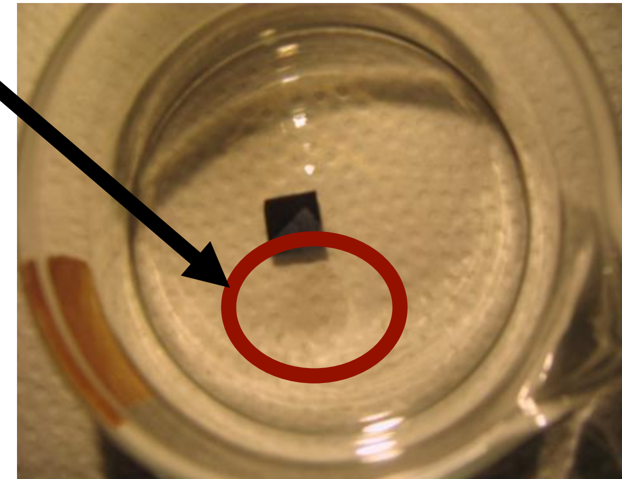


CVD graphene & transfer



SEM

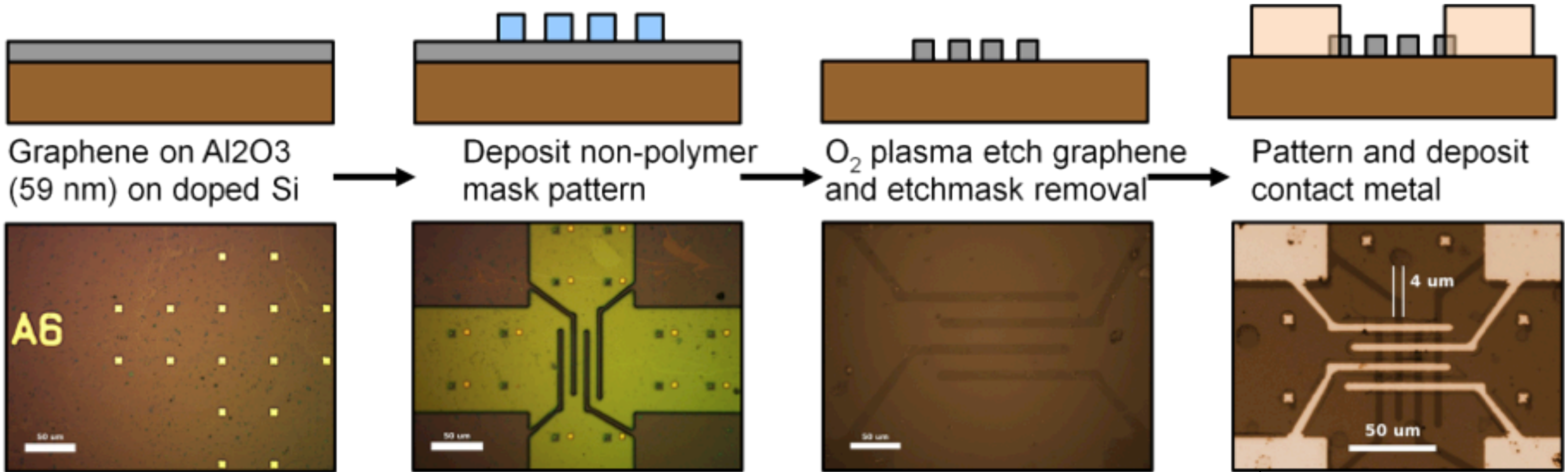
Graphene

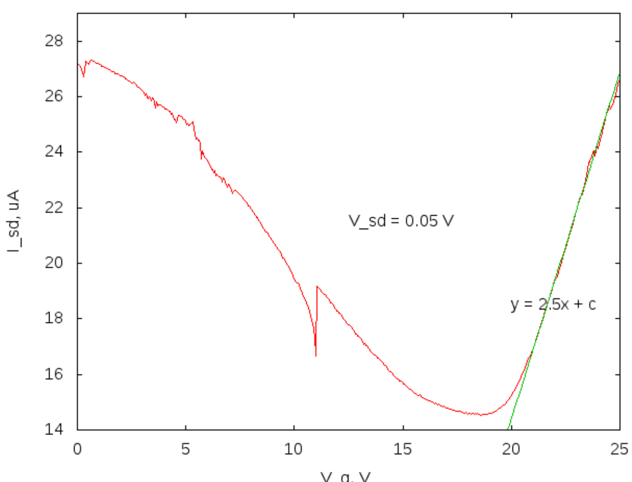


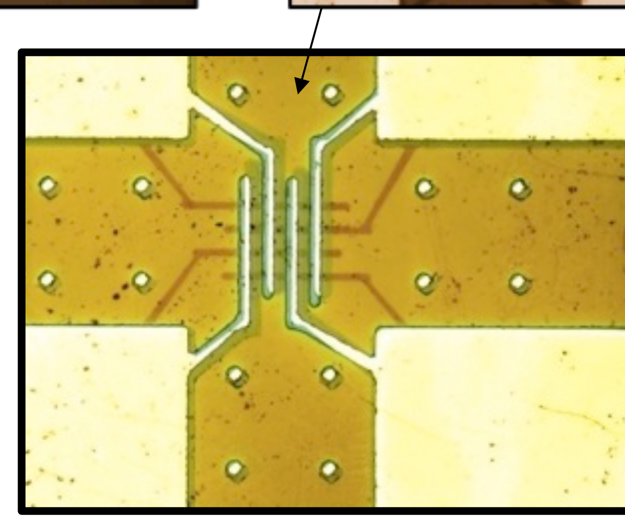
•Optical images of graphene films transferred to glass slides

S. Kumar et al. Chem Comm 2010

Structuring graphene devices

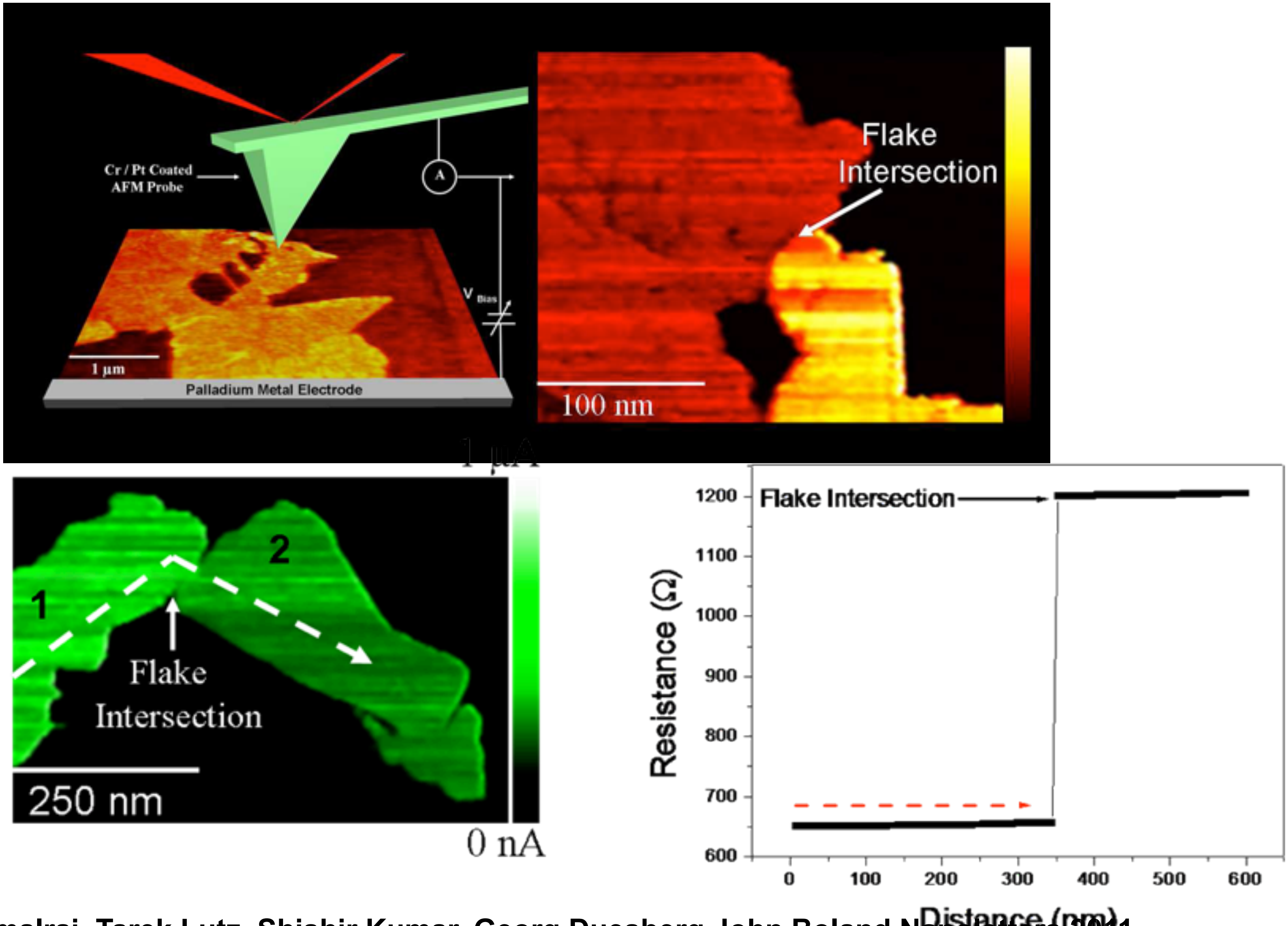






Kumar, S.; Peltekis, N.; Lee, K.; Kim, H. Y.; Duesberg, G. S.
***Nanoscale Research Letters,* 2011, *6*, 390**

Conductive AFM in graphene films



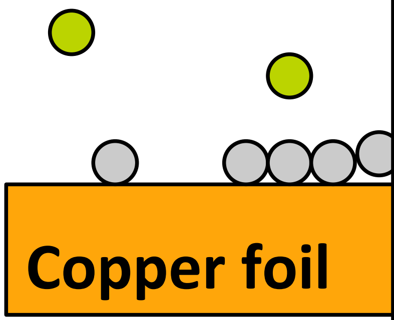
Peter Nirmalraj, Tarek Lutz, Shishir Kumar, Georg Duesberg John Boland Nanoletters 2011

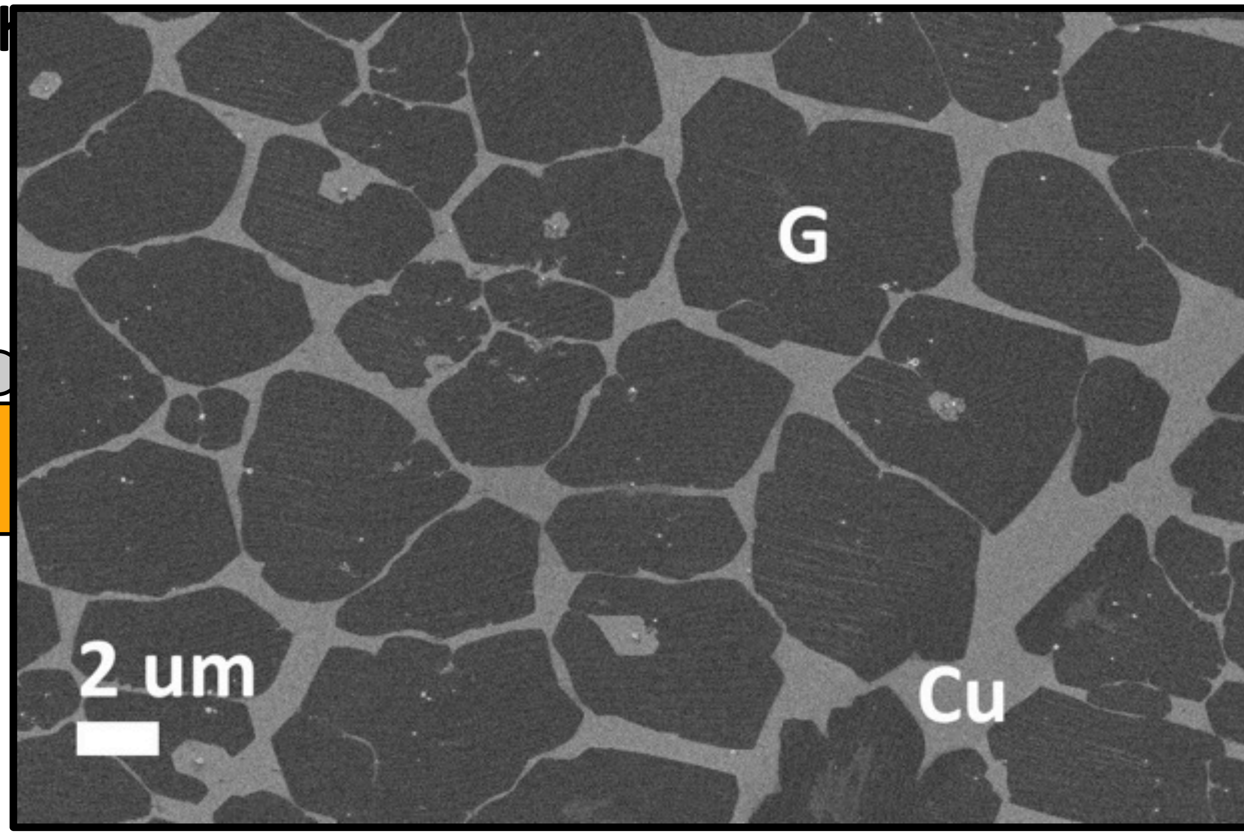
Graphene on Copper

Low solubility of carbon

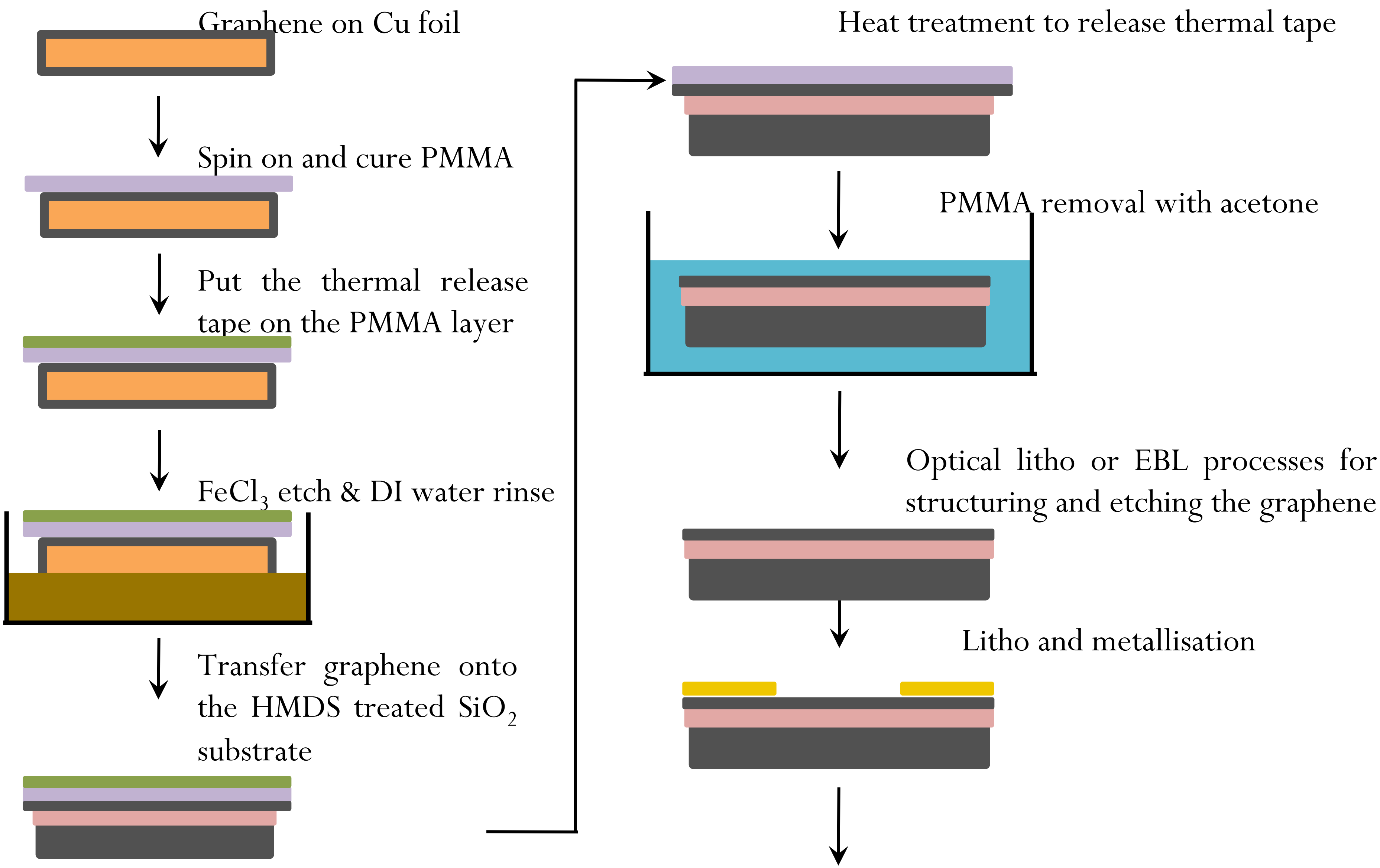
Less catalytic th

Lattice match



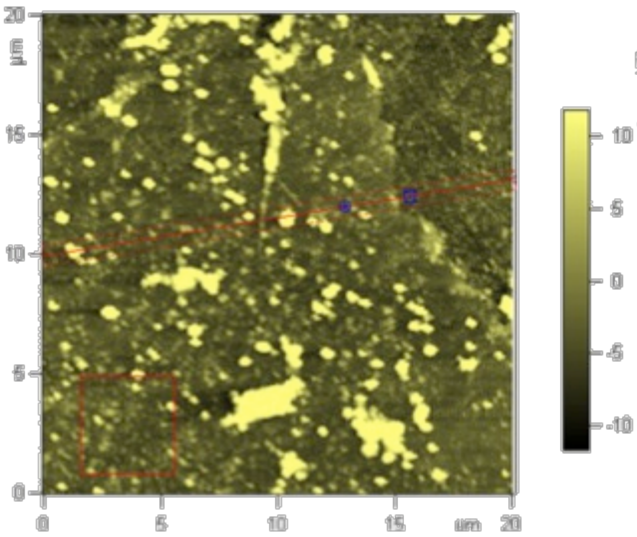


Polymer transfer technique for graphene

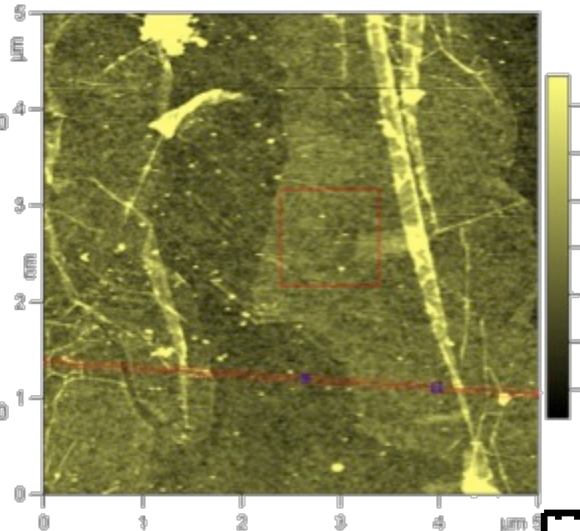


Analysis of plasma cleaned graphene

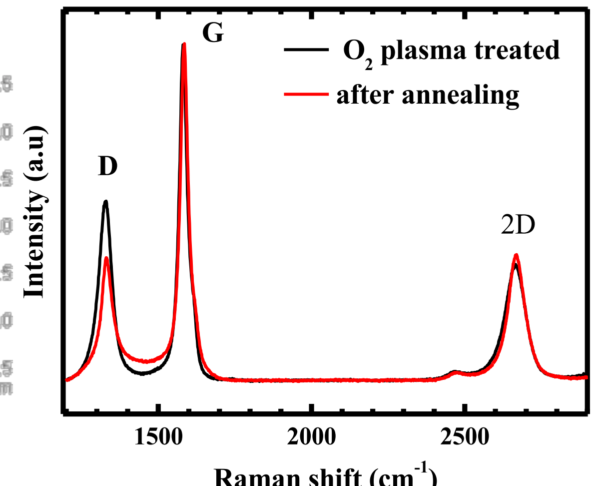
Graphene transferred with polymers is cleaned with remote plasma at low temps

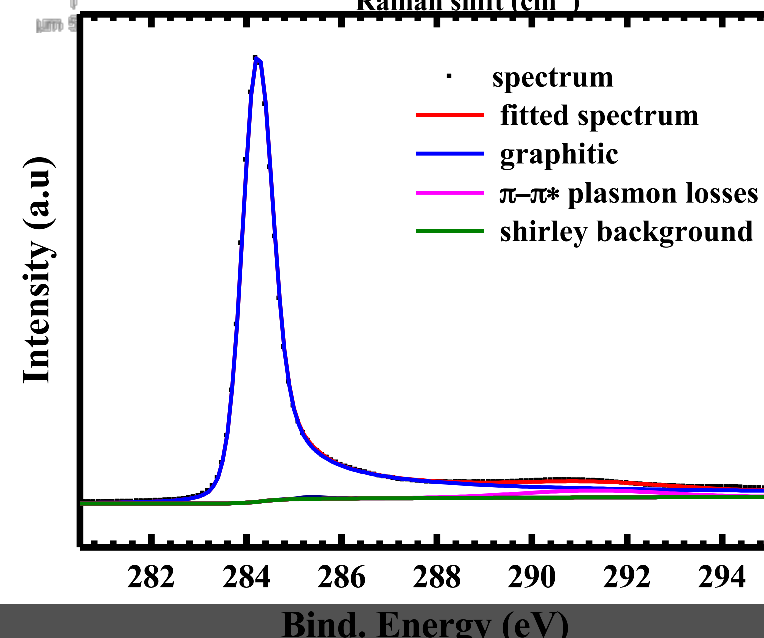


AFM Before



AFM After

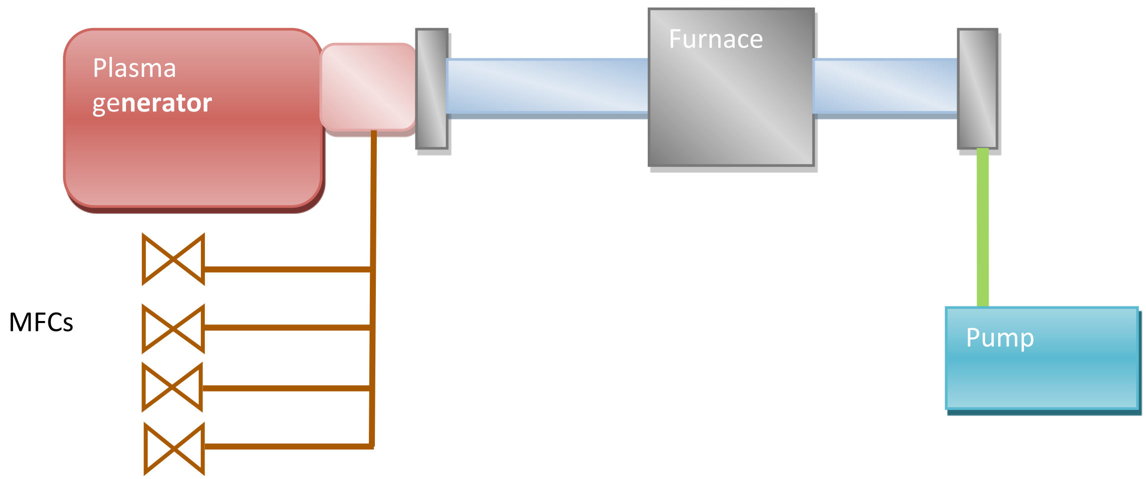


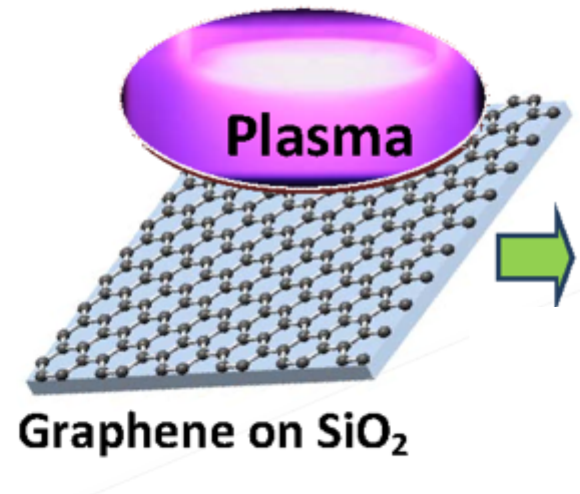


XPS C1s FWHM=0.68eV after annealing, perfectly clean graphitic spectrum.

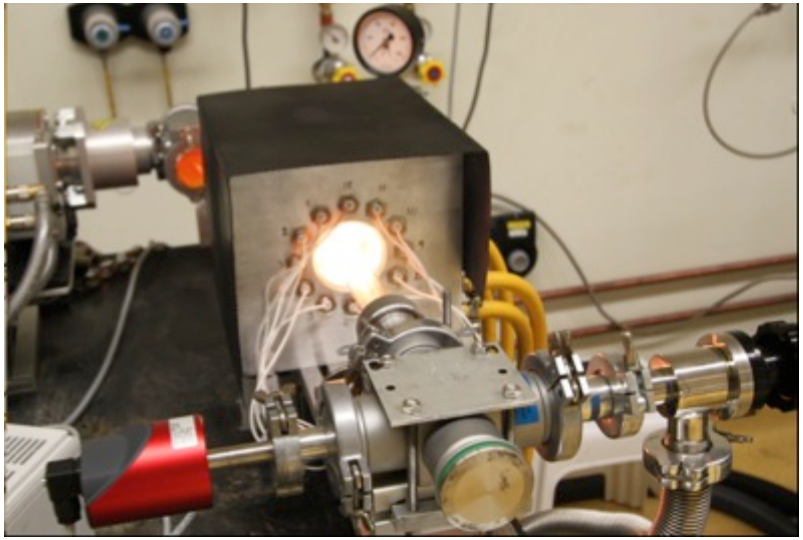
Peltekis, Duesberg et al. Carbon, accepted

Cleaning of graphene with plasmas

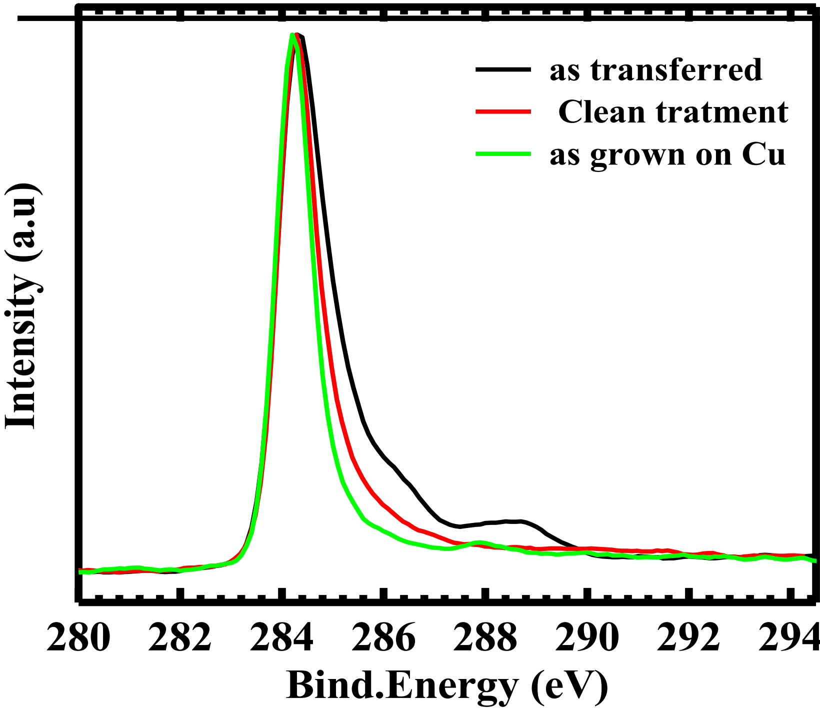


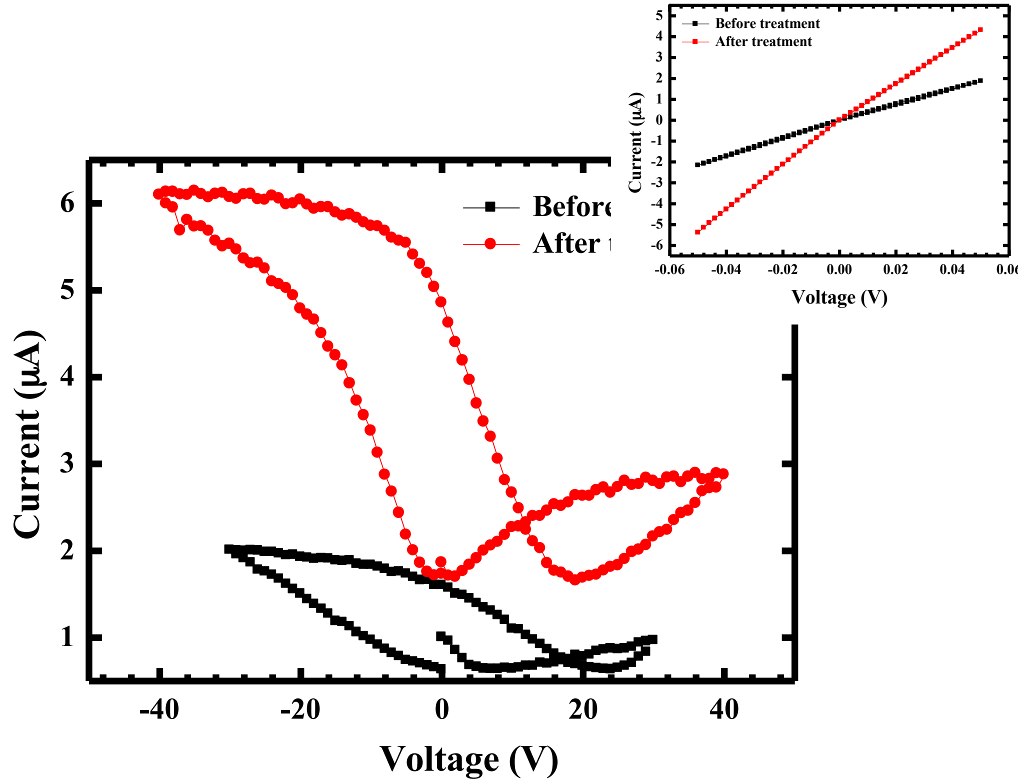


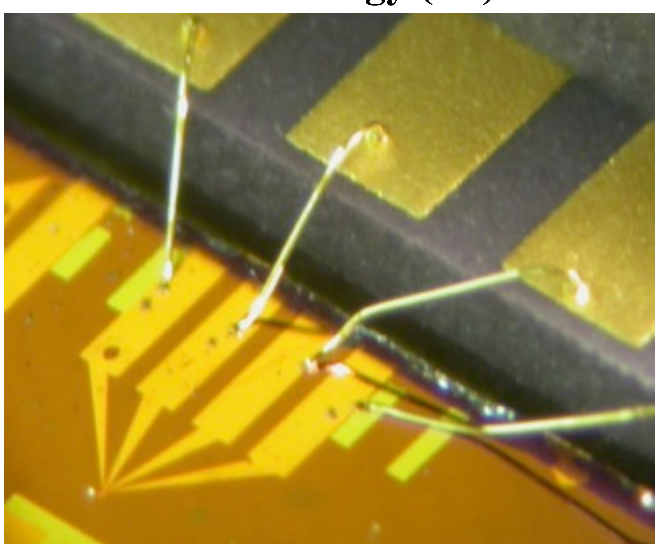
"Chemical" plasma by a remote source *(R^3T* TWR 2000-GEN, 400V) 1000W . pressure of 1 torr flow rates of 100 sccm Oxygen and Hydrogen



Cleaning of graphene with plasmas only





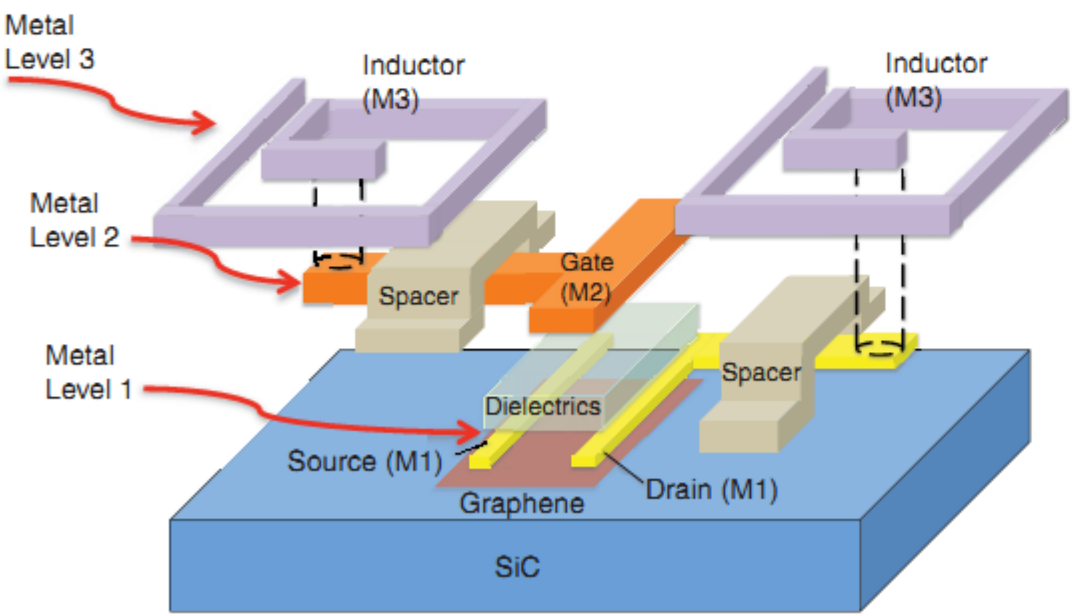


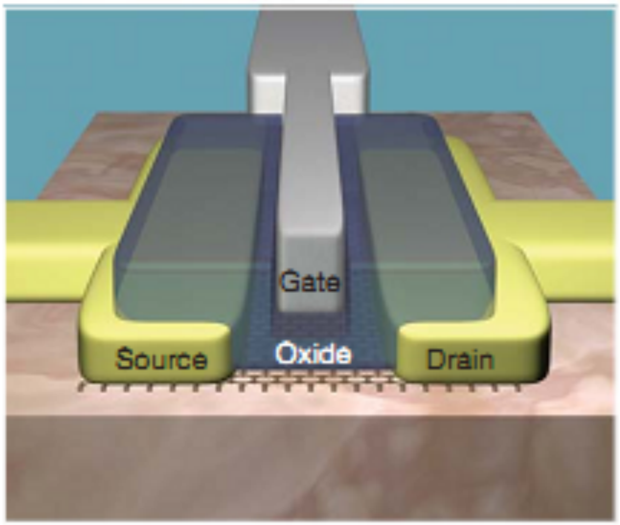
In-situ cleaning possible!
Conductivity and mobilities increased ~ 200 cm²/Vs after plasma treatment
This applies to all graphene type samples

Peltekis, Duesberg et al. Carbon, accepted

Graphene transistors

Band gap ?

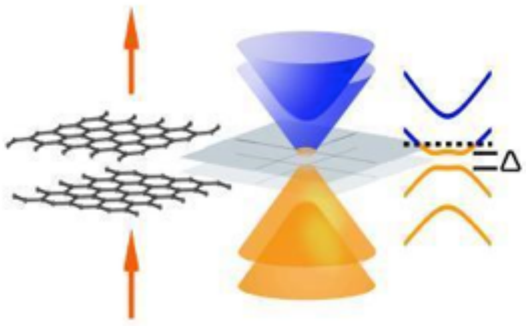




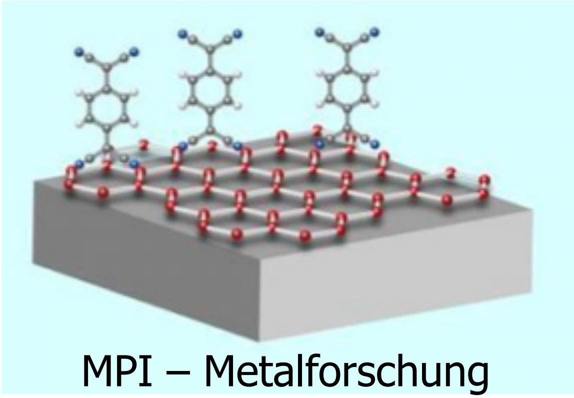
Avouris group IBM

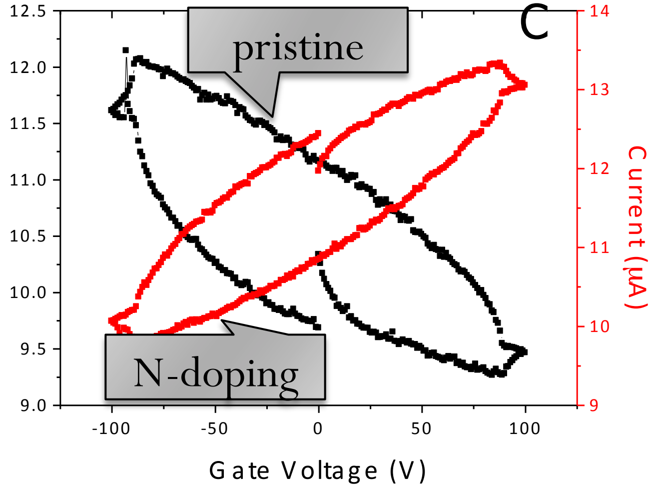
Band gap engineering in graphene

Double layers
Zhang et al. 2009 Nature

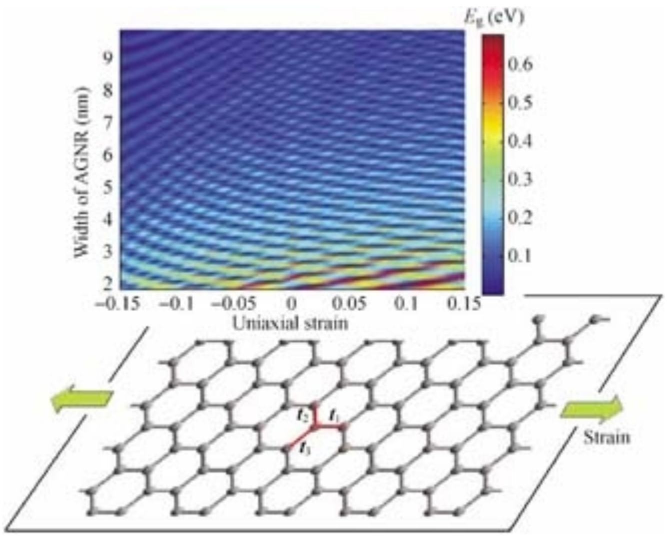


Functionalisation/ Doping

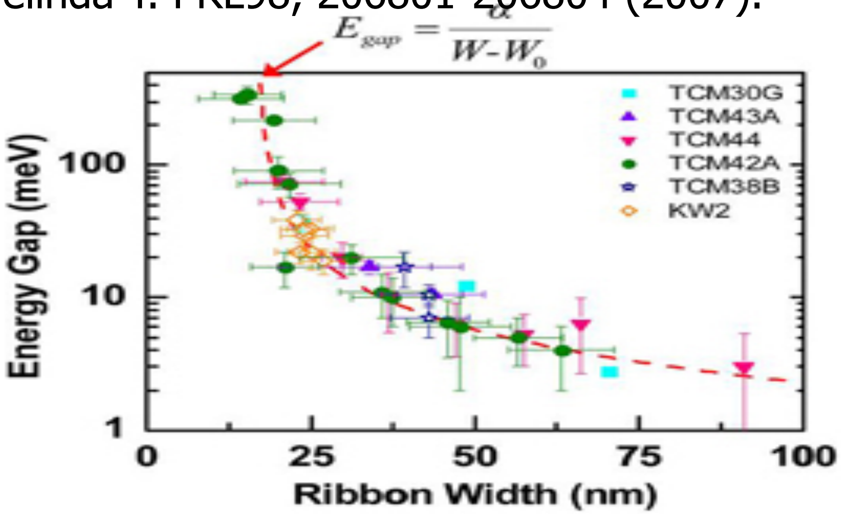




Stress
Lu, Nano Research 2009

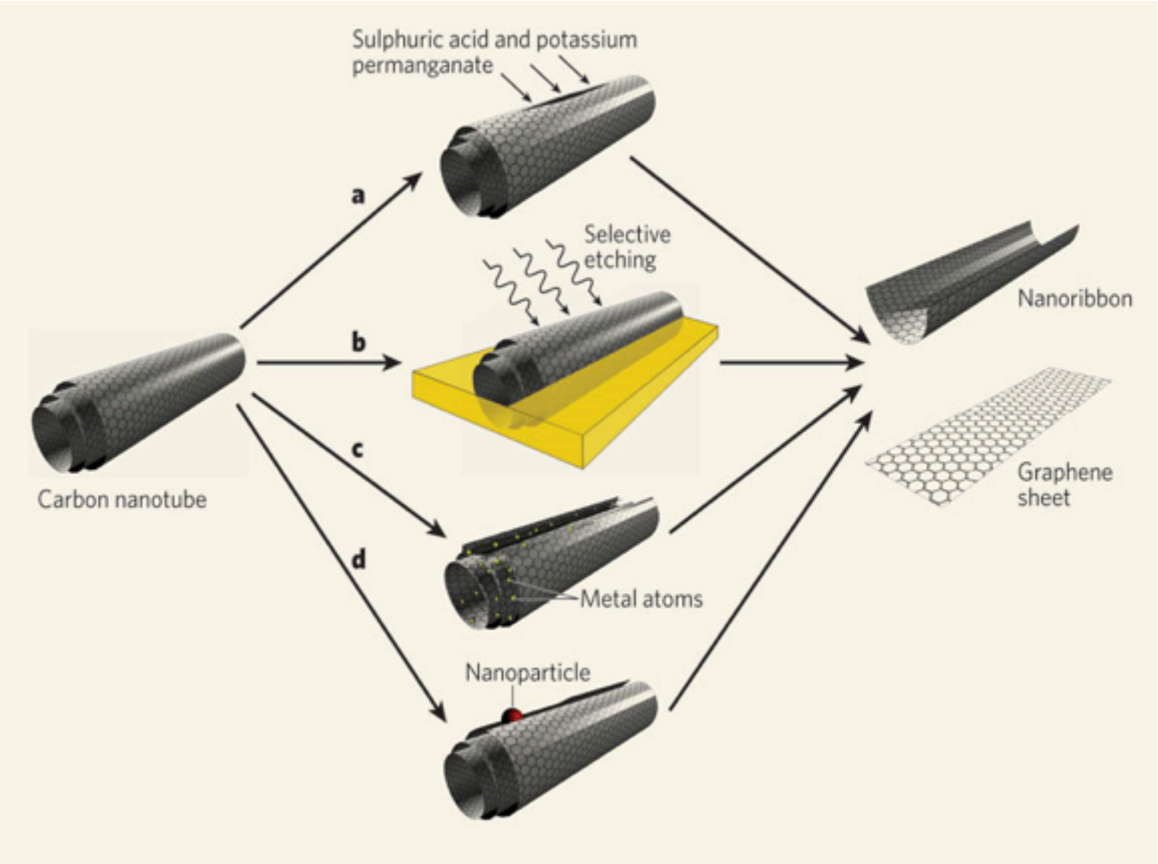


Cut out/size effect
Melinda Y. PRL98, 206801-206804 (2007).

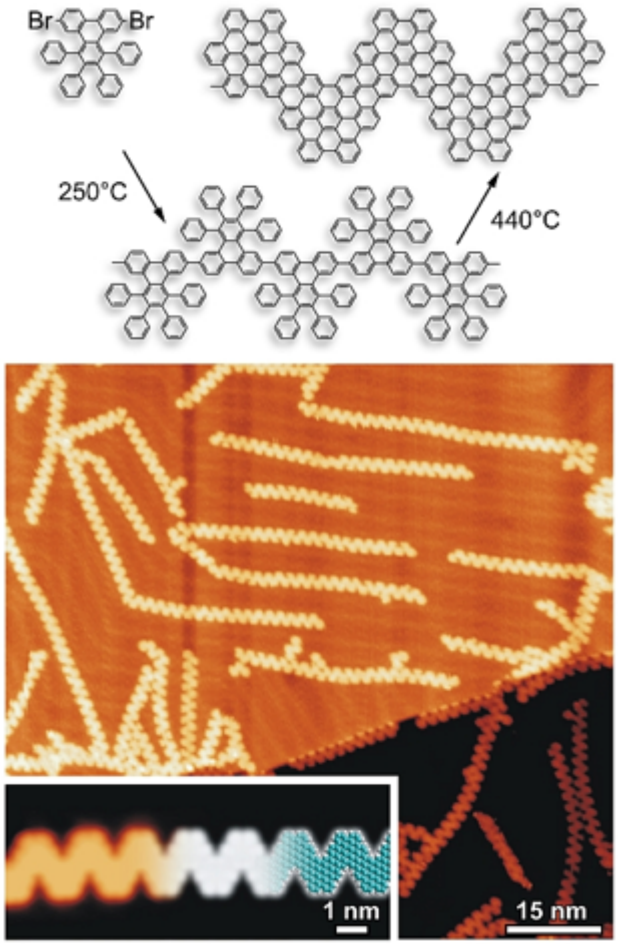


Graphene ribbons – chemical routes

Materials science: Nanotubes unzipped
Mauricio Terrones
Nature 458, 845-846(16 April 2009)



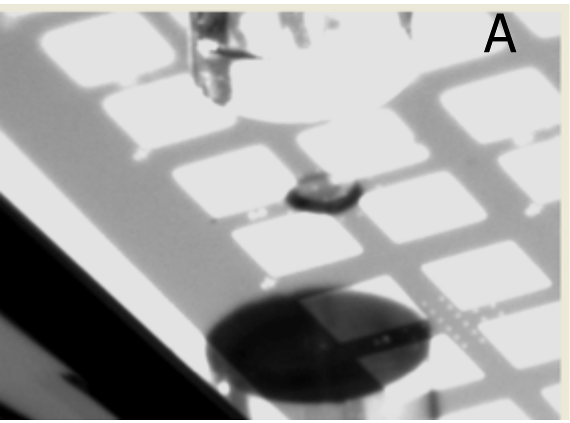
Atomically defined structures!

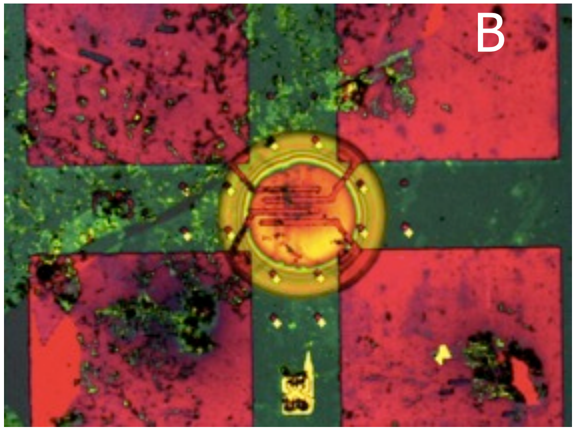


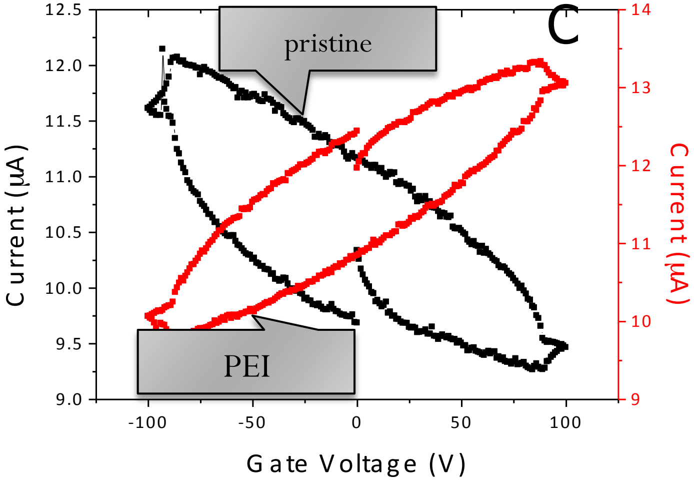
J. Cai, et al.Nature, 2010

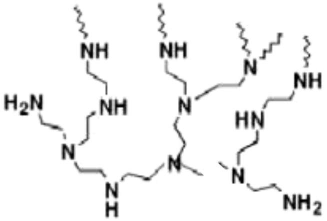
Same or even more problems as with nanotubes

Top coated graphene Fets

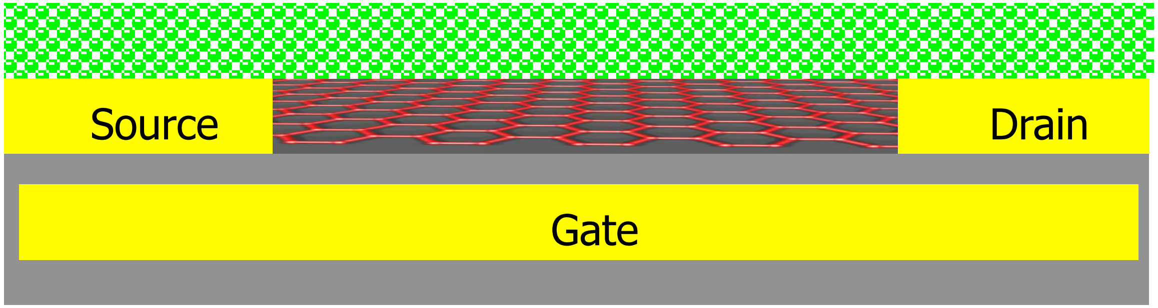








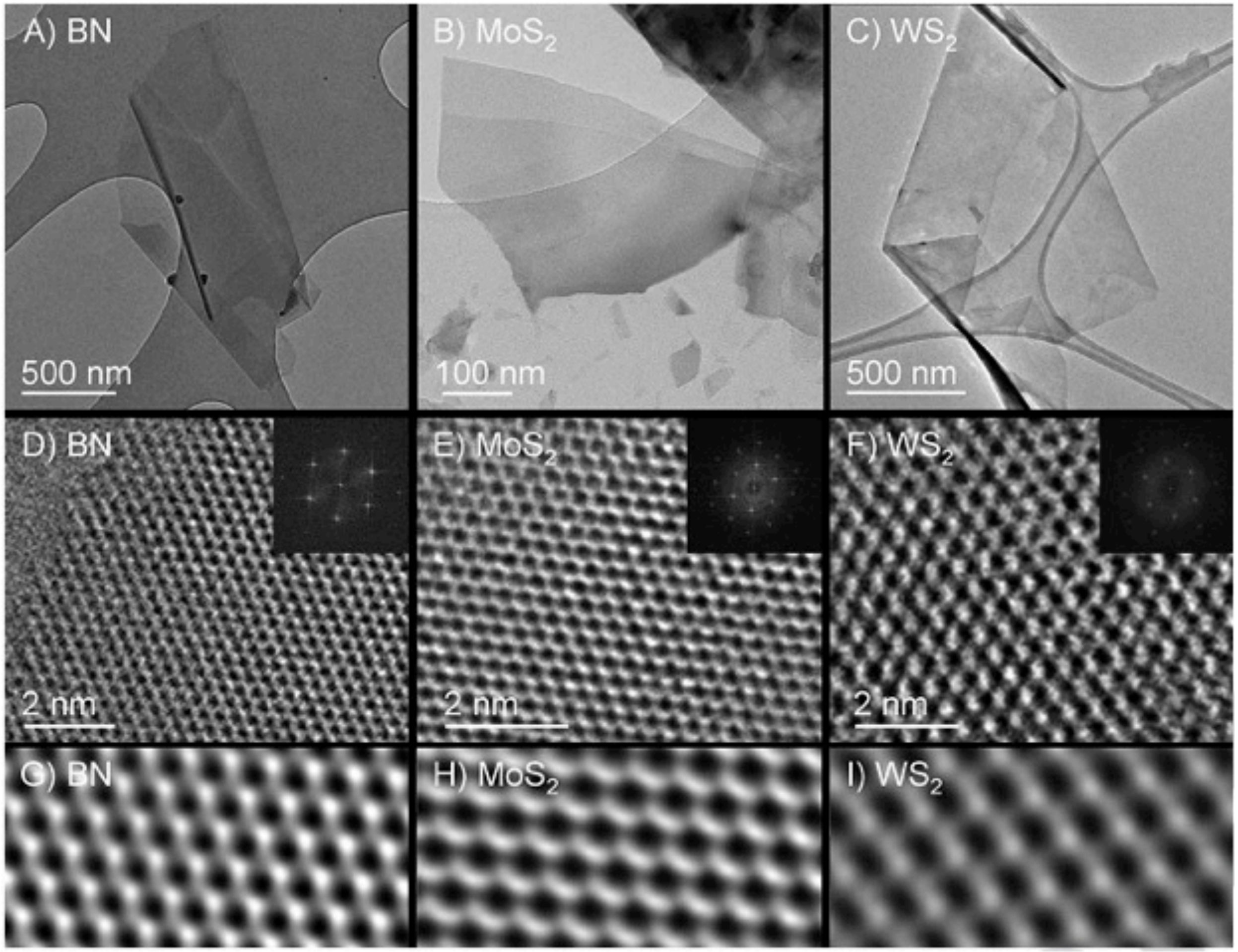
n–Doping : Polyethylenimine (PEI)



Outline

- Carbon Nano-structures: Applications in microelectronics
- Vertical Carbon devices
- Graphene Processing
- Other 2D Materials
- Carbon NEMS?
- Conclusions

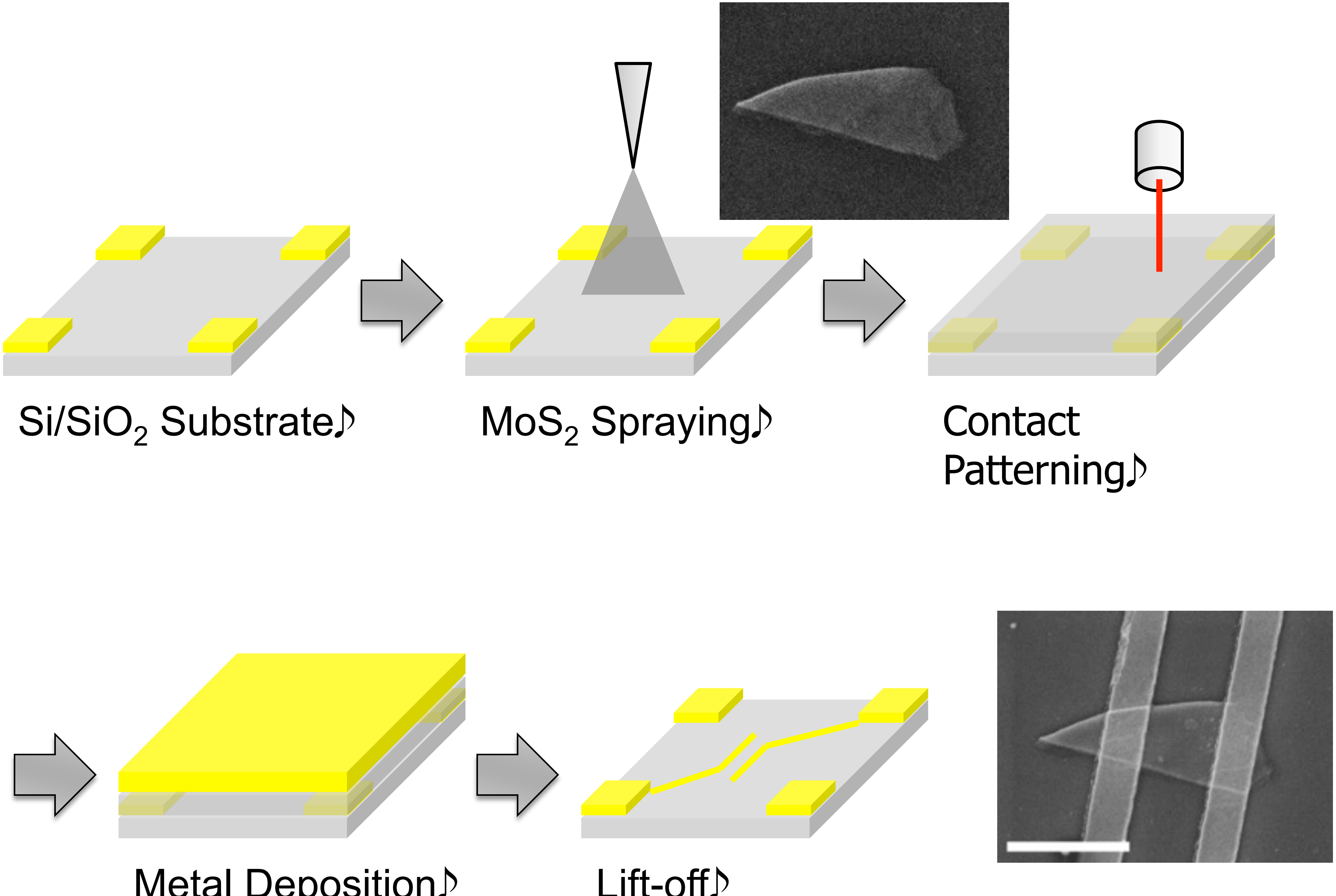
Liquid Exfoliation of 2D materials



Layered compounds such as MoS_2,WS_2, $MoSe_2$, $MoTe_2$, $TaSe_2$, $NbSe_2$, $NiTe_2$, BN, and Bi_2Te_3 can be efficiently dispersed (also topological insulators?!)

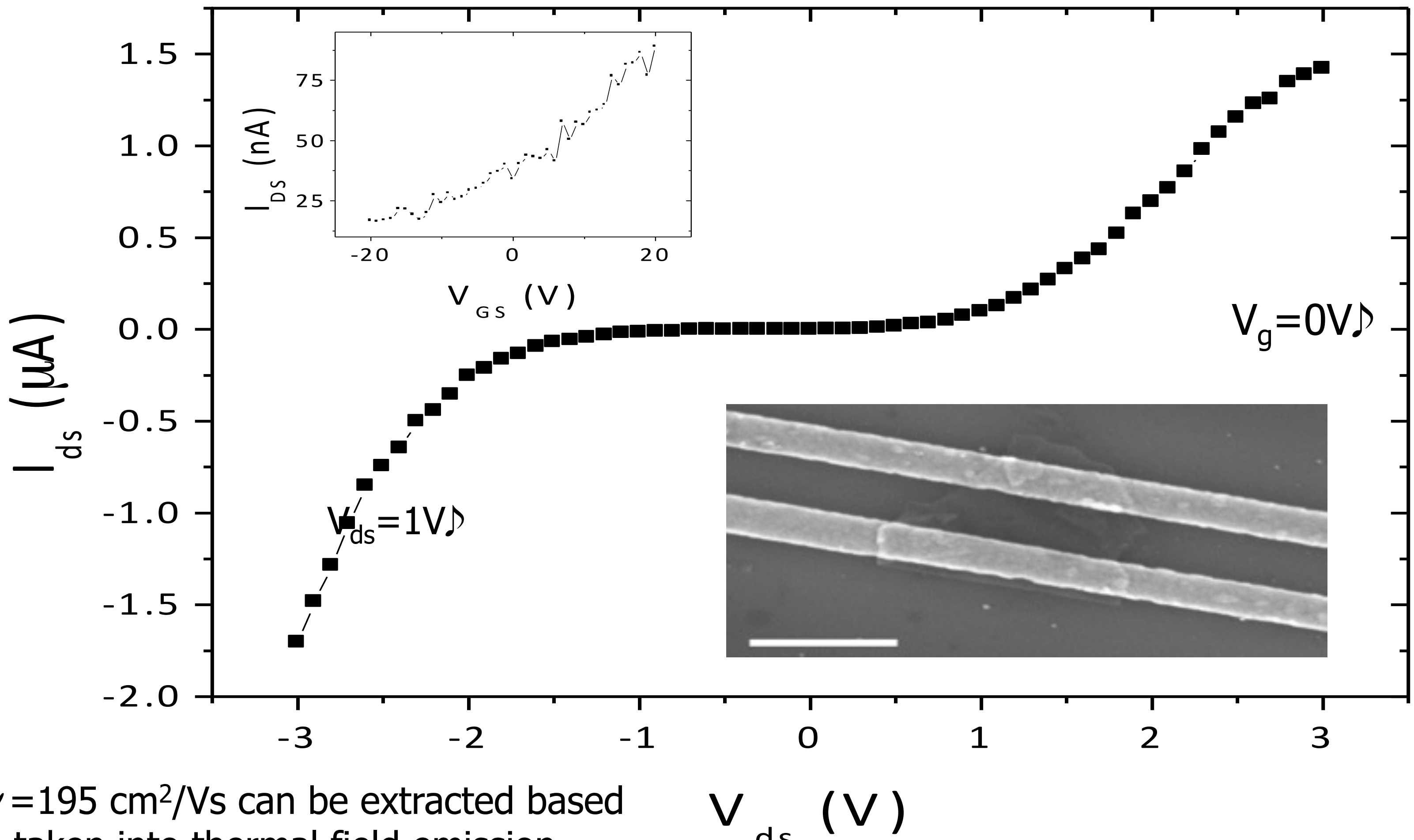
Jonathan N. Coleman, Hye-Young Kim, Kangho Lee, Gyu Tae Kim, Georg S. Duesberg, Nicolosi, et al, "Two-Dimensional Nanosheets Produced by Liquid Exfoliation of Layered Materials", **Science**, 568-571, 2011

Contacting individual MoS_2 flakes



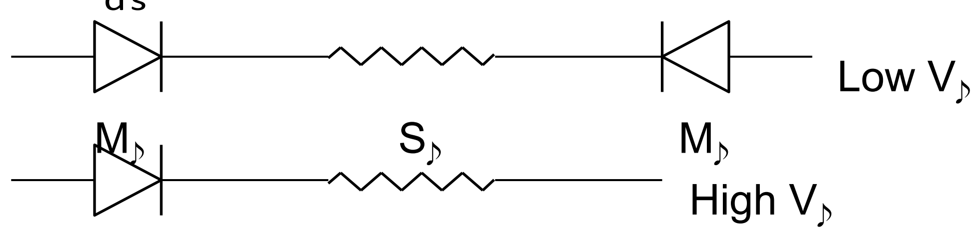
(a)

E-beam contacted MoS_2 flake



Up to μ=195 cm^2/Vs can be extracted based a model taken into thermal field emission (MSM). (similar to B. Radisavljevic , A. Kis, Nature Nano 2011)

Lee, Kim, Duesberg et al. Adv Mater., 2011



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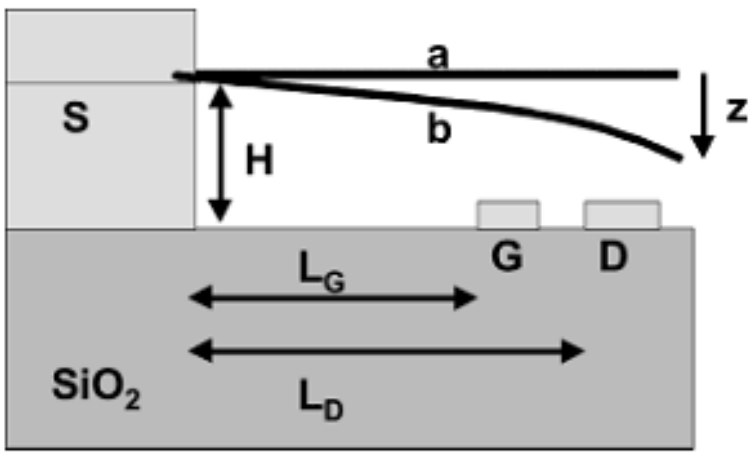
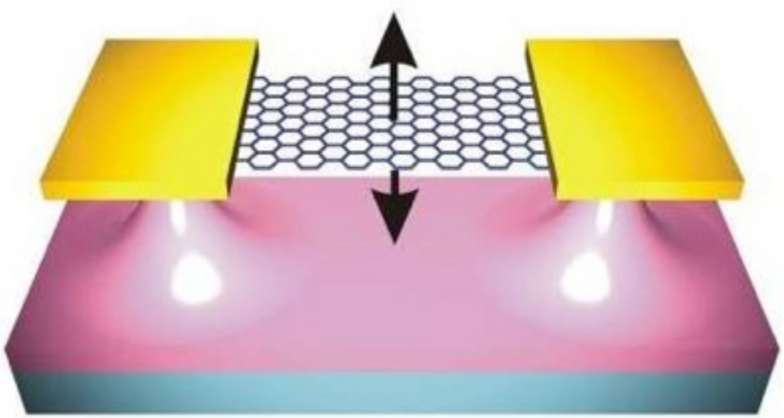
CNT relay and graphene resonator

- High on/off ration
- Low power
- High speed
- Carbon stable and light = high Q factors

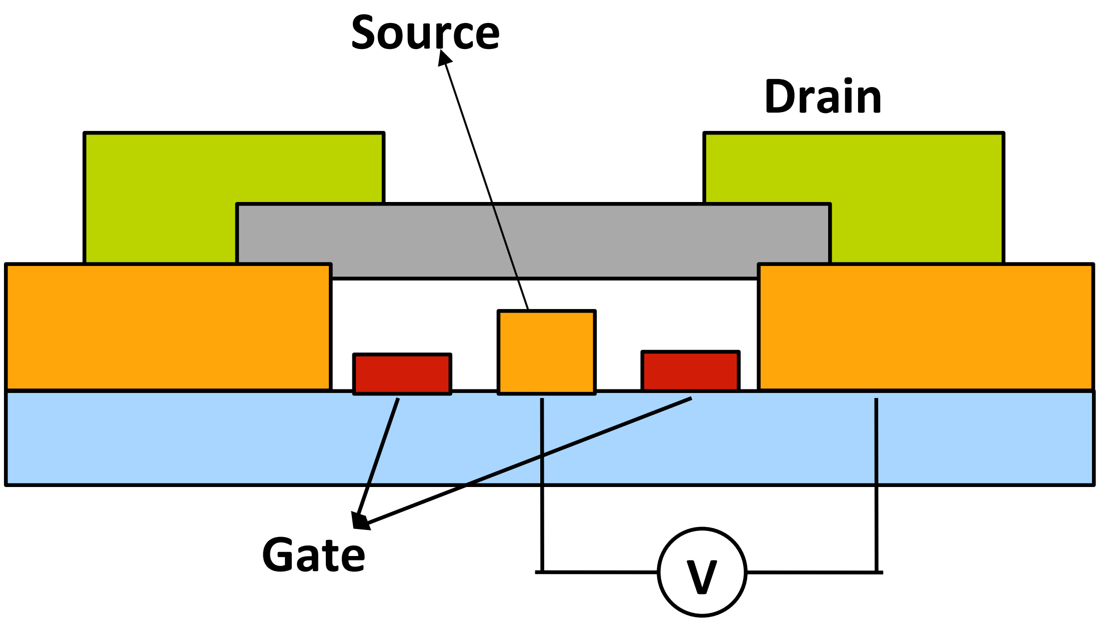


Nanorelay, Lee et al.
Nanoletters 2003



Bachthold et al. 2009

Micromechanical switch

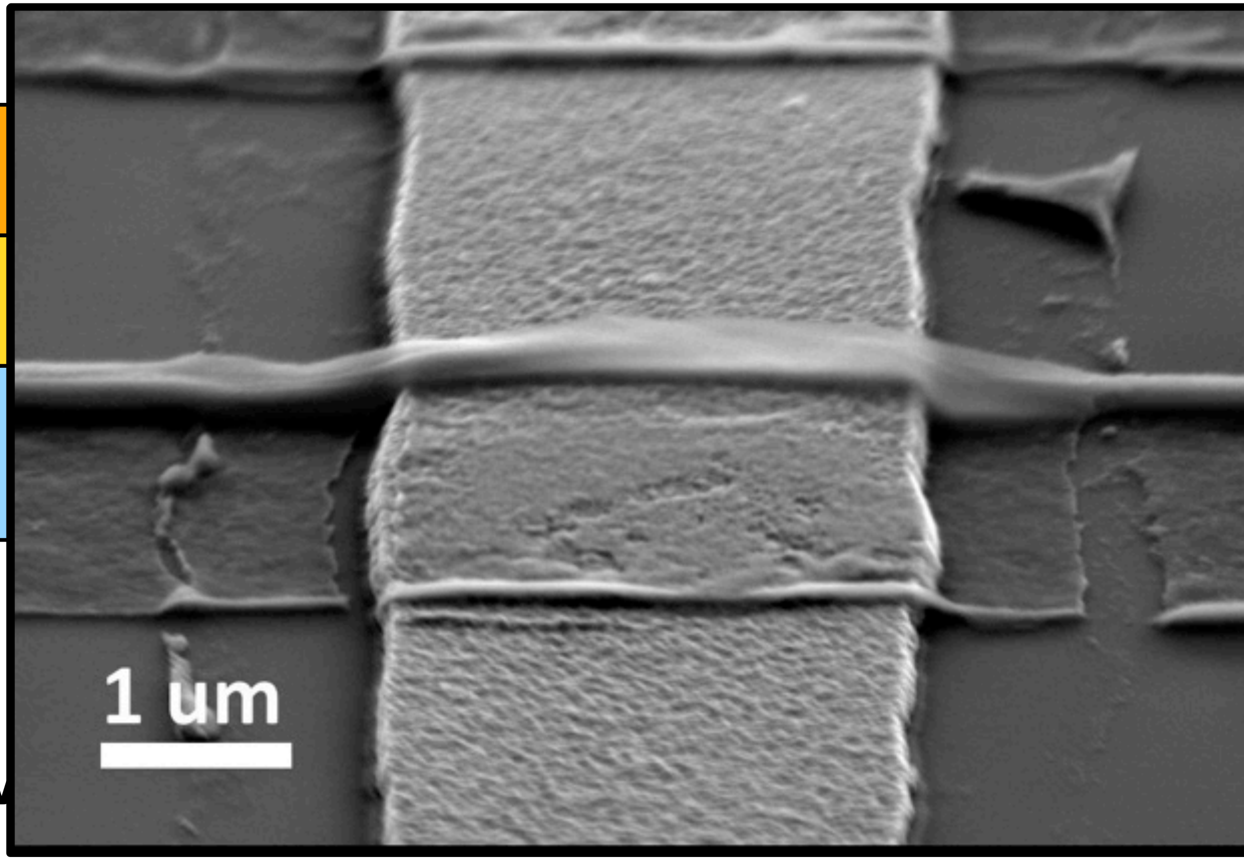


Advantages

- very high on-off ratios
- can have very high operating frequencies
- can be used with loaded graphene for sensing applications
-robust in extreme environments

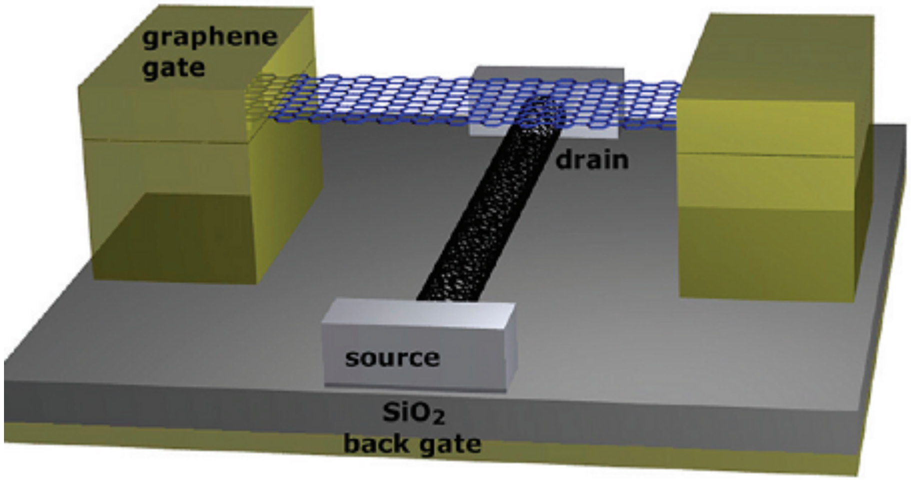
Kumar et al. unpublished

Suspended graphene



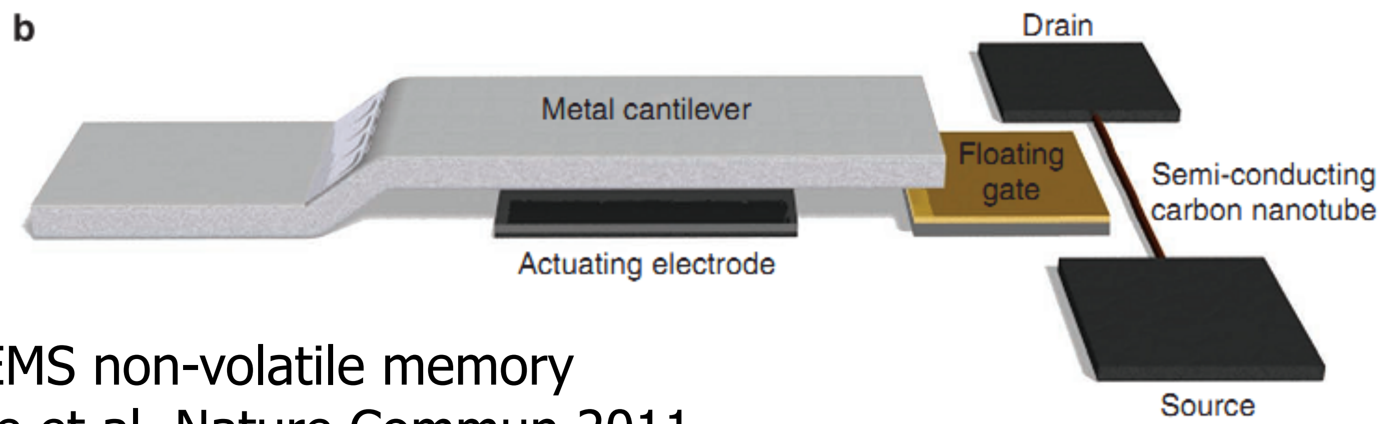
Surface tension breaks G → use critical point dryer

Carbon NEMS devices



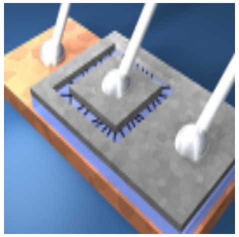
Overcome Subthreshold limit

Moving gate,
Svenson et al. Nanoletters 2011

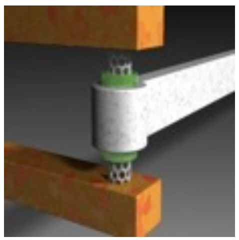


NEMS non-volatile memory
Lee et al. Nature Commun 2011

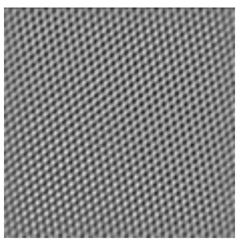
Conclusions



Lateral carbon FETs may have application as power transistors or in flexible, transparent electronics, sensors etc. (More than Moore)

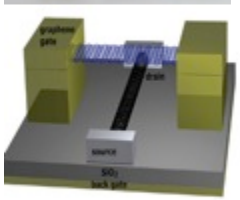


Vertical FET face integration challenges (high k, contact engineering, Growth of CNTs) but have a lot of potential



Graphene can be synthesized and processed on the large scale but band gap engineering/passivation is crucial – potential for Spintronics and NEMS

New 2D Materials have a lot of potential for electronics and energy harvesting



Carbon NEMS have superior properties

Acknowledgements

Collaborators

Prof G.T Kim – Korea University

Prof. Coleman – TCD

Prof. Boland - TCD

Group: Shishir Kumar, Niall McEvoy, Chan Young Yim, Gareth Keeley, Ehsan Rezvani, Hugo Nolan, Nikos Peltekis (now Intel) Anne Weidlich, Toby Halham, Chris Murray (Intel),

Hye-Young Kim, Kangho Lee (KU)

Support by Science Foundation Ireland, Enterprise Ireland, Embark Initiative HEA, EU for Marie Curie, FP7 (Electrograph)

Intel Ireland LTD, Hewlett Packward, Infineon AG