Graphene: the Route from Touch Screens to Digital Nanoelectronics

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http://www.nanotechnology.hu/

Human History (may be) regarded from the point of view of materials science

- From the Stone Age the development of civilization was made possible by the discovery of new materials and new ways of modifying materials
  - Stone Age (Paleolithic, Neolithic)

  - Bronze Age
  - Iron Age
  - ……….
  - Steel Age (end of XIX., first half of XX. cent.)

  - Silicon Age (IC, PC, mobile phone, etc. end of XX. century, beginning of XXI. century)

  - (**NANO**)CARBON Age?

Electronic history

Electronic tube 1920

First transistor 1947

First commercial transistor 1950

Integrated circuit 1990

Piece of furniture

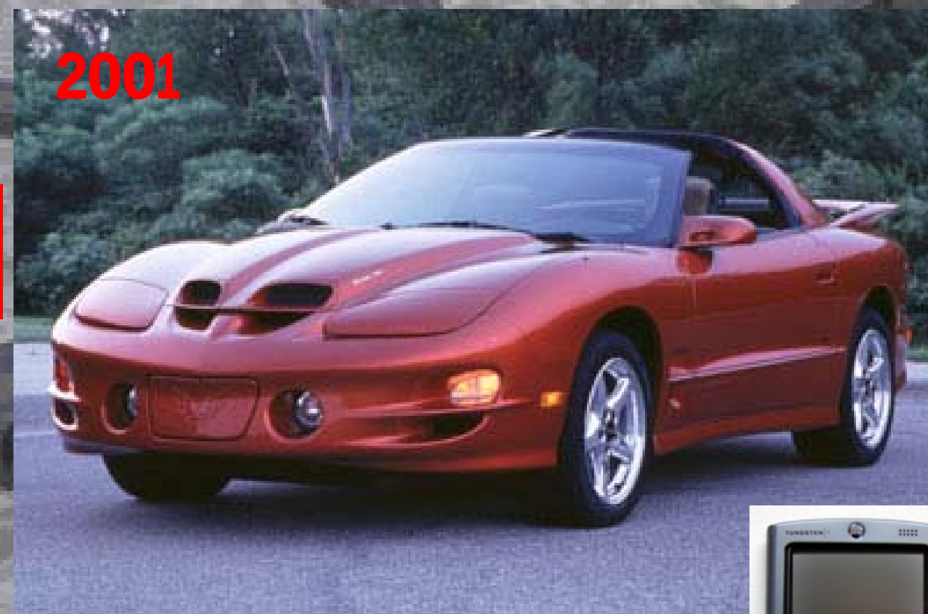
Portable

Smart & pocket size

Technical (r)evolution induced by materials & effects on everyday life

The first car was in fact a chaise without horses ....

Steel



ENIAC, 20.000 electronic tubes ...

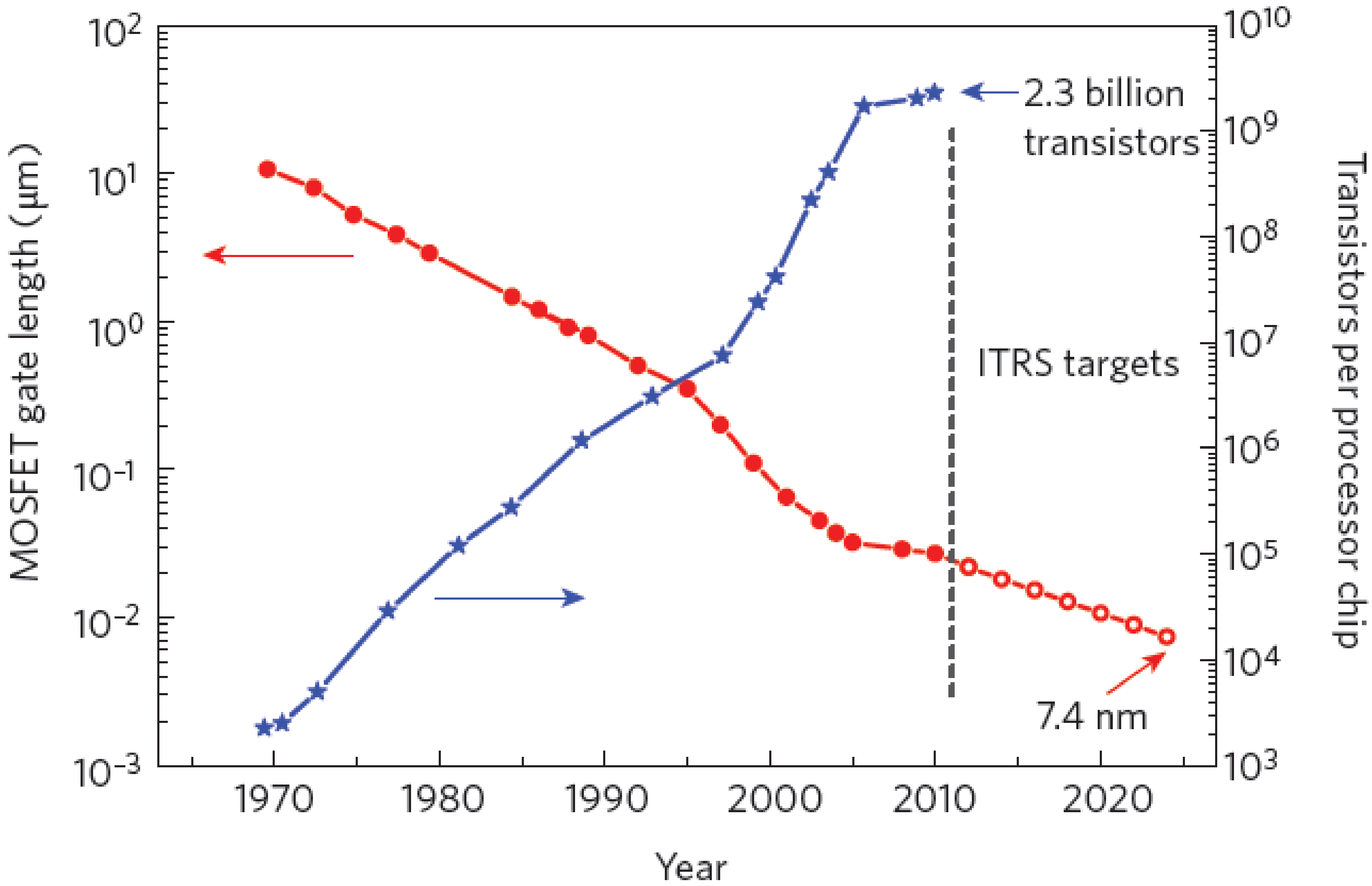
Silicon

2002

Trends in digital electronics

F. Schwierz, Nat. Nanotech. Published online: 30 May 2010

doi: 10.1038/nnano.2010.89



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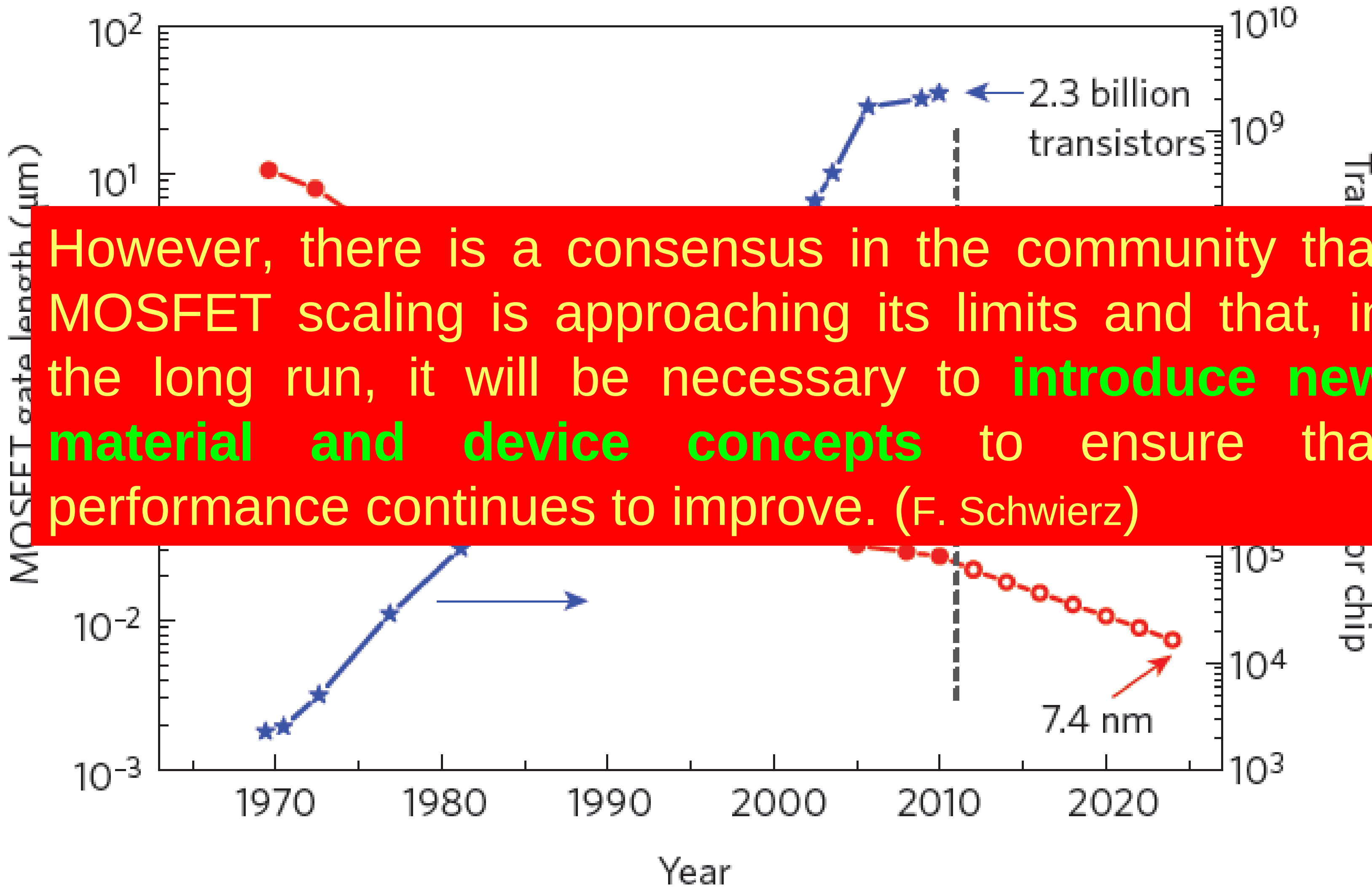


However, there is a consensus in the community that MOSFET scaling is approaching its limits and that, in the long run, it will be necessary to **introduce new material and device concepts** to ensure that performance continues to improve. (F. Schwierz)

End of the ROAD(map)

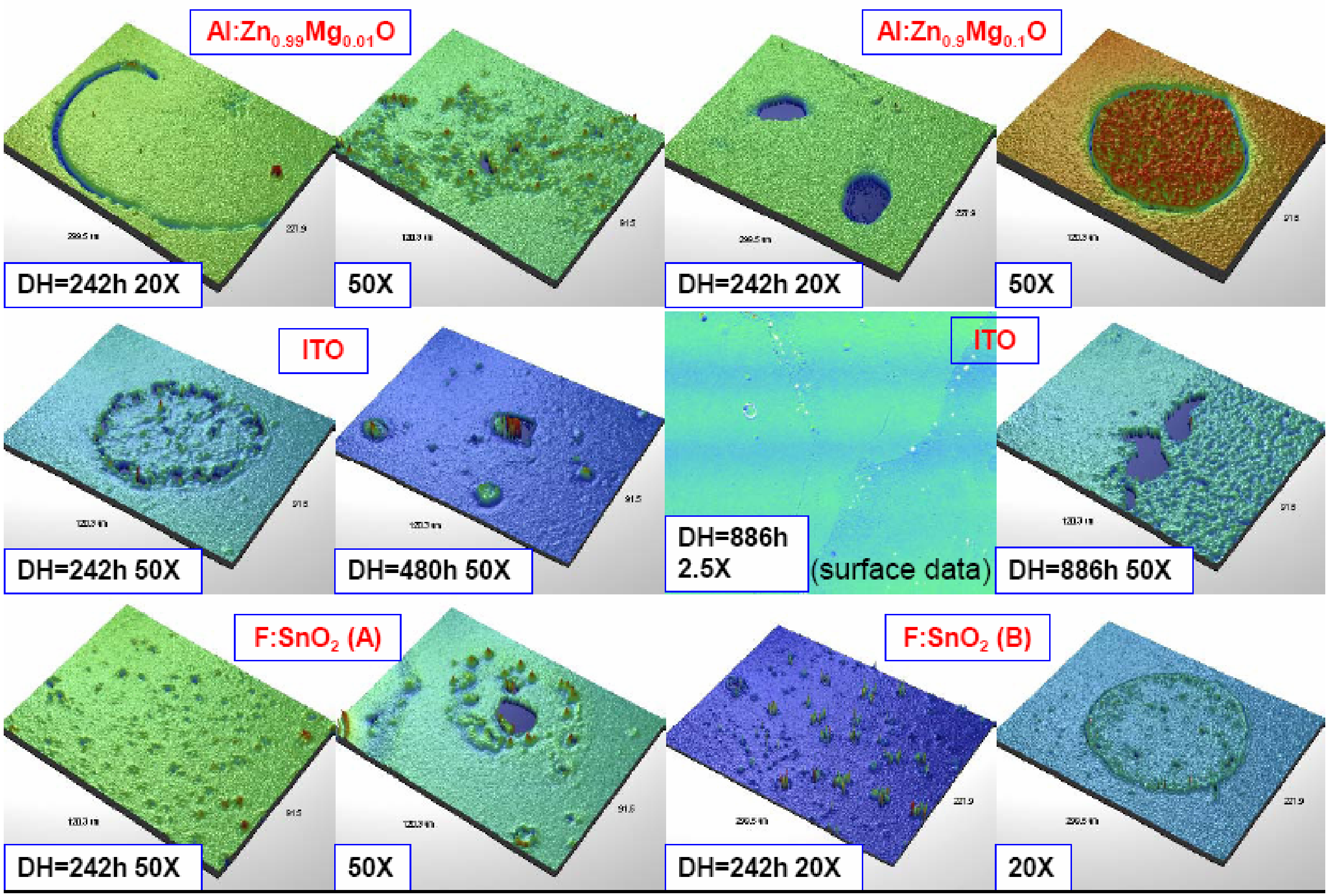
The International Technology Roadmap for Semiconductors[1] (ITRS), which is sponsored by the five leading chip manufacturing regions in the world (Europe, Japan, Korea, Taiwan, and the United States), and has the objective of ensuring cost-effective advancements in the performance of the integrated circuit, has clearly identified an end-of-life for scaled complementary metal–oxide–semiconductor (CMOS) technology around 2022. The causes for the demise of silicon-based

ITRS International Technology Roadmap for Semiconductors

http://www.itrs.net/

(**NANO**)CARBON?

Stability Issues of Transparent Conducting Oxides (TCOs) for Thin-Film Photovoltaics



Indium is becoming a „problem" material

From: Prof. J. Pern, NREL

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy operated by the Alliance for Sustainable Energy, LLC

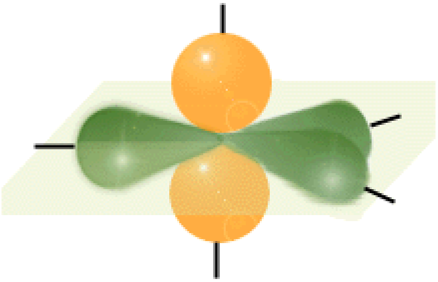
Graphene vs. Si

- Charge carrier mobility
  - 200.000 cm^2/Vs (Si: 1400 cm^2/Vs)
- Charge carrier density
  - 3×10^{12} cm^{-2} (Si: 1.3×10^{10} cm^{-3} intrinsic)
- Current density
  - 2.3×10^9 A/cm^2 (Si: 3×10^5 A/cm^2 on transistor)
- Thermal conductivity
  - 5000 $Wm^{-1}K^{-1}$ (Si: 163 $Wm^{-1}K^{-1}$ at room temp.)
  - (heat dissipation on nanoscale is a serious issue!!!)

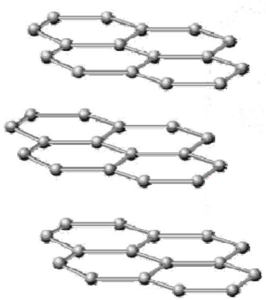
Transparent & the strongest material known

Carbon before1985

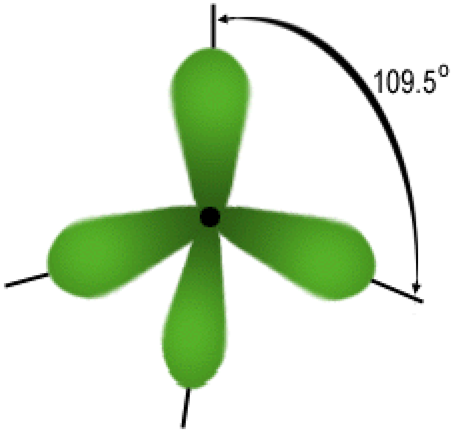
sp²

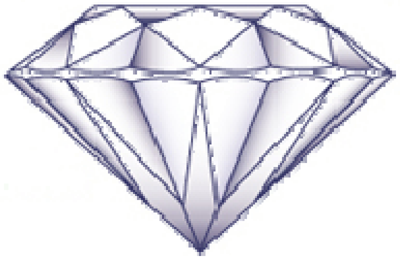


Graphite

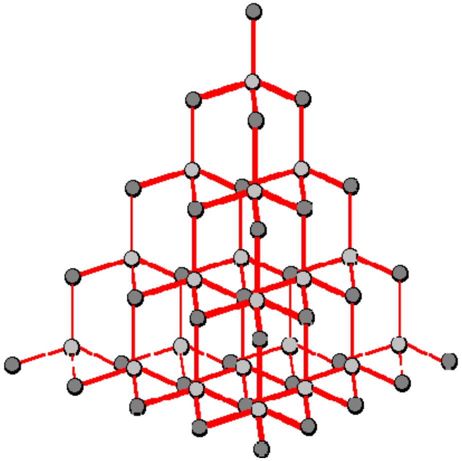


sp³

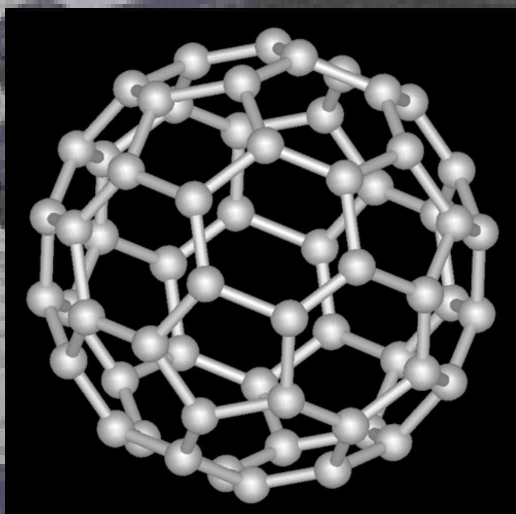
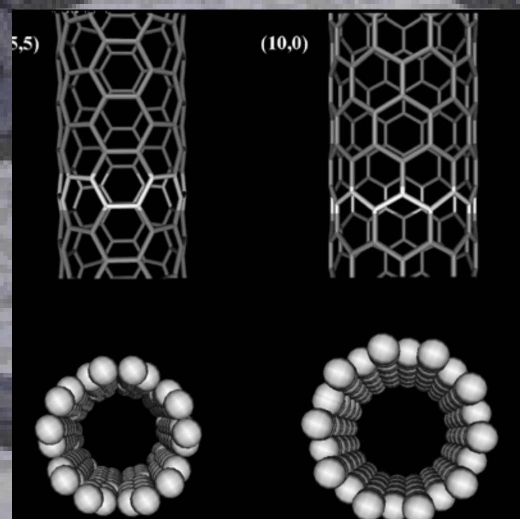
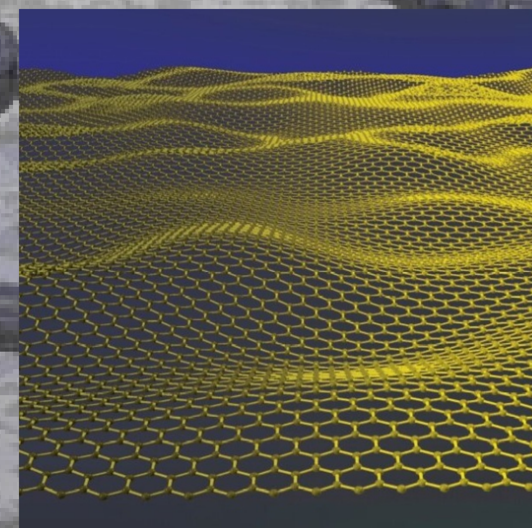


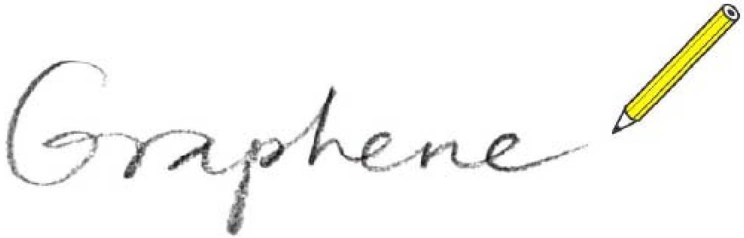


Diamond



The family of carbon nanostructures

Fullerene	Carbon nanotube	Graphene
	 	
1985 **H.W.Kroto, R. Smalley & R. Curl**	**1991** **S. Iijima**	**2004** **K. S. Novoselov & A. Geim**
Nobel Prize 1996	Kavli Prize 2008	Nobel Prize 2010



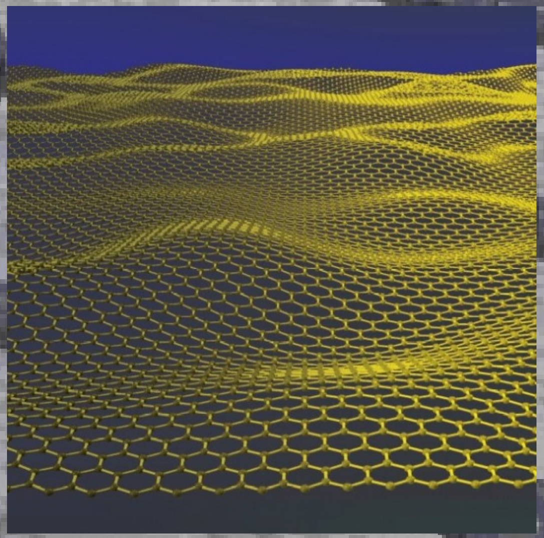
[redacted] nanostructures

be

Graphene

Andre Geim **Kostya Novoselov**

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

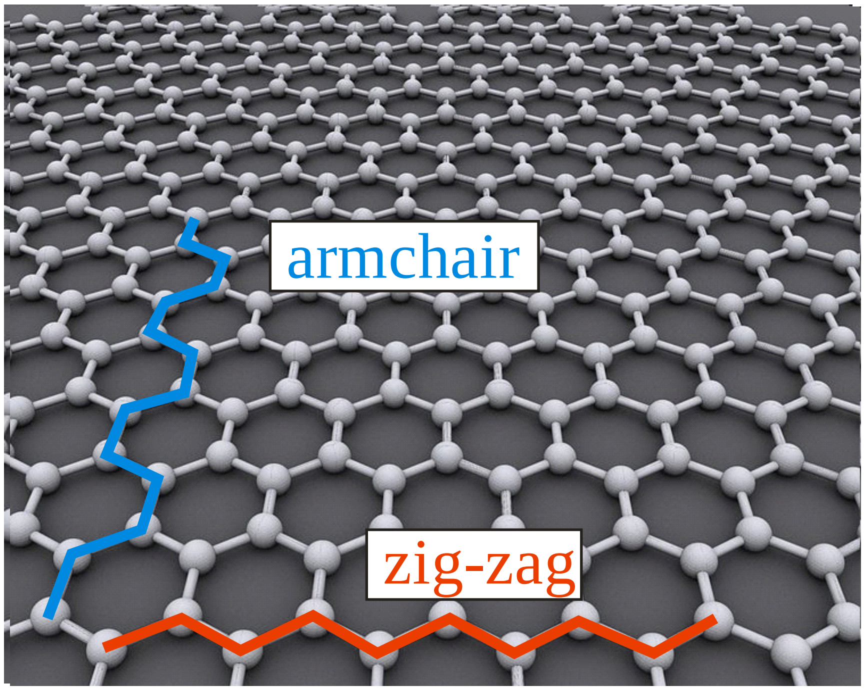


2004

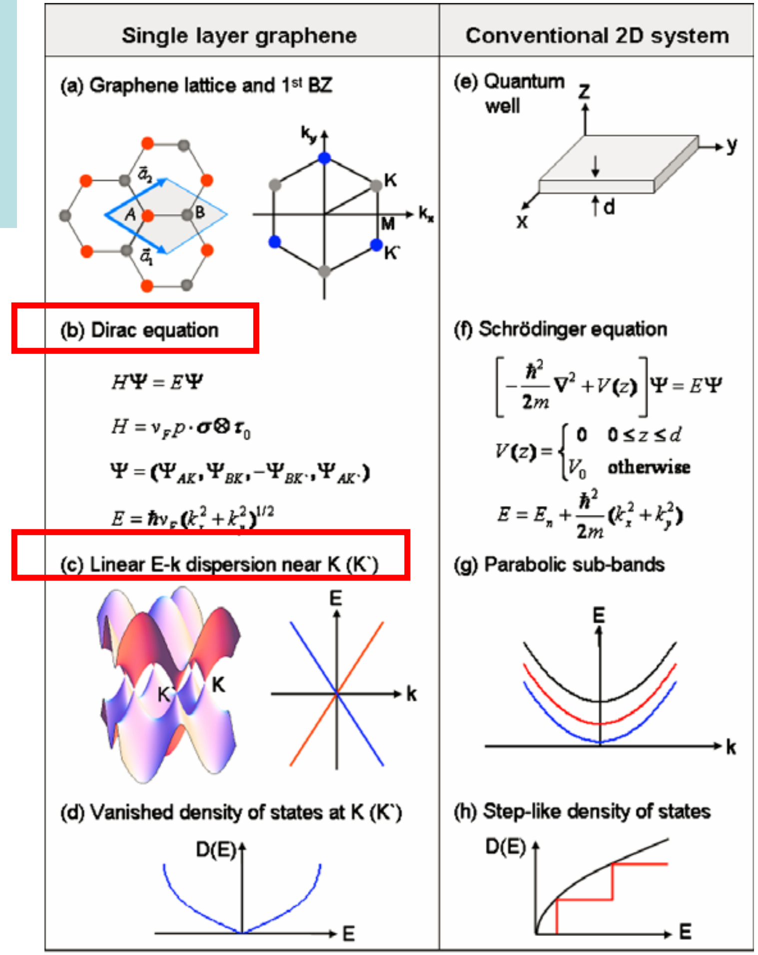
KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

THE NOBEL PRIZE IN PHYSICS 2010

Structure & Electronic structure



http://en.wikipedia.org/wiki/File:Graphen.jpg

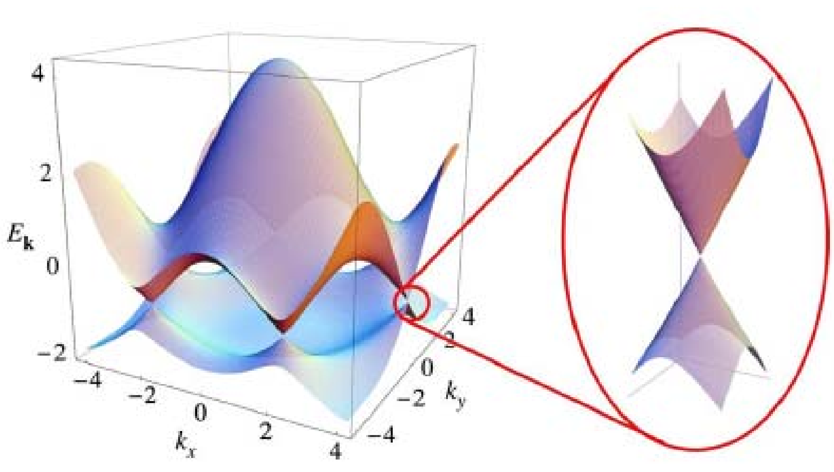


Wu, Y. H.; Yu, T.; Shen, Z. X. *J. Appl. Phys.* **2010**, *108*, 071301.

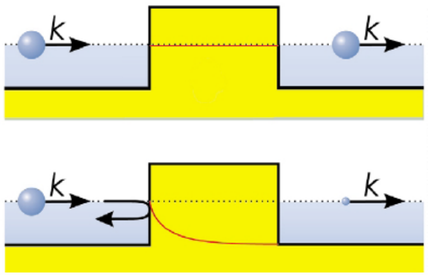
C-C bond shorter than in diamond!

The FIRST truly one single atom thick material!
Different properties along different crystallographic directions.
EXTRAORDINARY electronic structure!

Linear dispersion & Klein tunneling



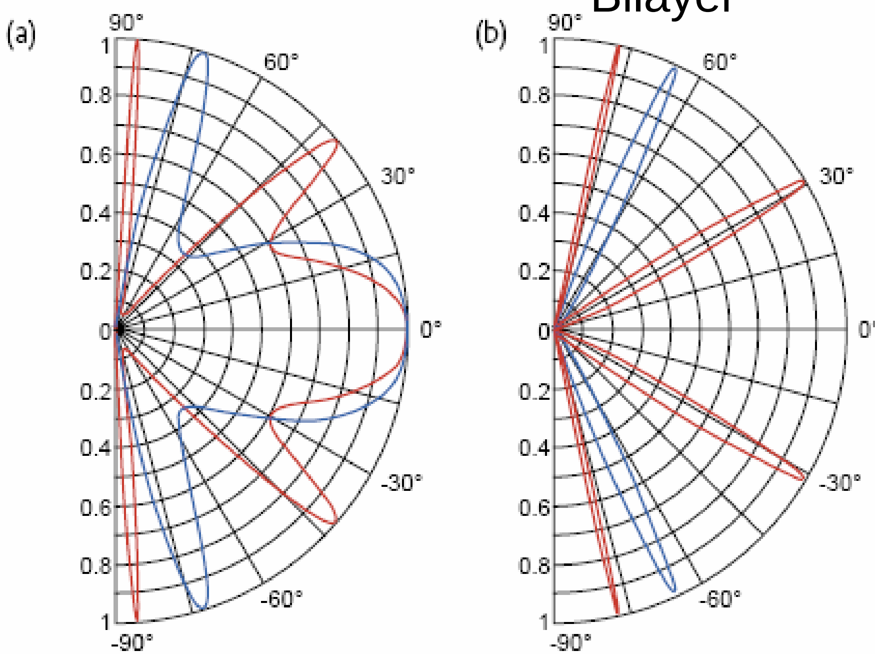
A. H. Castro Neto et al., *Rev. Mod. Phys.* **2009**, *81*, 109-162



Graphene

Regular material

Bilayer



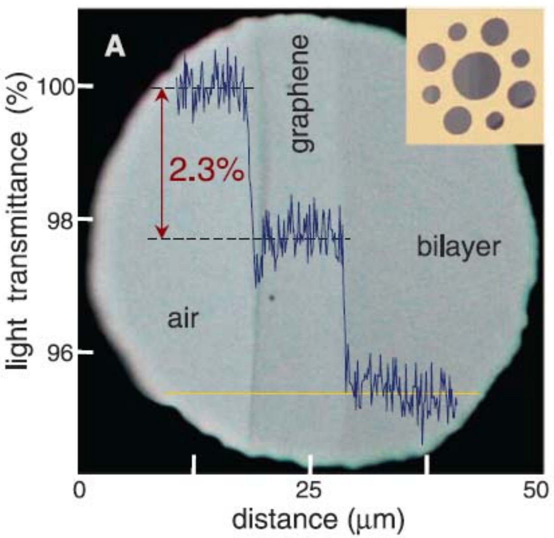
Katsnelson, M. *Materials Today* **2007**, *10*, 20-27.

$p = 1 \times 10^{12}$ cm^{-2}

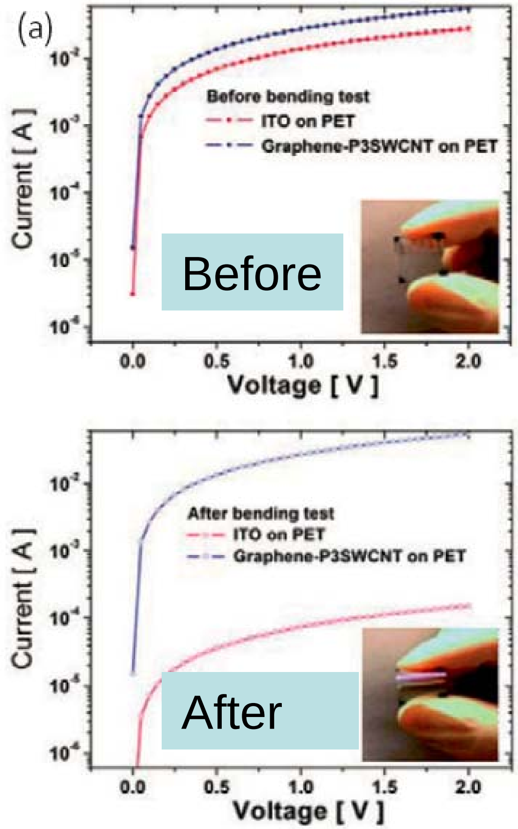
$p = 3 \times 10^{12}$ cm^{-2}

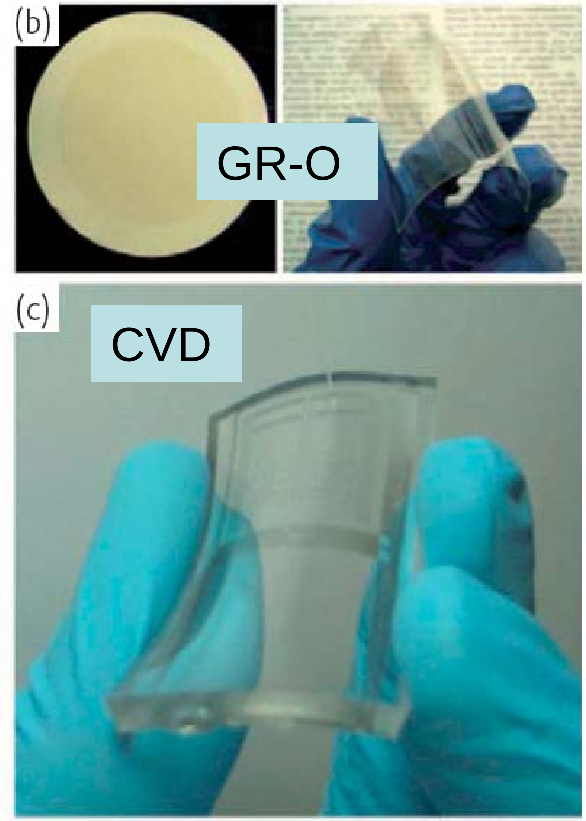
The charge carriers cannot be confined by electrostatic barriers like in conventional semiconductors

Transparent & flexible material



Nair, R. R. et al. *Science* **2008**, *320*, 1308.

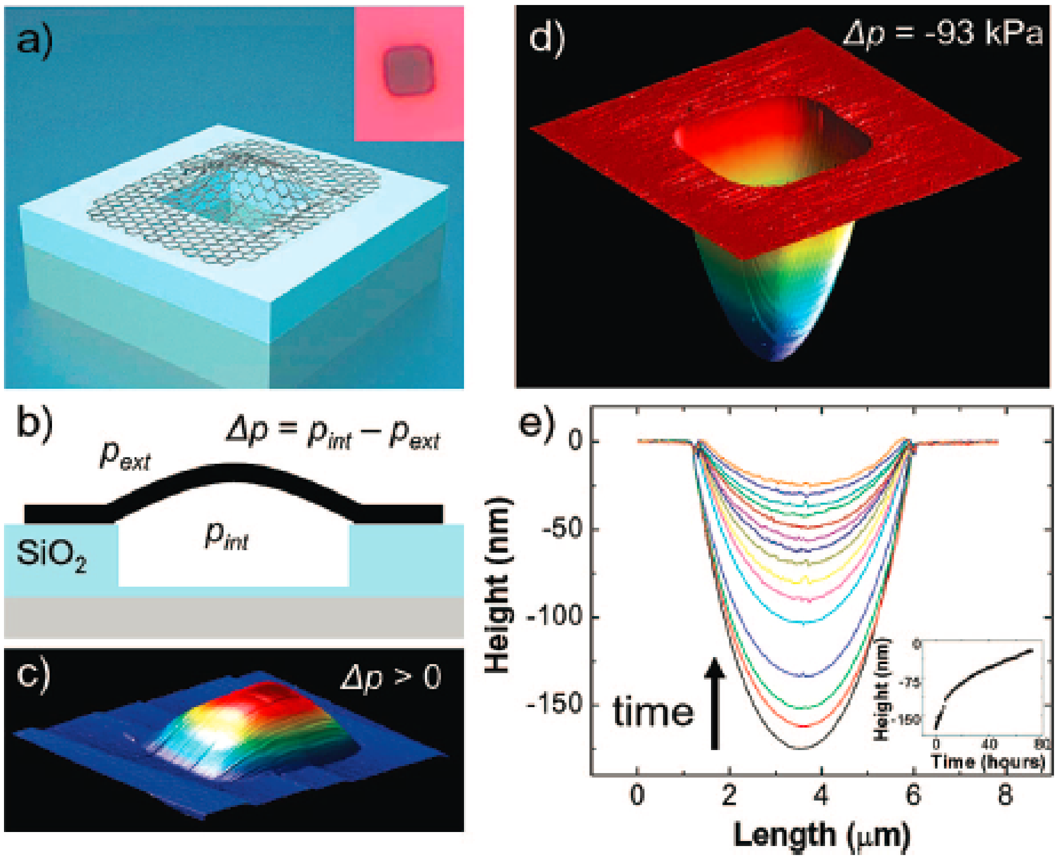




Bending graphene vs. ITO on PET

Wassei, J. K.; Kaner, R. B. *Materials Today* **2010**, *13*, 52-59.

Highly stretchable material, impermeable to gases



AFM image Δz = 175 nm

AFM linecuts in time (3 days!)

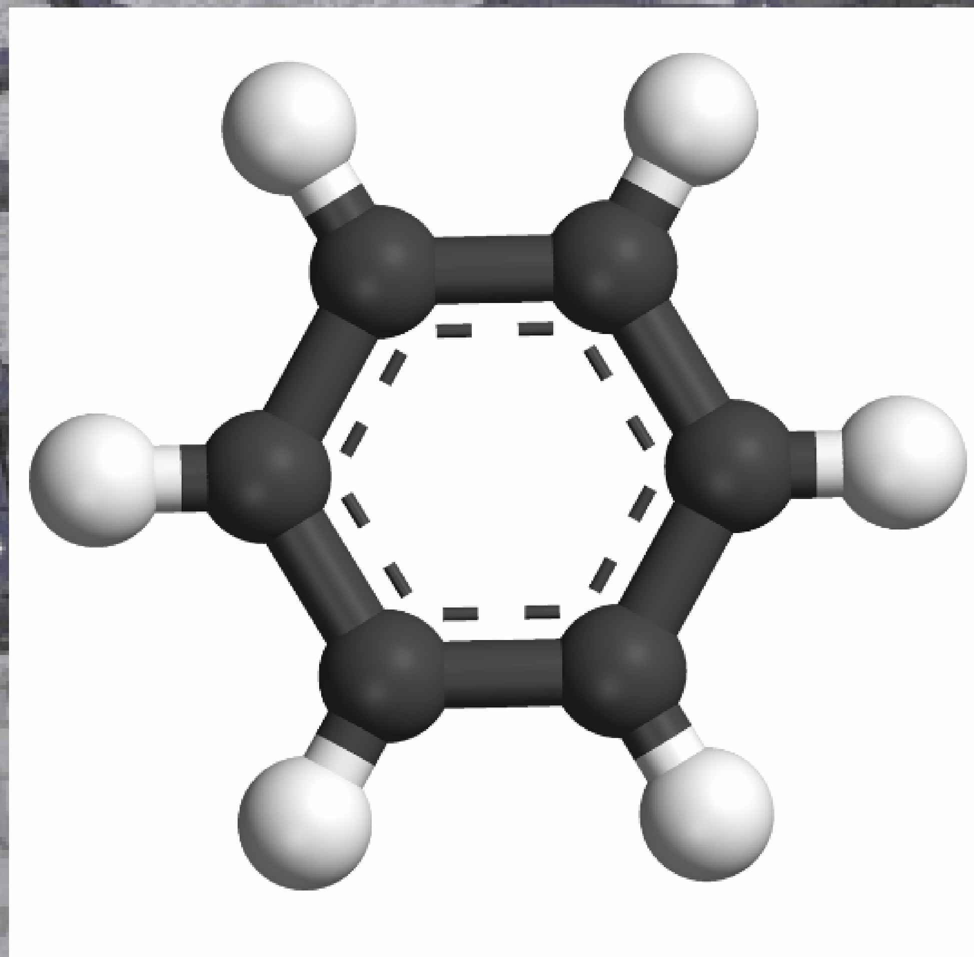
Bunch, J. S. et al, *Nano Lett.* 8 (2008) 2458 .

Properties & Applications

Linear dispersion

High mobility

Unique optical properties



One atom thin

High strength

Highly stretchable

Properties & Applications

Quantum Hall Effect & Spintronics

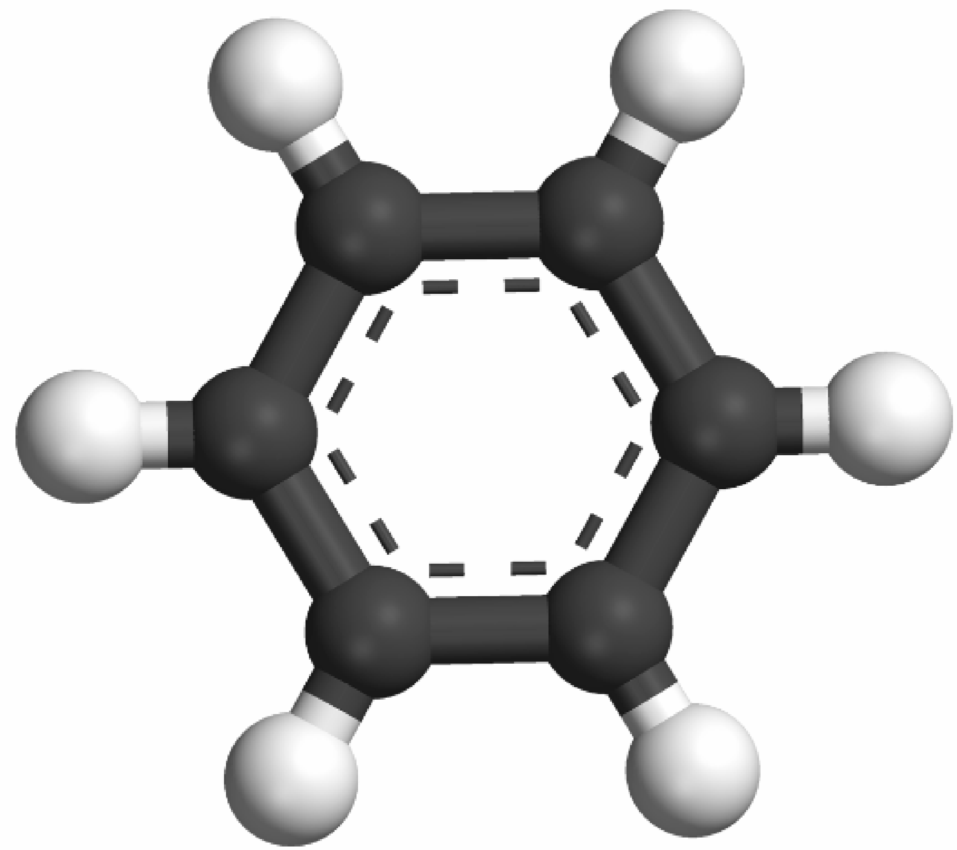
Linear dispersion

Transistors

High mobility

Photovoltaics

Unique optical properties



One atom thin

Membranes, ultracapacitors

High strength

Composites

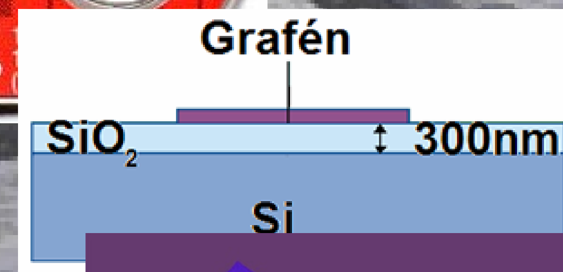
Highly stretchable

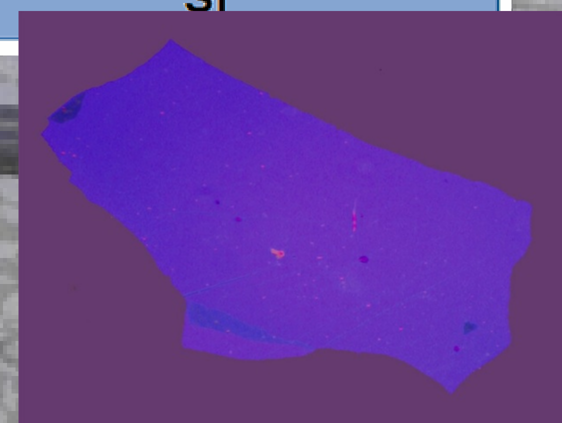
Transparent & flexible conductors

Production of graphene

- Micromechanical cleavage

- Epitaxy on SiC
- **CVD (**Ni, Pt, Rh**, Cu)**
- Chemical exfoliation (G-O, oxigene removal!)
- CNT „unzipping”
- and many other exotic methods ….





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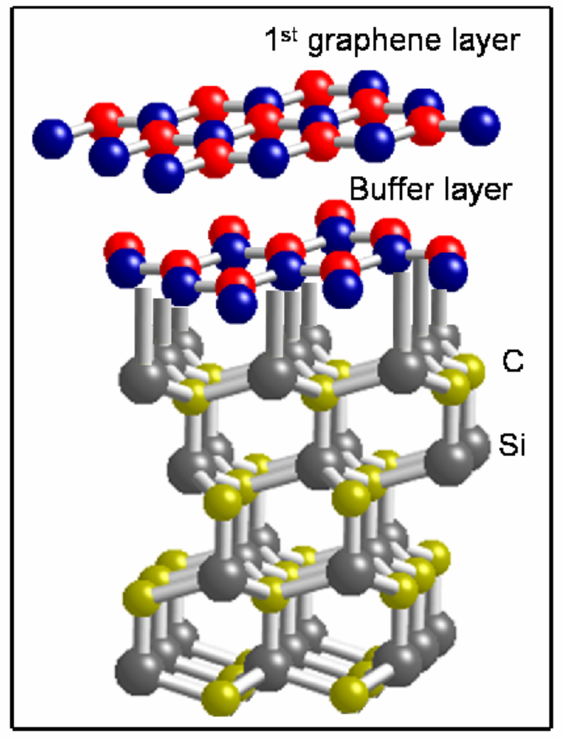

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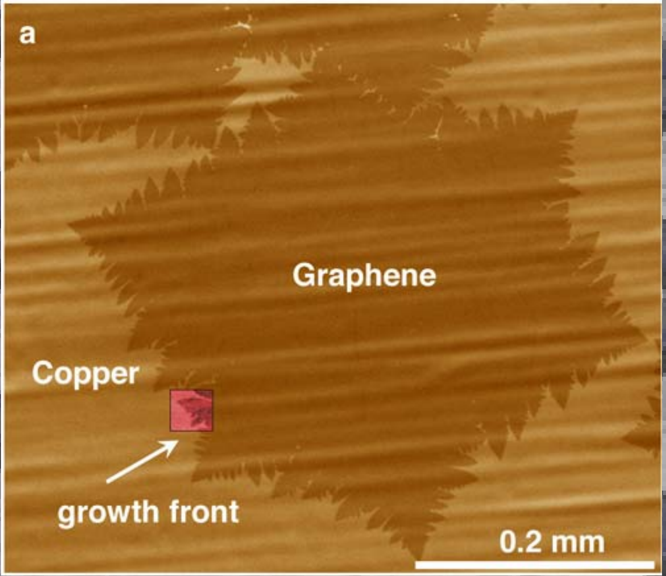

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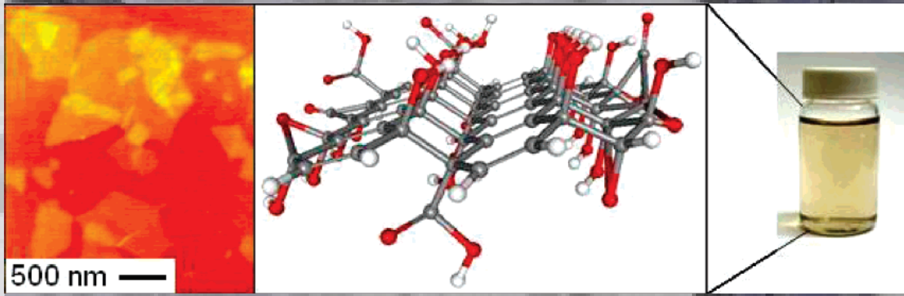

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„Roll-to-roll" large size CVD graphene

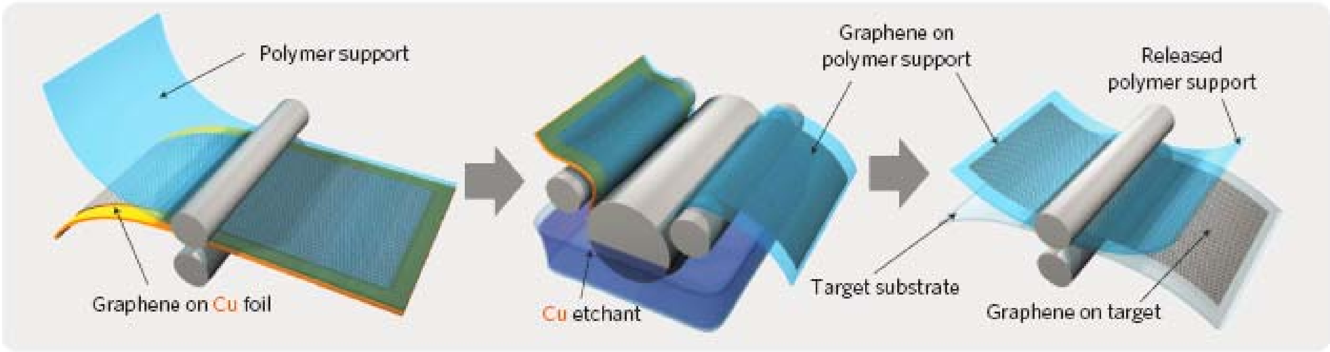
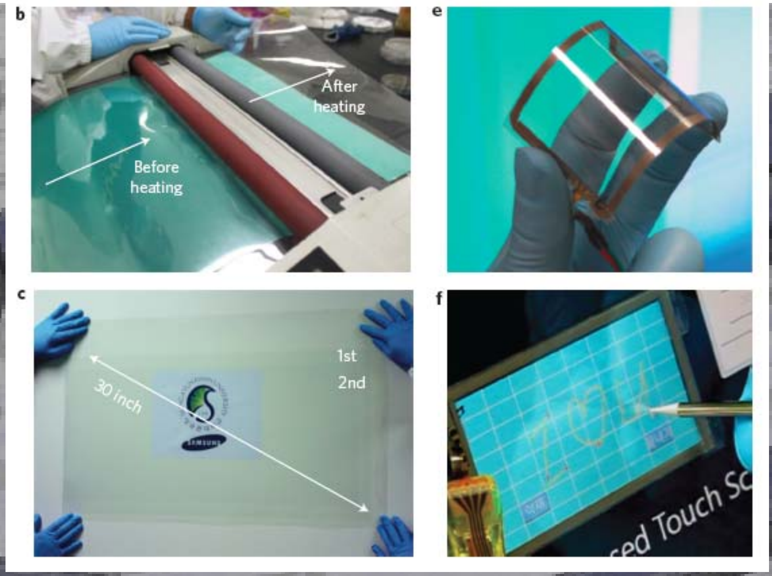


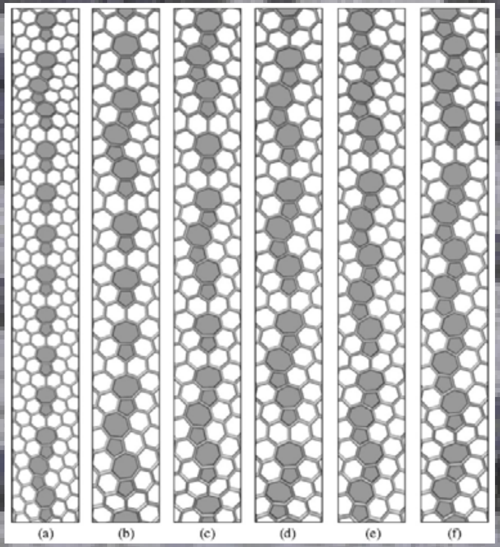
Figure 1 | Schematic of the roll-based production of graphene films grown on a copper foil. The process includes adhesion of polymer supports, copper etching (rinsing) and dry transfer-printing on a target substrate. A wet-chemical doping can be carried out using a set-up similar to that used for etching.



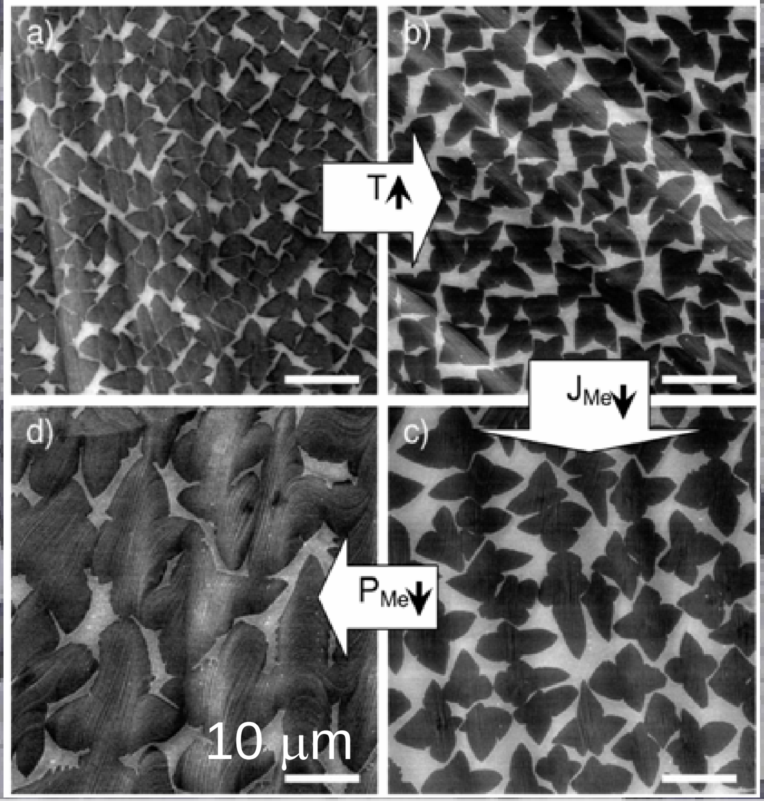
Bae, S. et al.,. *Nature Nanotechnology* **2010**, *5*, 574 .

The quality of the material is well suited for transparent conducting & flexible electrodes => market ready!

Grain boundaries in CVD grown graphene



Liu, T.-H., et al., *Carbon* **2011**, *49*, 2306



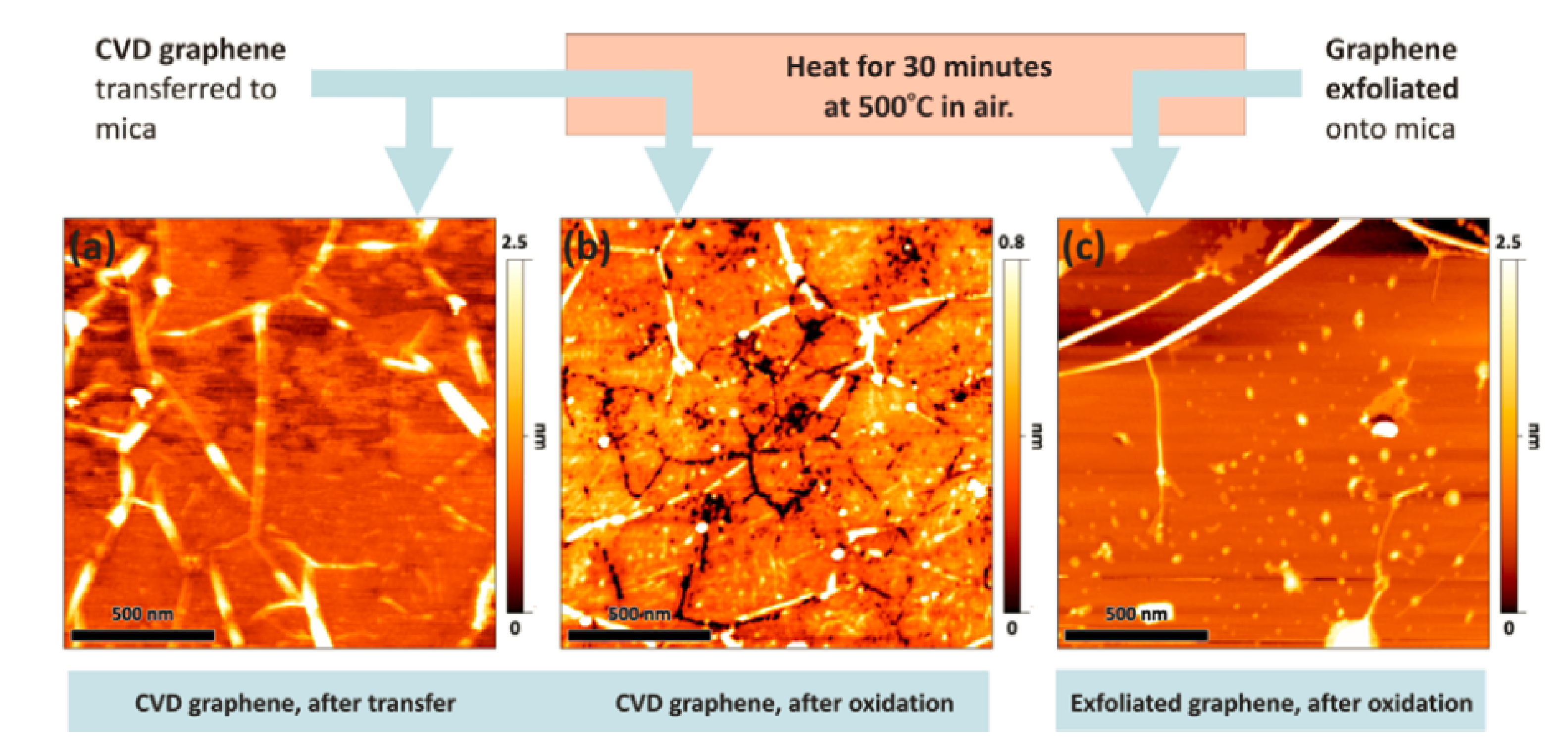
Li, X. et al. *Nano Letters* ***10*** *(* 2010) 4328.

The grain boundaries decrease the very high mobility values by 10 – 100 times.

The grain structure must be revealed for the optimization of the growth conditions.

Random nucleation => many grain boundaries

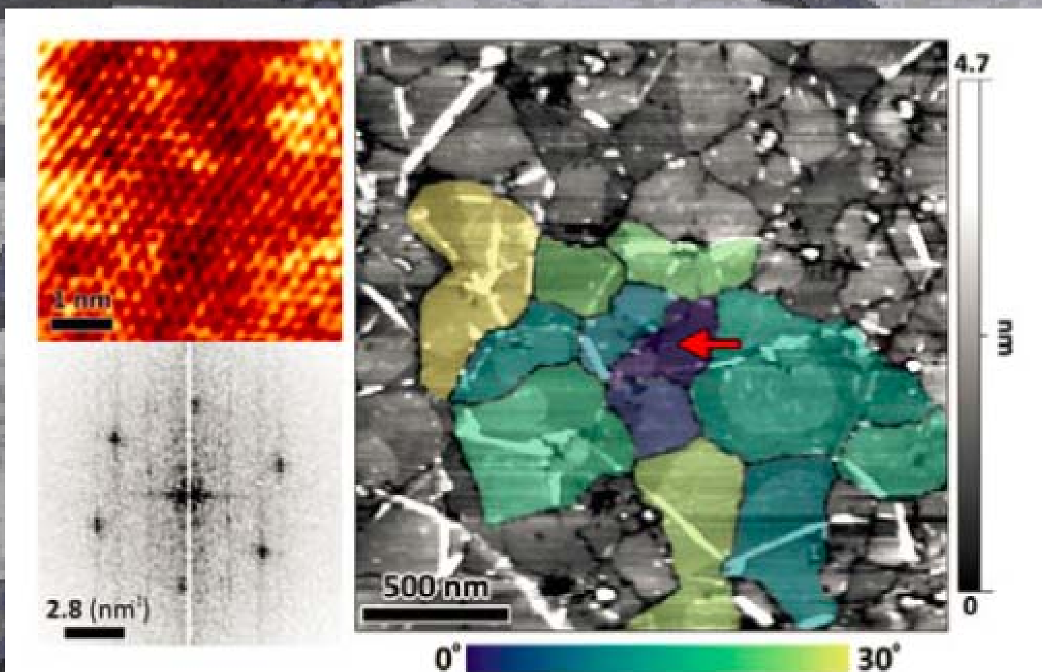
Characterization of grain structure by AFM

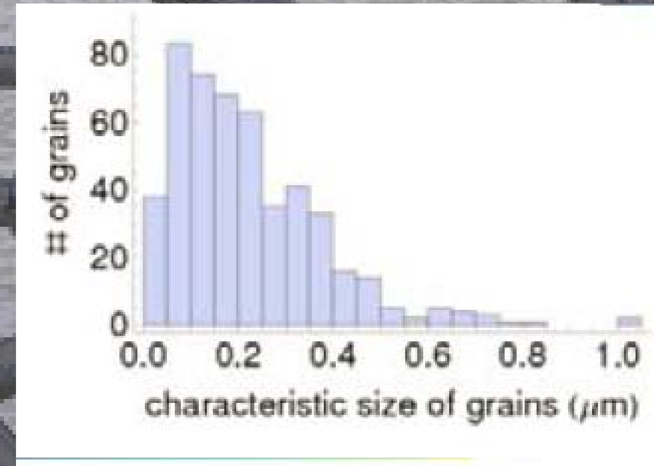


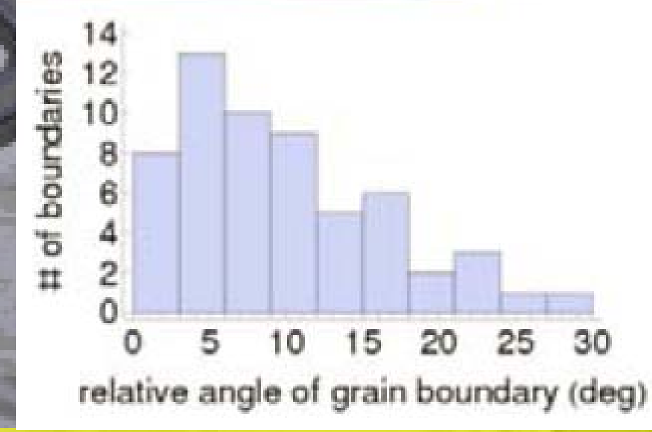
1. STEP: Reveal the grain boundaries by selective oxidation (negative comparison exfoliated graphene)

P. Nemes-Incze et al. Submitted to Appl. Phys. Lett

Characterization of grain structure by AFM







2. STEP: Analyze the grain size and the relative angle of grain boundaries by atomic resolution AFM images

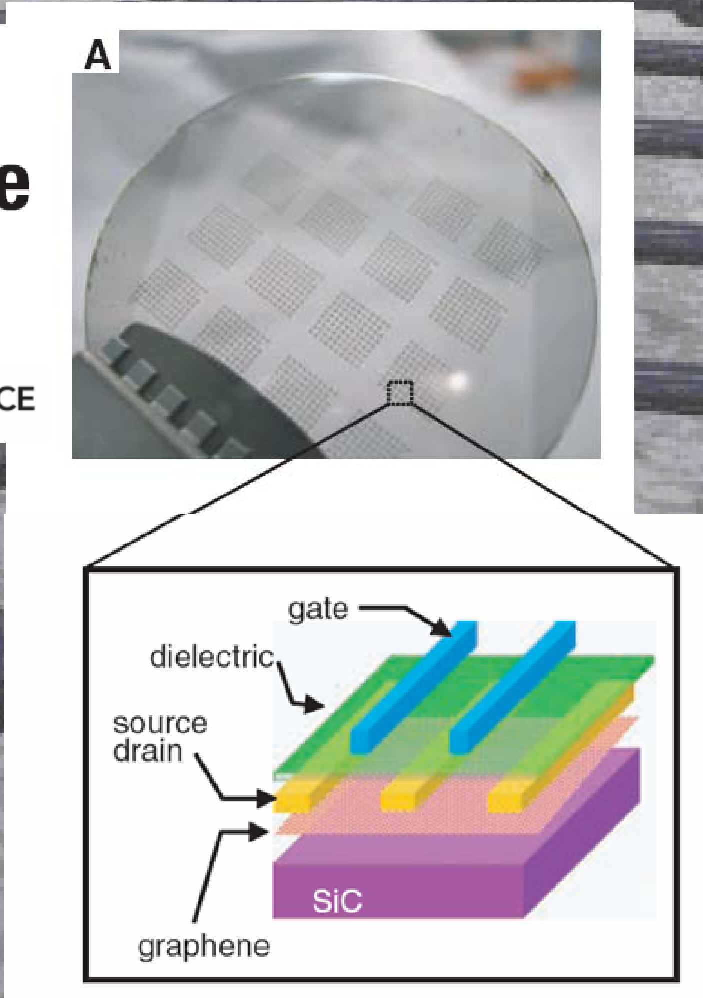
P. Nemes-Incze et al. Submitted to Appl. Phys. Lett

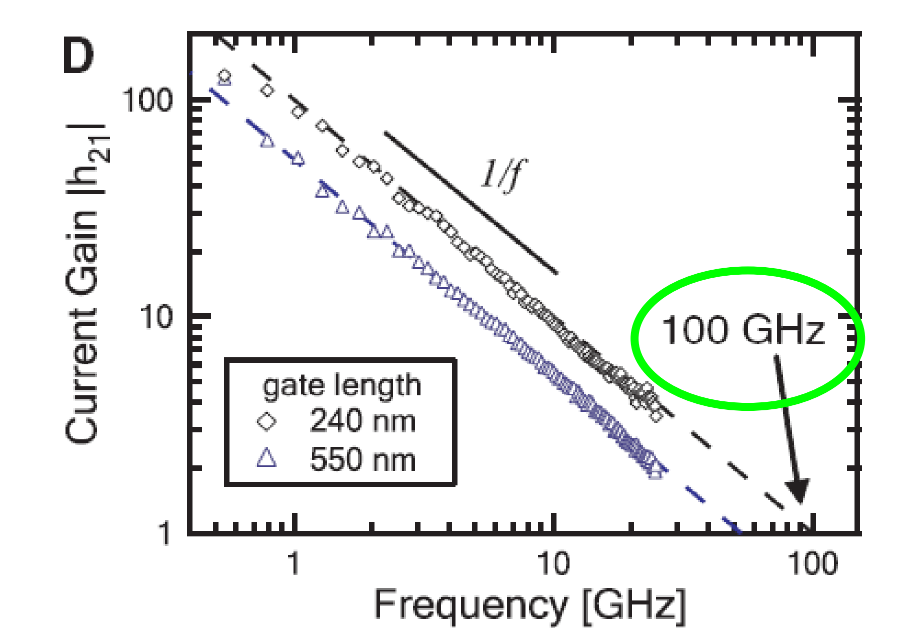
Application in high speed nanoelectronics

100-GHz Transistors from Wafer-Scale Epitaxial Graphene

Y.-M. Lin,* C. Dimitrakopoulos, K. A. Jenkins, D. B. Farmer, H.-Y. Chiu, A. Grill, Ph. Avouris*

662 5 FEBRUARY 2010 VOL 327 SCIENCE



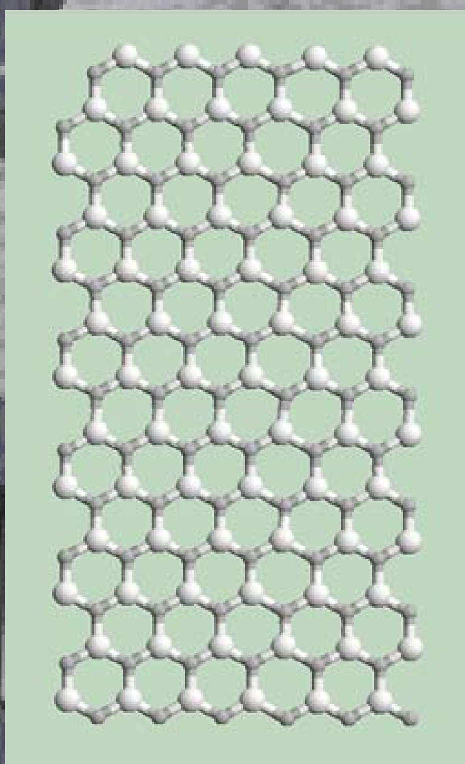


NO „switched off" state => **NO** DIGITAL applications

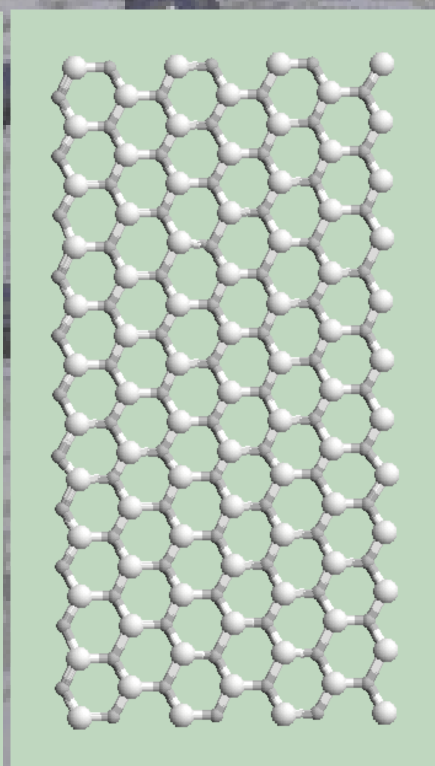
The electronic structure has to be reengineered – Badgap induced by confinement

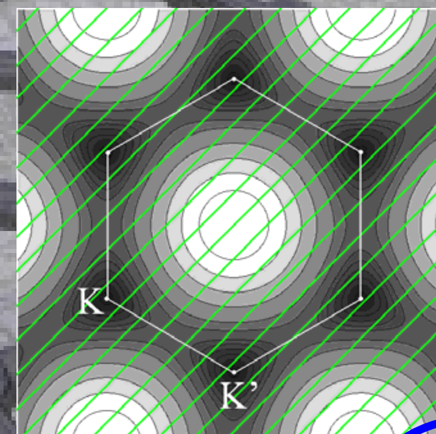
Graphene nanoribbons

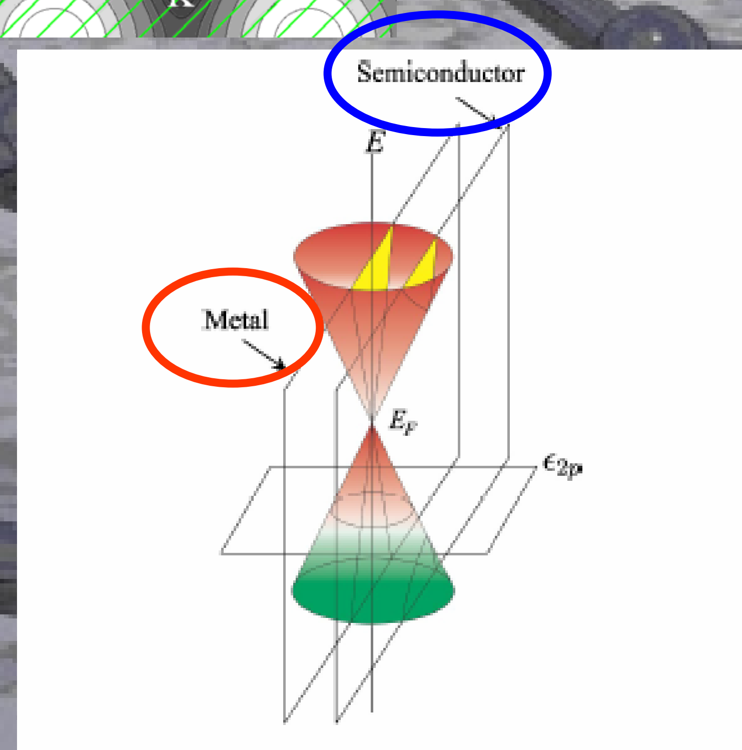
Armchair



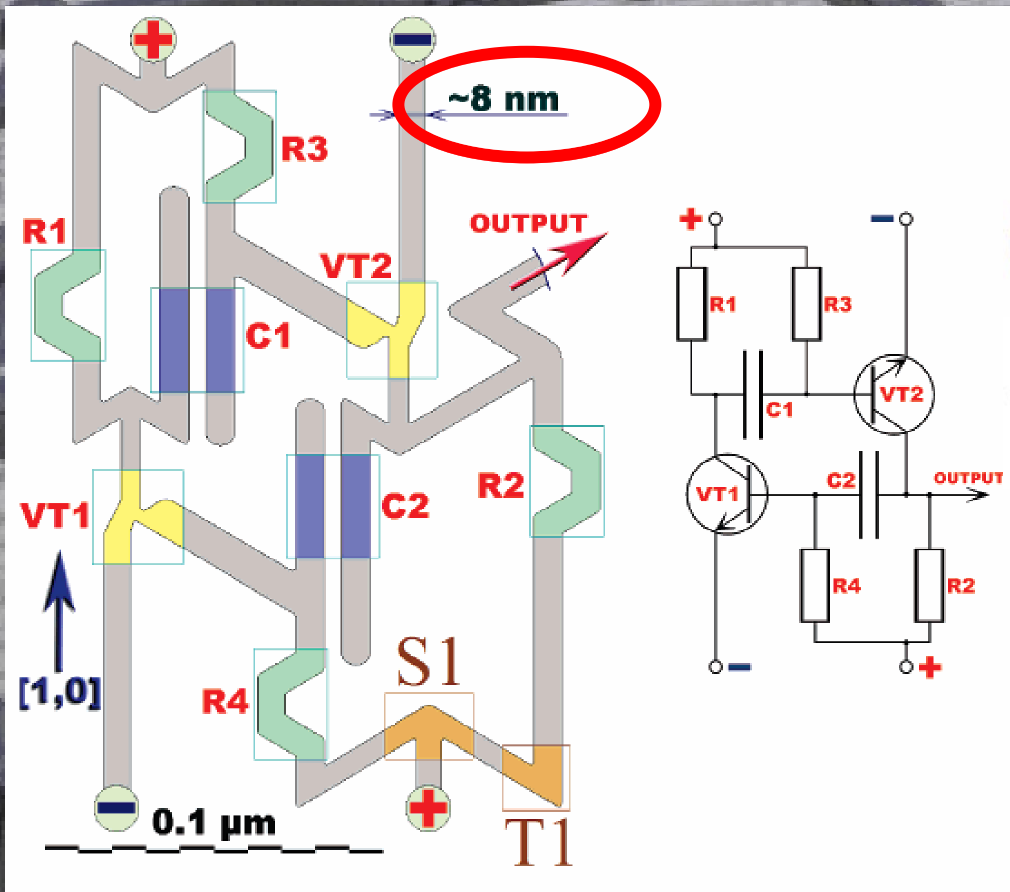
Zigzag

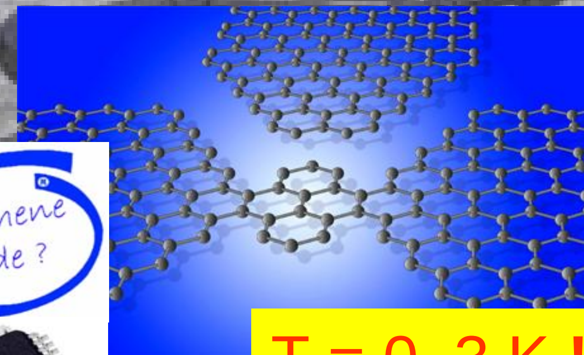




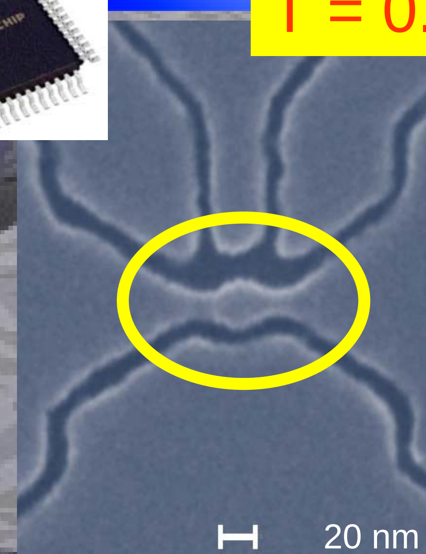


ALL GRAPHENE nanoelectronics





T = 0. 3 K **!!!**

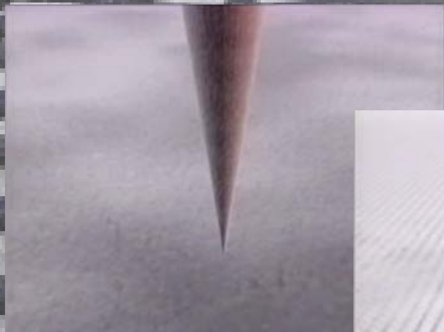


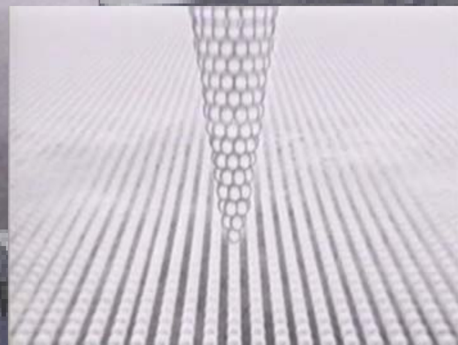
SET

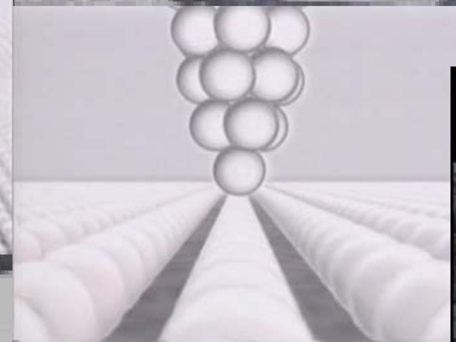
Areshkin, D. A.; White, C. T. *Nano letters* **2007**, *7*, 3253

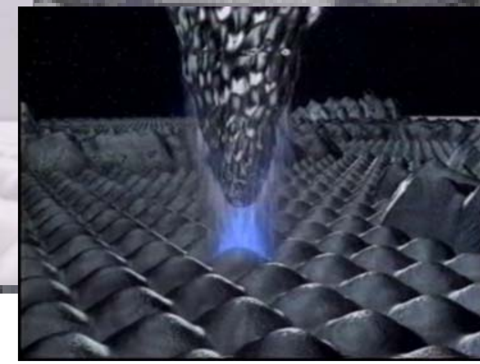
Ponomarenko, L.. *Science* **2008**, *320*, 356-

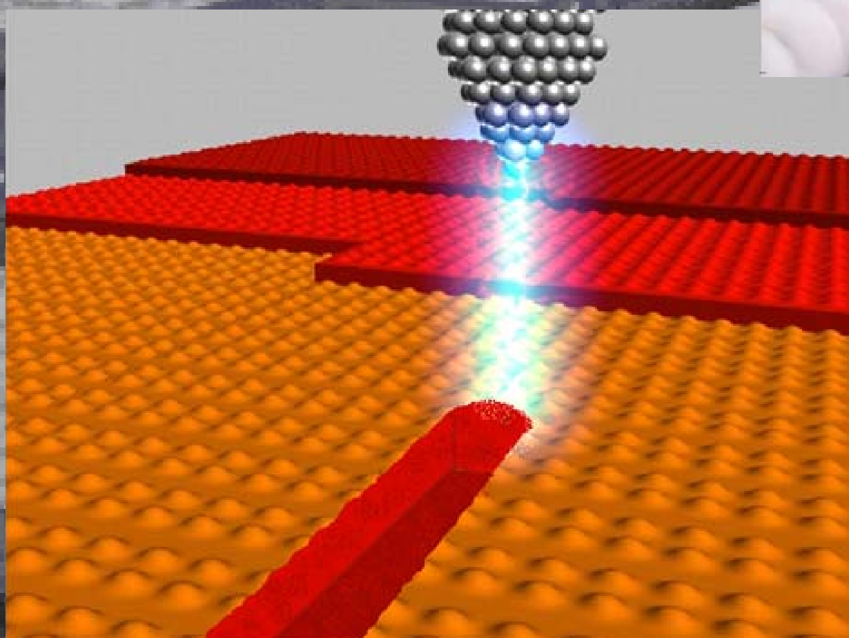
STM lithography









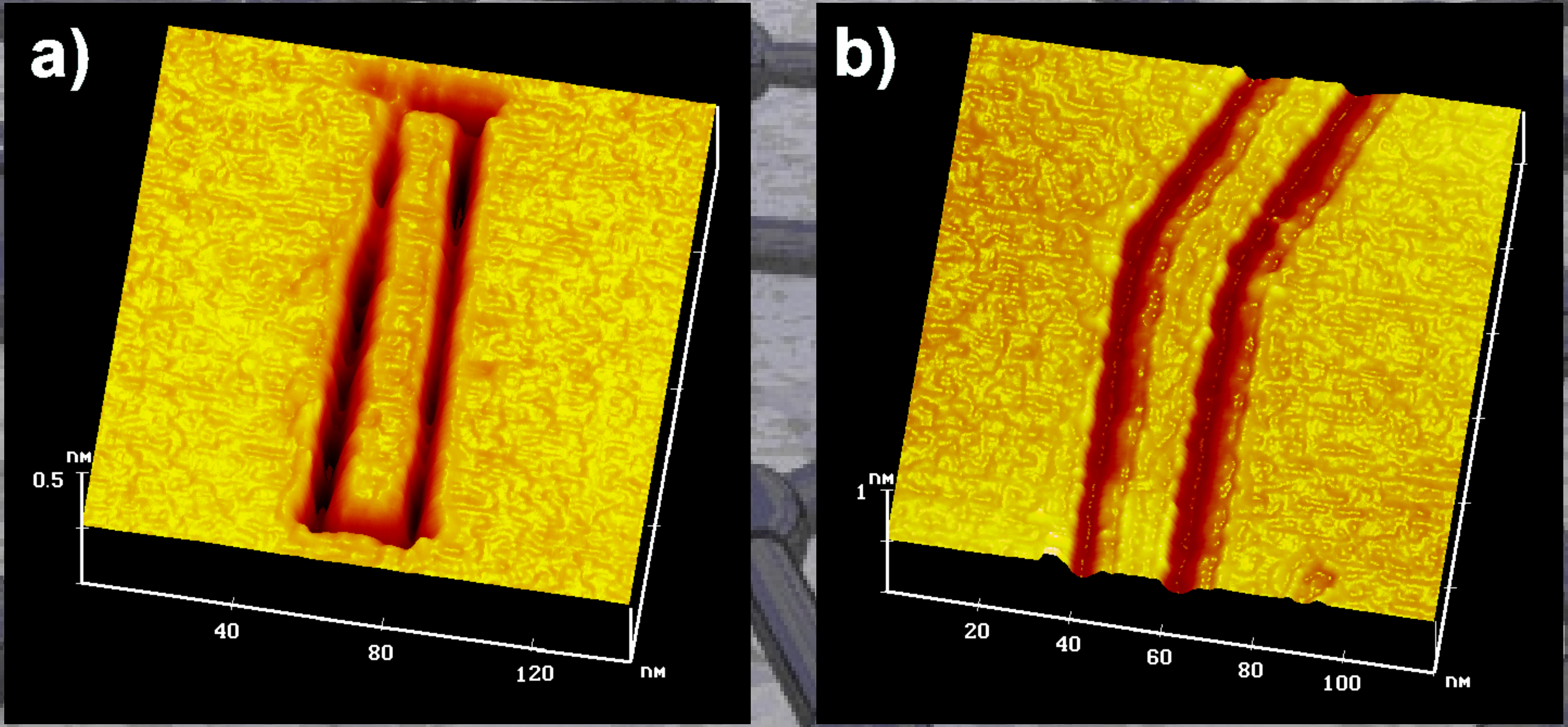


- **Local modification of sample surface**
- **Atomically precise tip positioning**
- **Atomic resolution imaging**

To solve:

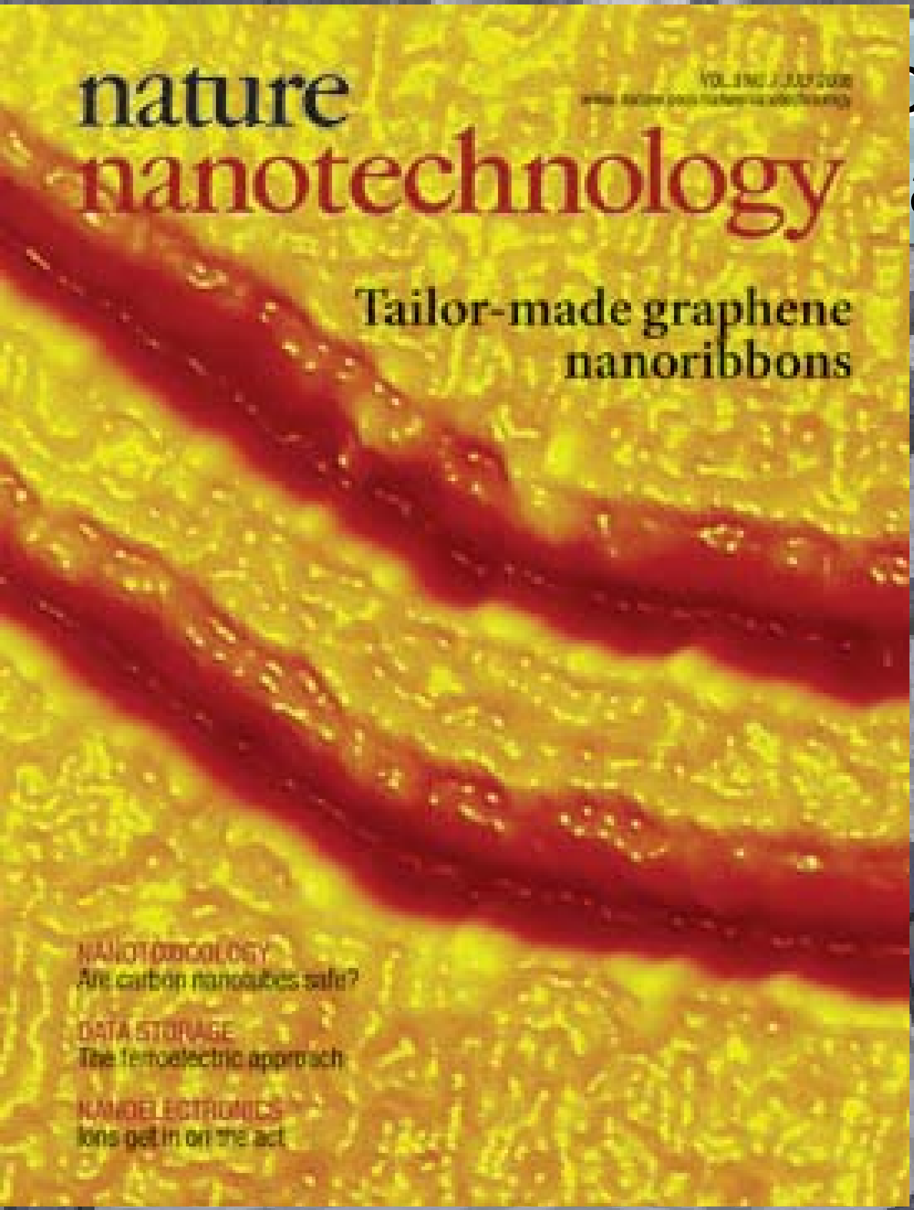
- Control the etching process, realize the first true nanometer precision lithography

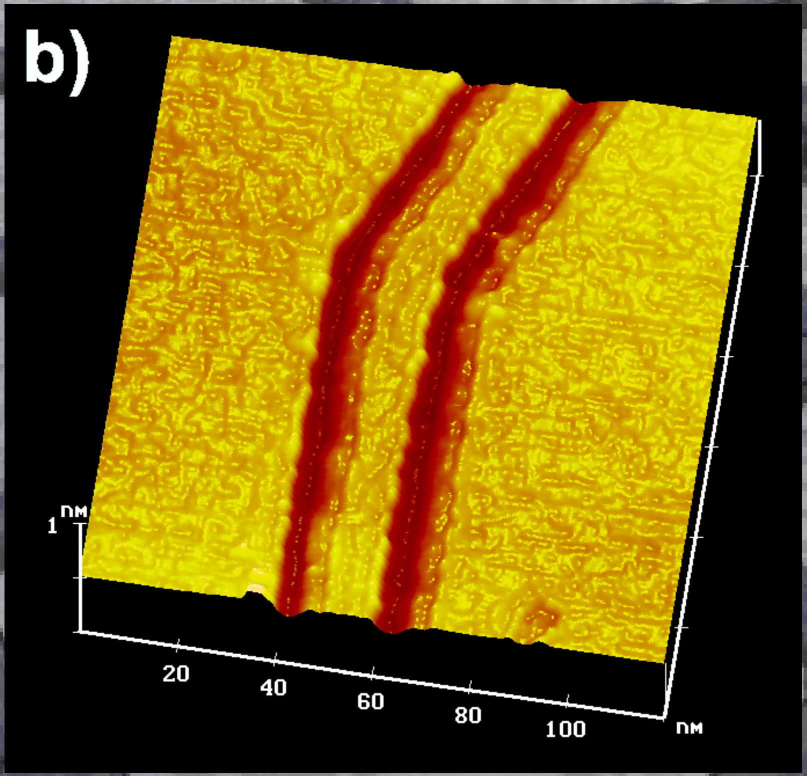
Graphene nanoribbons created by STM lithography



L. Tapasztó et al. Nature Nanotechnology, 4, 937 (2008)

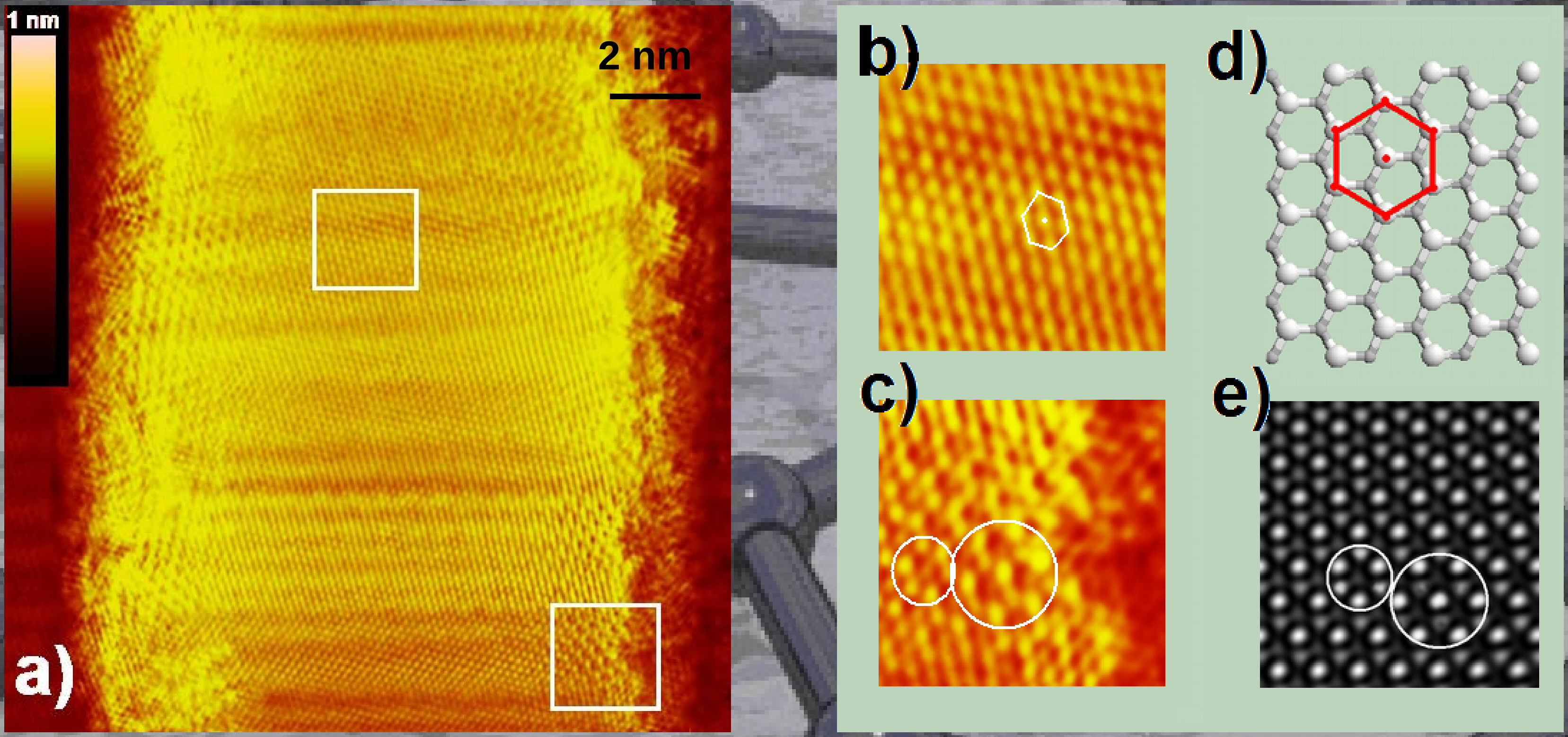
ons created by
aphy





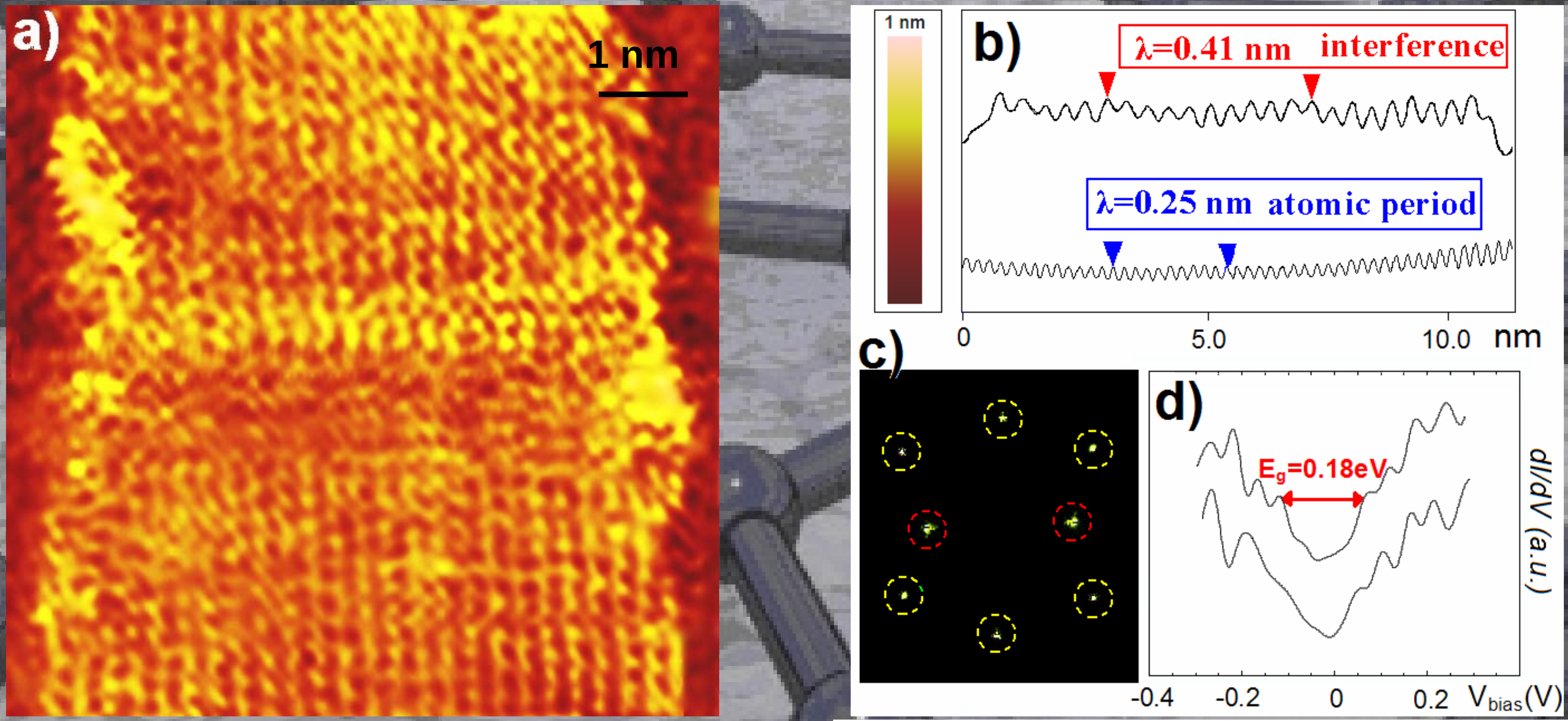
L. Tapasztó et al. Nature Nanotechnology, 4, 937 (2008)

Atomic resolution STM imaging of GNRs



L. Tapasztó et al. Nature Nanotechnology, 4, 937 (2008)

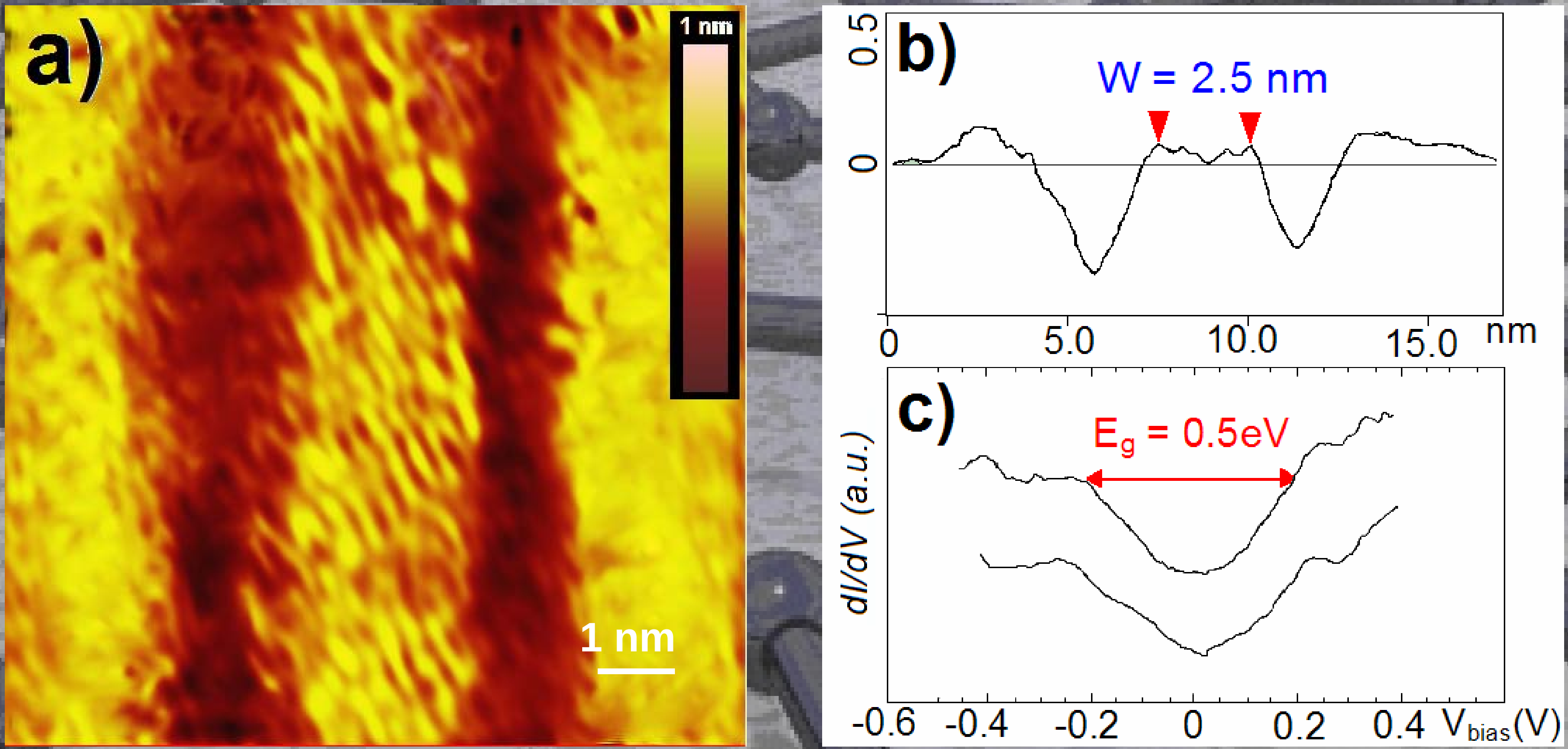
Electron standing waves at room temperature



$$E_g(W) = \pi\hbar v_0/W \approx (2eV \cdot nm)/W$$

L. Tapasztó et al. Nature Nanotechnology, 4, 937 (2008)

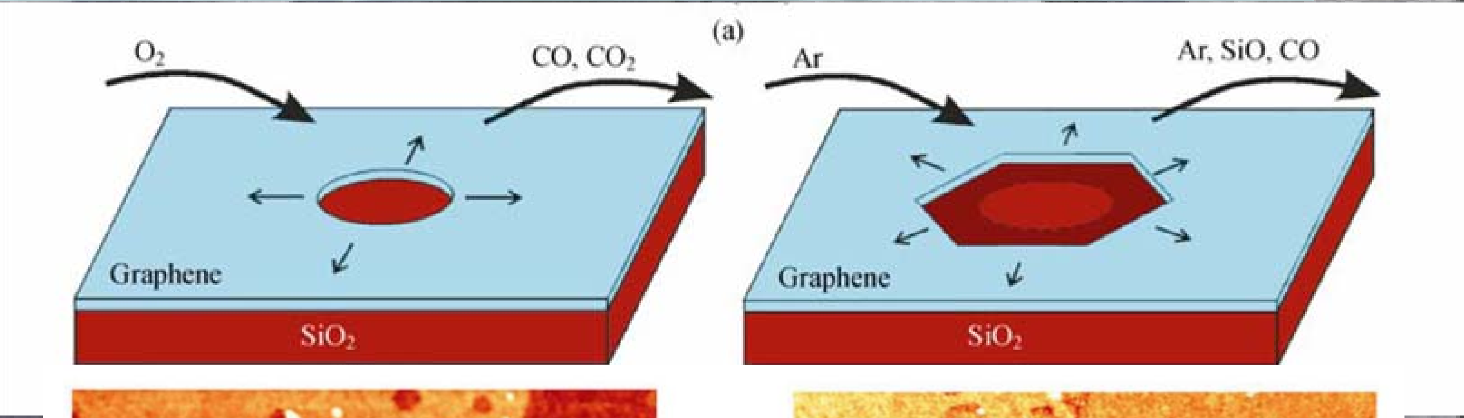
STILL the best lithographic resolution today

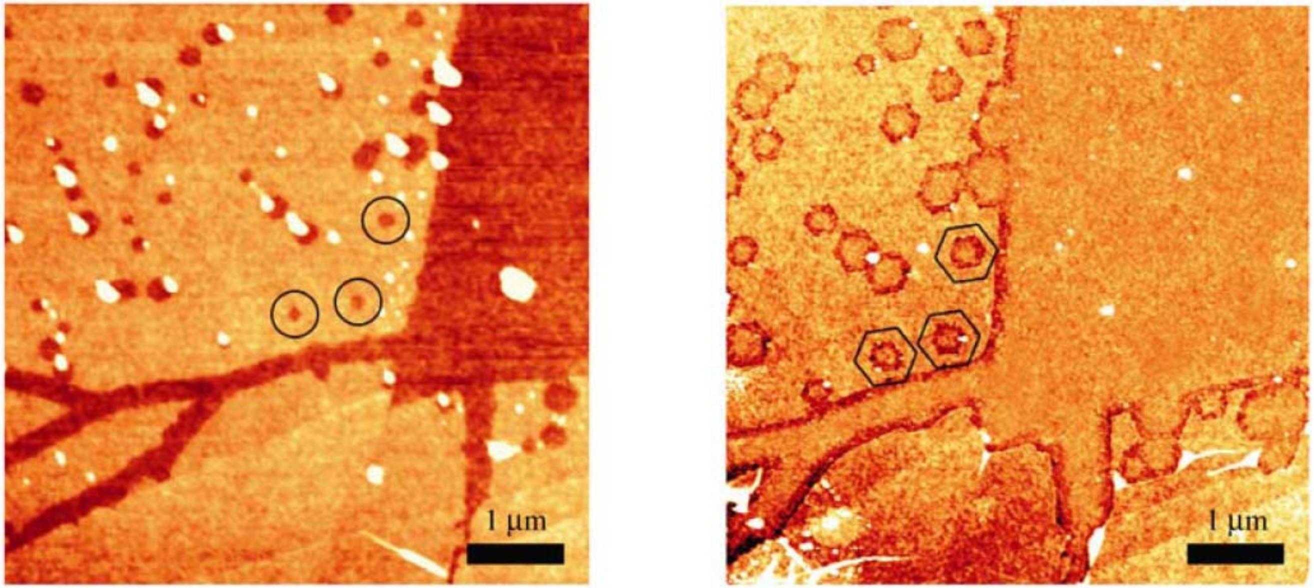


L. Tapasztó et al. Nature Nanotechnology, 4, 937 (2008)

E_g = 0.5 eV allows room temperature operation!

Atomically perfect zigzag edges by: Carbothermal Etching (CTE)

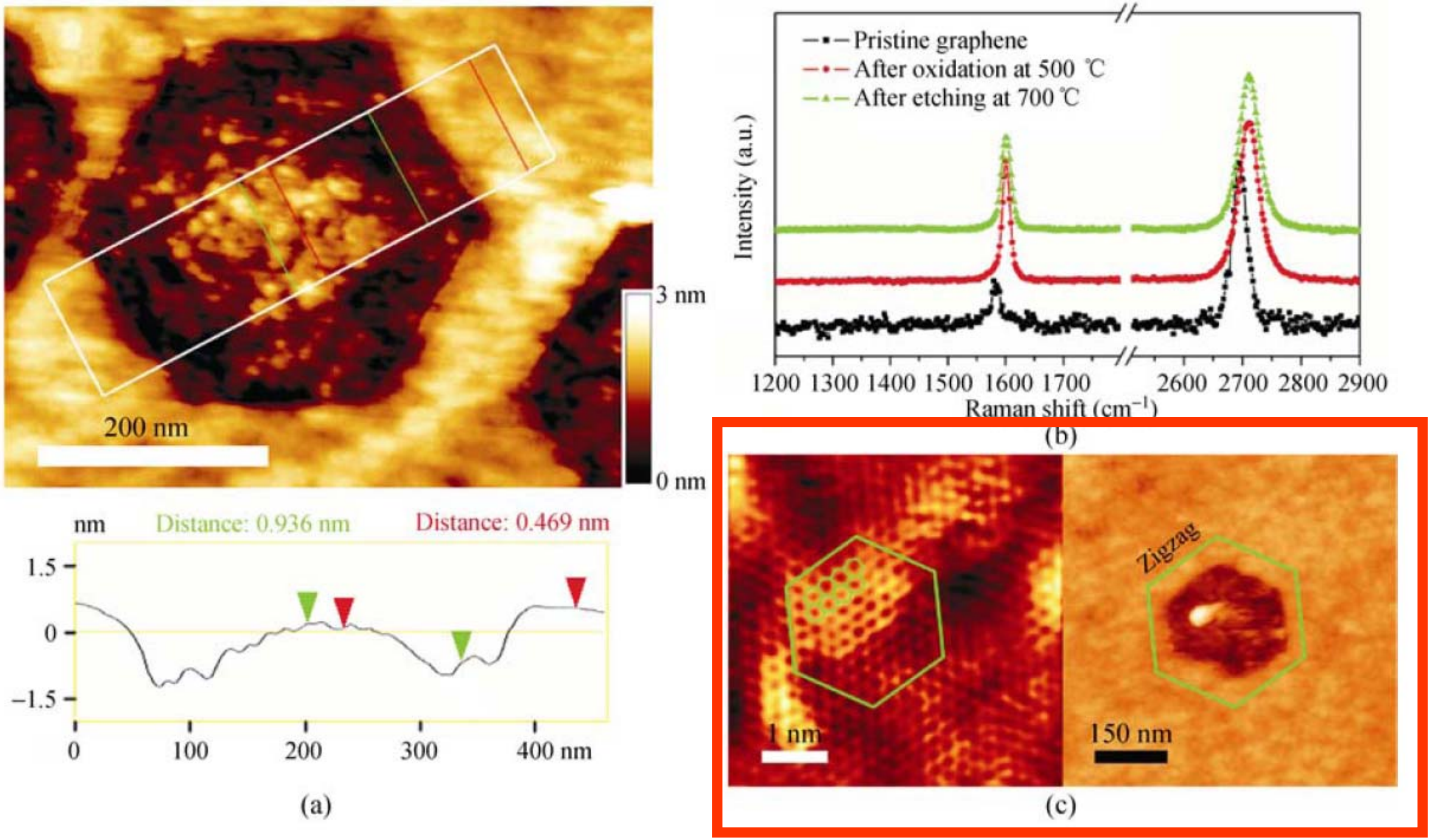




(a) (b)

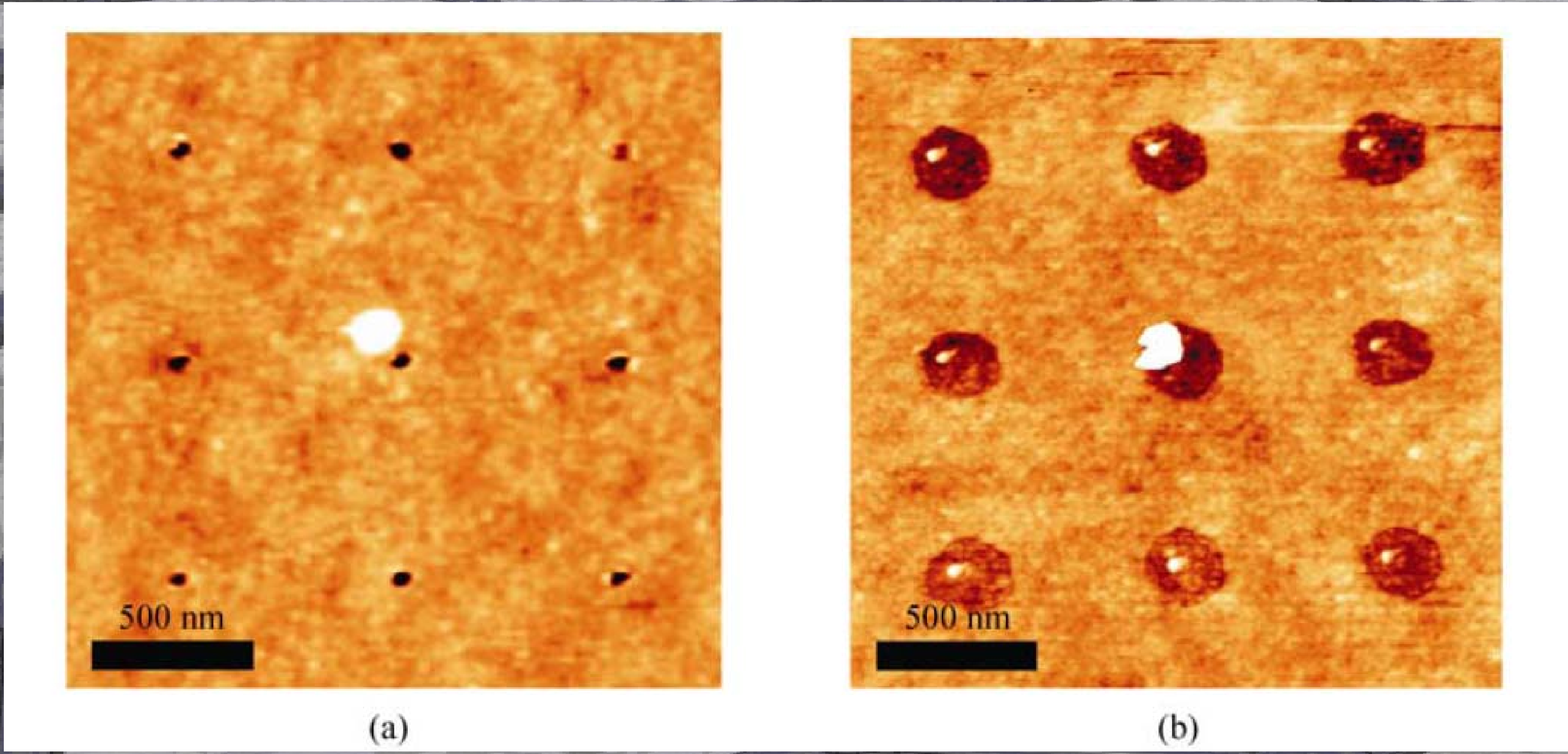
P. Nemes-Incze et al., Nano Res. 3 (2010) 110

Edge orientation by STM



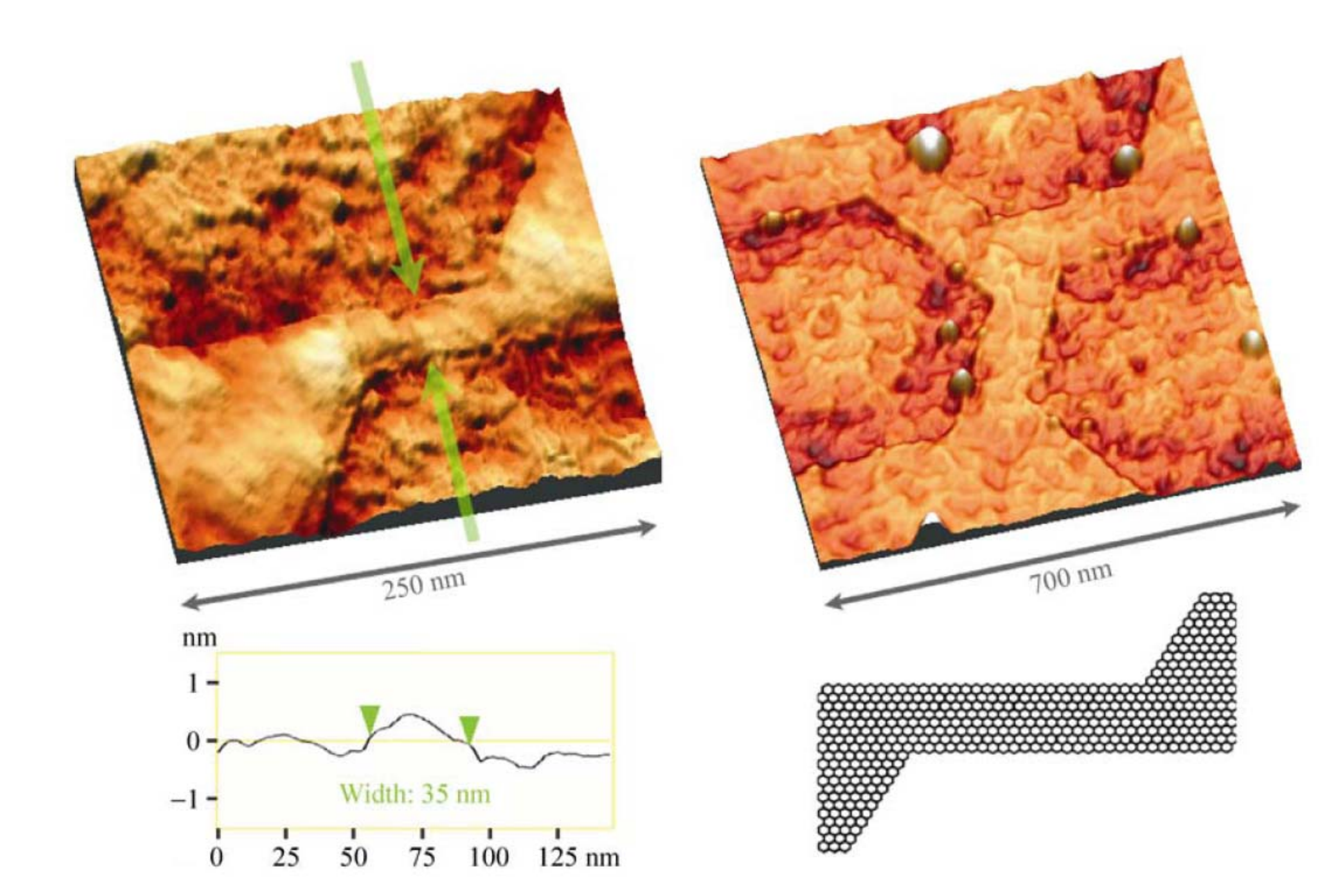
P. Nemes-Incze et al., Nano Res. 3 (2010) 110

Starting point fixed by AFM indentation



P. Nemes-Incze et al., Nano Res. 3 (2010) 110

Nanoarchitectures: graphene
nano-**Y Junction**



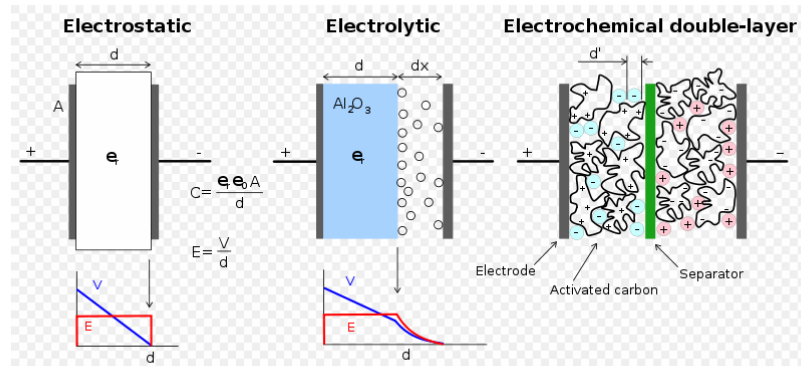
P. Nemes-Incze et al., Nano Res. 3 (2010) 110

Further applications

http://en.wikipedia.org/wiki/File:Maxwell_MC_and_BC_ultracapacitor_cells_and_modules.jpg

Graphene-Based Ultracapacitors

Meryl D. Stoller, Sungjin Park, Yanwu Zhu, Jinho An, and Rodney S. Ruoff*



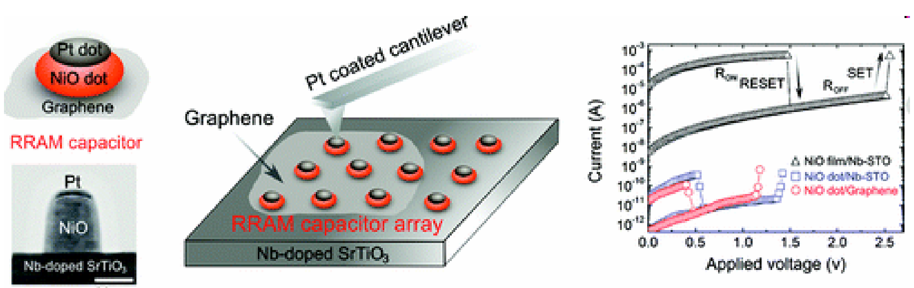
Nano Letters 8 (2008) 3498

Supercapacitors (Ultracapacitors?)

Electronic two-terminal bistable graphitic memories

YUBAO LI[1]*, ALEXANDER SINITSKII[1]* AND JAMES M. TOUR[1,2†]

Nature Materials 7 (2008) 966

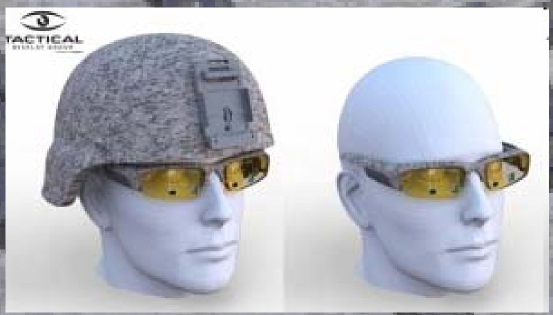


NiO Resistive Random Access Memory Nanocapacitor Array on Graphene

ACS Nano, 2010, 4 (5), pp 2655

Memory devices

FLEXIBLE (Trasistors + memory + energy source) = WEARABLE (nano)Electronics



Augmented-reality-holographic sunglasses

http://www.crunchwear.com/vuzix-and-darpa-team-up-to-create-augmented-reality-holographic-sunglasses/

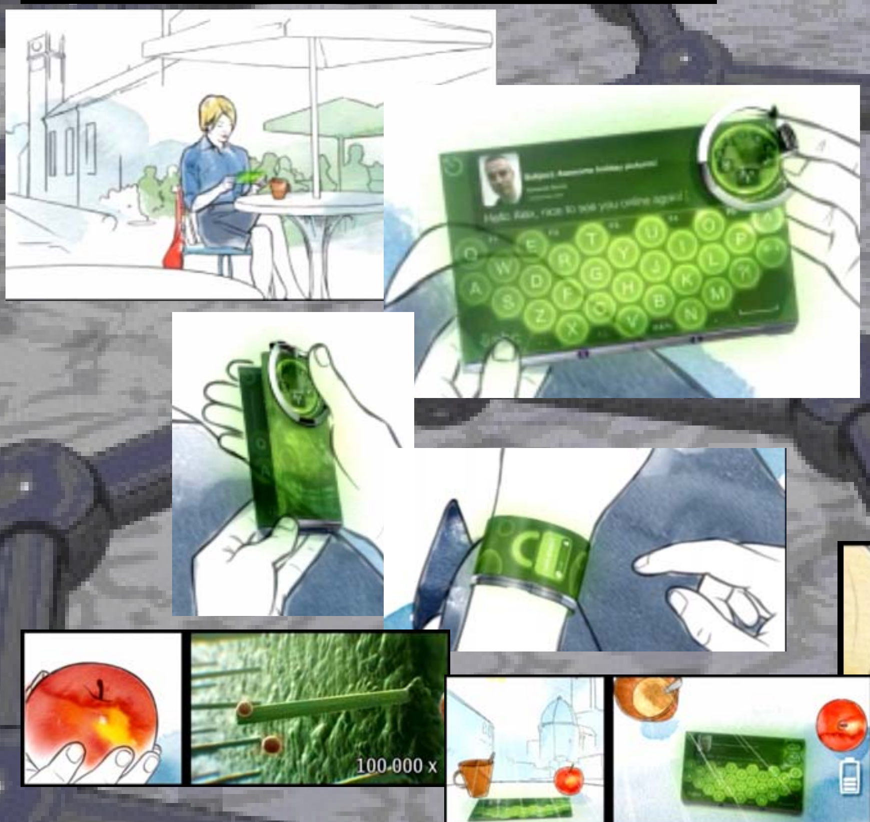
Solar Soldier system to take the weight off infantry soldiers

http://www.gizmag.com/solar-soldier-power-system-for-infantry/18140/

http://www.crunchwear.com/cute-circuit-galaxy-led-dress/

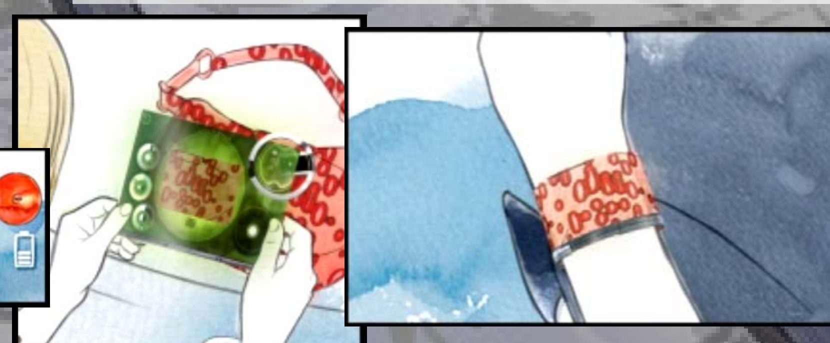
NOKIA

Morph is a concept demonstrating some of the possibilities nanotechnologies might enable in future communication devices



Let’s stop here …

http://www.gizmag.com/body-to-body-networks/16769/



Summary

- Graphene is the first of the family of single atom (molecule) thin materials
- It has many extraordinary properties
- It has short range application possibilities in flexible flat screens and photovoltaic devices
- It has long range perspectives to replace silicon in nanolectronic devices – bandgap reengineering needed – atomic precision nanolithogrpočetapy
- Flexible and wearable electronics from power source to fast logic and memory

Acknowledgments

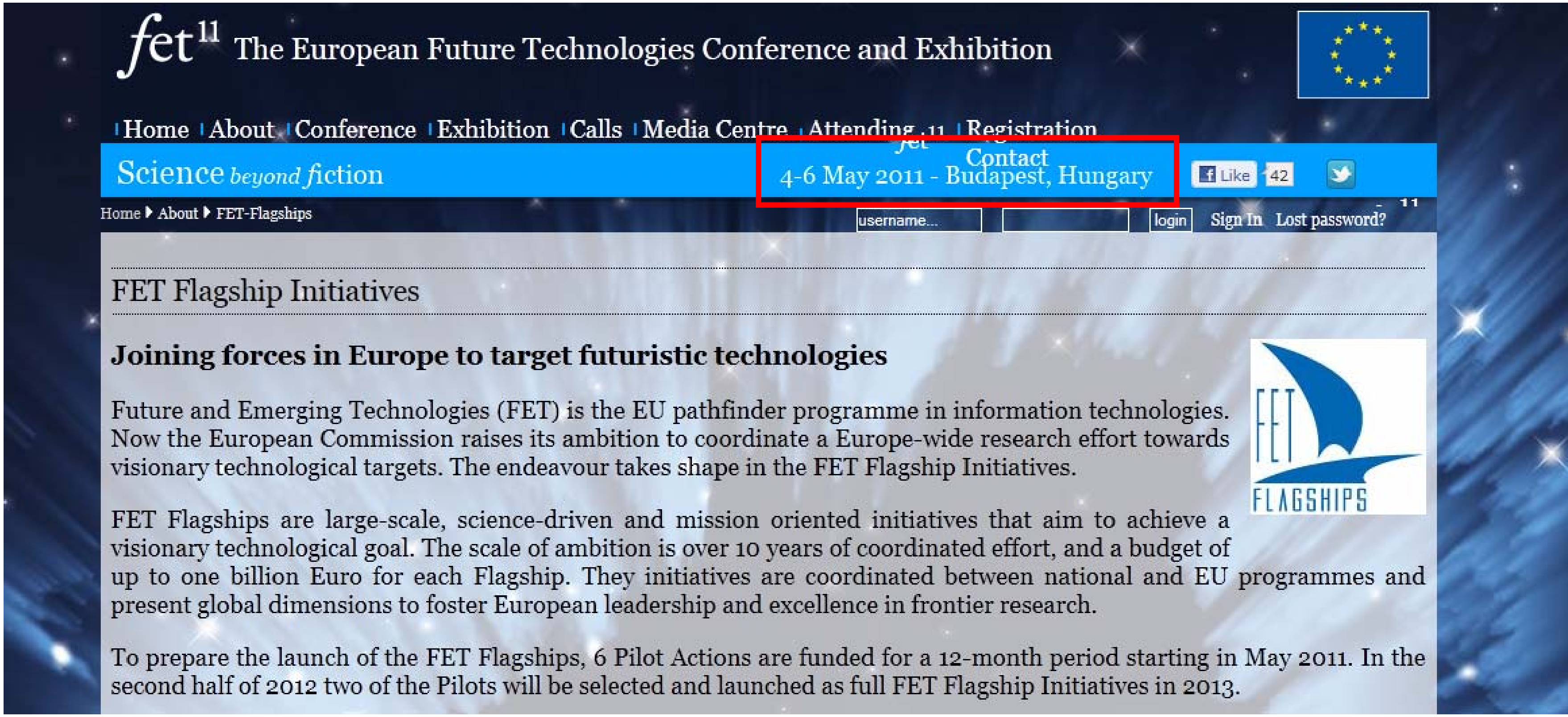
- Funding: In Hungary OTKA-NKTH: K67793 „Nanoarchitectures from nanostructures”

Korean-Hungarian Joint Laboratory for Nanosciences

- **MFA**: P. Nemes-Incze, G. Dobrik**,** P. Vancsó, G. I. Márk, Z. Vértesy, Z. E. Horváth, L. Tapasztó,
- **KRISS**: K. J. Yoo & C. Hwang

Thank you for your attention!

Graphene „FLAGSHIP" – EU-FP7



fet11 The European Future Technologies Conference and Exhibition

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Science *beyond fiction*

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FET Flagship Initiatives

Joining forces in Europe to target futuristic technologies

Future and Emerging Technologies (FET) is the EU pathfinder programme in information technologies. Now the European Commission raises its ambition to coordinate a Europe-wide research effort towards visionary technological targets. The endeavour takes shape in the FET Flagship Initiatives.

FET Flagships are large-scale, science-driven and mission oriented initiatives that aim to achieve a visionary technological goal. The scale of ambition is over 10 years of coordinated effort, and a budget of up to one billion Euro for each Flagship. They initiatives are coordinated between national and EU programmes and present global dimensions to foster European leadership and excellence in frontier research.

To prepare the launch of the FET Flagships, 6 Pilot Actions are funded for a 12-month period starting in May 2011. In the second half of 2012 two of the Pilots will be selected and launched as full FET Flagship Initiatives in 2013.

The six FET Flagship Pilot Actions to be launched are:

- FuturICT - The FuturICT Knowledge Accelerator and Crisis-Relief System: Unleashing the Power of Information for a Sustainable Future
- Graphene - Graphene Science and technology for ICT and beyond
- Guardian Angels - Guardian Angels for a Smarter Planet
- HBP - The Human Brain Project
- ITFoM - IT Future of Medicine: a revolution in healthcare
- RoboCom - Robot Companions for Citizens