Graphene technology for future mobile devices

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Nokia Research Center

Cambridge UK

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The Risk-Taking Future-Looking Arm of Nokia

Global research facilities

- Global spread of research teams across thirteen locations

Open innovation

- Engaging the World’s Leading Institutions

Cambridge UK

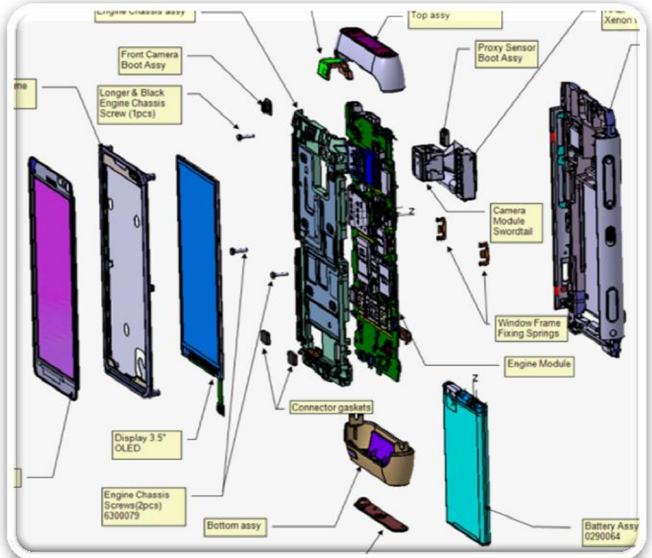
- Nanotechnologies for mobile devices
- Adaptive & transformable device platform (‘Morph’)
- Nanoscale signal processing architectures, sensors, biosensors & diagnostics

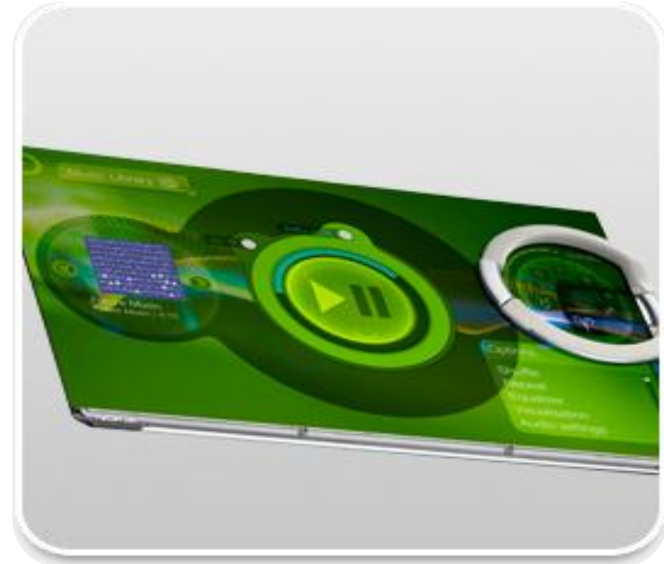
EUROLAB CAMBRIDGE
Year Founded:
2006

Lab Director:
Tapani Ryhänen

Contact:
Tapani.Ryhanen@nokia.com

Our future products rely on future technologies



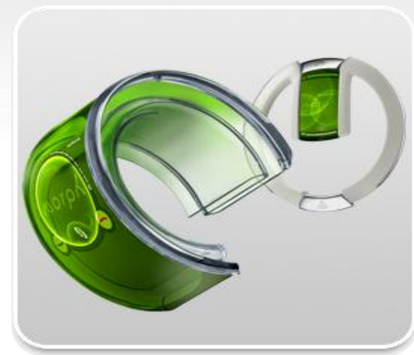


Role for graphene in Nokia products:

- In existing phones: **enhancing** performance and/or reducing costs.

Examples: replace ITO in displays; high frequency electronic components

- In future (flexible) phones: **enabling** new concept devices based on key technologies:
    - printable electronics;
    - flexible electronics;
    - integrated multi-sensing platforms



Enabling Morph - Reconfigurable, Conformable, Transparent

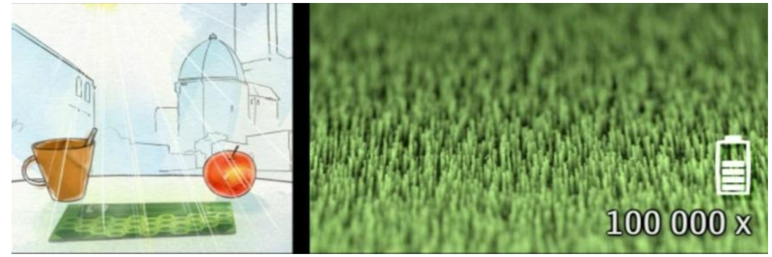
Can ~~nanotechnology~~ graphene enable power-efficient, energy-autonomous mobile devices with reconfigurable form factors and conformal, wearable UI surfaces that sense their local environment?

Research Themes

1. Nano-enabled Energy

How can nanotechnology enable **increased energy- and power densities** for portable devices in environmentally-friendly, sustainable and safe ways using flexible, thin and (partly) transparent structures?

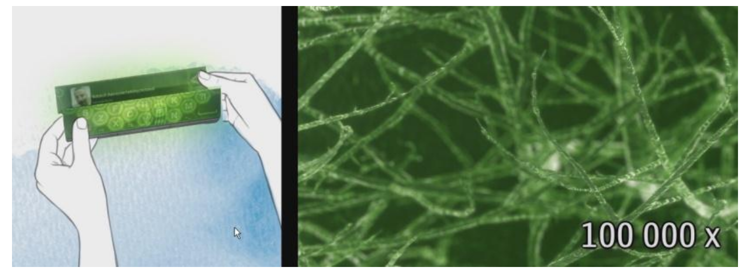
Goal: Enhanced, flexible energy storage based on nanostructured carbon anodes and novel electrolytes, ambient energy harvesting (solar)



2. Stretchable, transformable structures

How do we **integrate interconnects, substrates and circuits into transformable devices** using nanotechnologies?

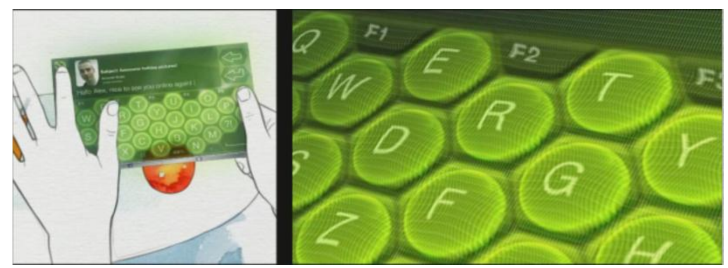
Goal: Stretchable electronics and structures (interconnects, substrates and circuits) that withstand extreme deformation to allow reconfigurable device form factors



3. Flexible UI sensor surfaces

How can we make **flexible, multifunctional sensing and UI surfaces** using nanotechnology enablers?

Goal: Multifunctional flexible and self-cleaning surfaces that combine sensing with tactile/haptic UIs



Can graphene technology address all these goals?

Thinness, talk time and flexibility: Graphene as an enabler?

Flexible batteries with polymers and carbon nanostructures

Supercapacitors under display for local power delivery

Thin batteries and integrated solar cell surfaces

Transparent / semi-transparent functional structures

Impact of nano energy storage and harvesting

- Ultra long standby and talk time
- Reduction in additional capacitor circuits and DC/DC converters
- Application enabler or performance enhancement
- Ultra thin; enabler for transparency
- Supercapacitor-battery hybrids may enable ultrafast charging
- Environmental, safe materials
- Cycling/durability, shelf life enhancement
- Potentially no charger, energy autonomy
- Flexible, printable, distributed – design freedom

Graphene for batteries and supercapacitors

Graphene for energy storage

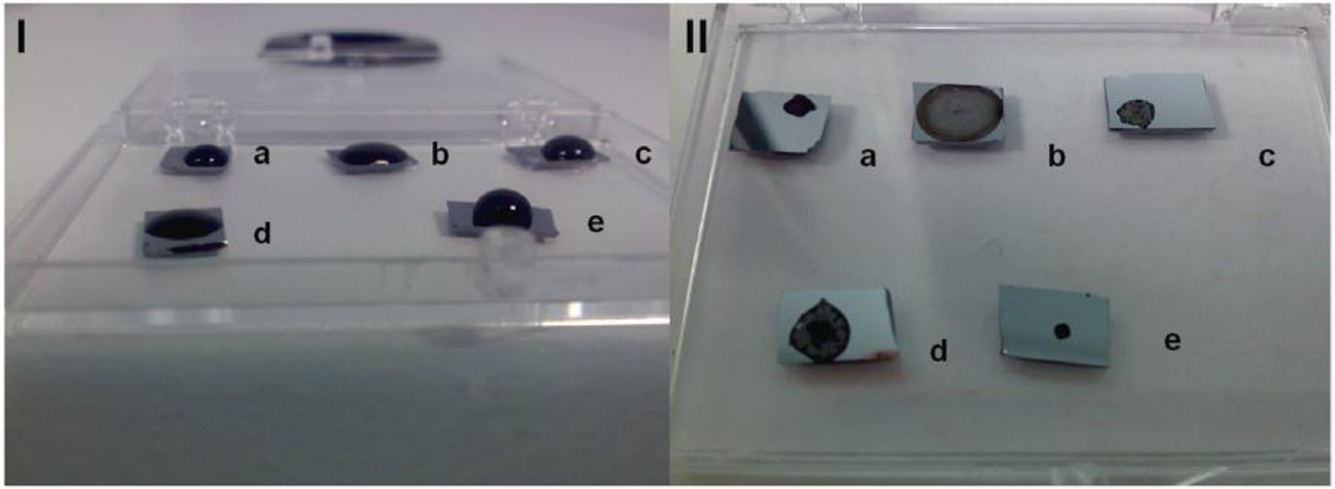
- Graphene provides high conductivity and transparency at the same time: flexible building block for constructing high surface area batteries and supercapacitors. Special electrode for transparent and flexible batteries.

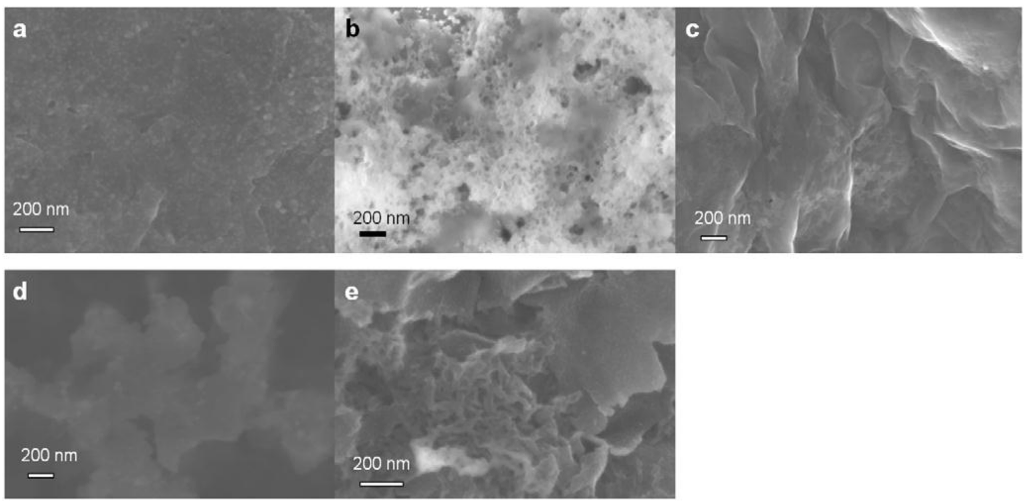
Chemical route to graphene:
Low-cost mass production

	Sheet Resistance (ohms/sq)	Transparency (%)
Chemical reduction of GO	1000-70,000 31,000-19M	<80% <95%
Liquid-phase exfoliation	520-3110 5000-8000	63-90

- The highly conductive property of graphene can be used as additives in batteries slurries. Graphene inks can couple with traditional printing process (R2R) to scale up printable batteries and supercapacitors.

Graphene inks





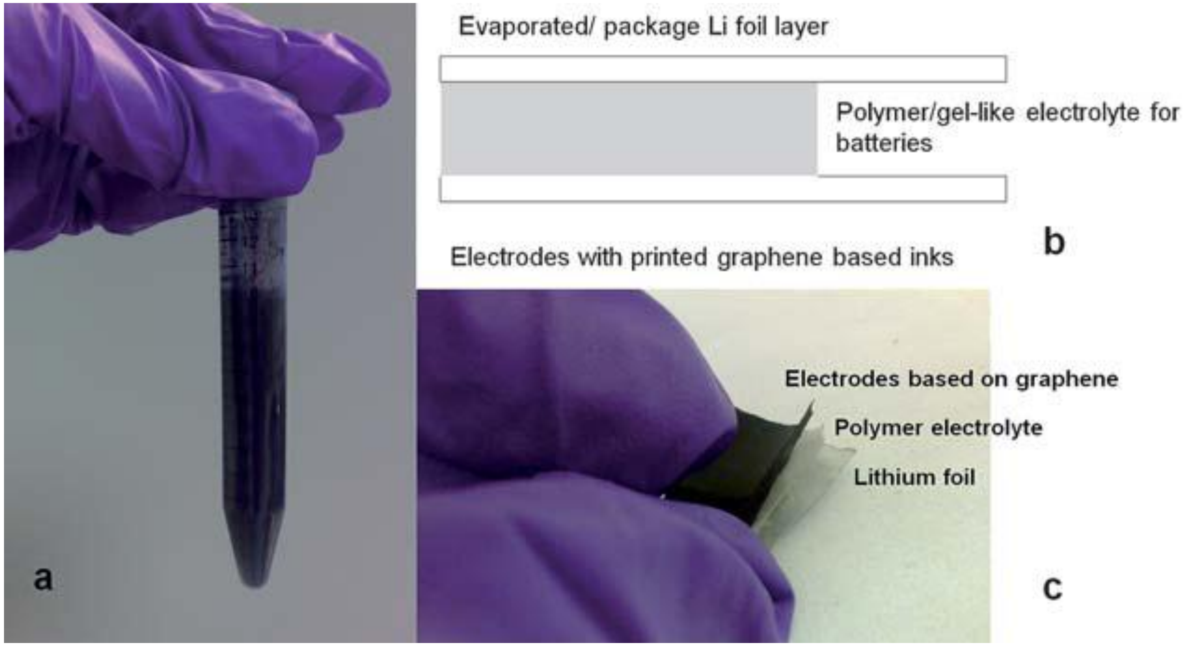
Di Wei et al. Nanotechnology **22** (2011) 245702

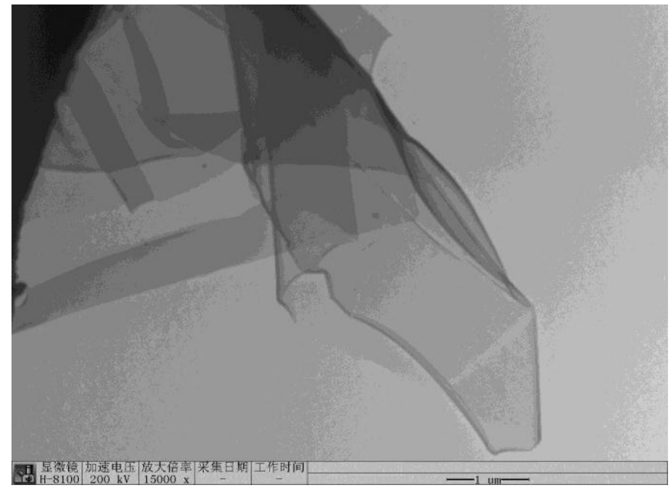
(cooperation with Changchun Institute of Applied Chemistry, China)

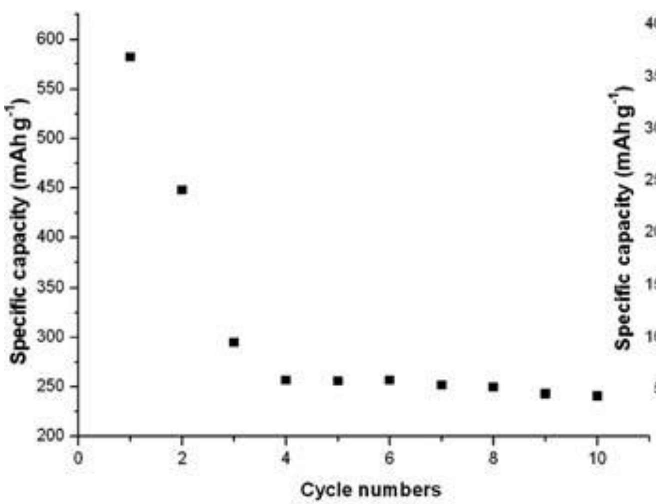
Graphene inks with different surface tensions :

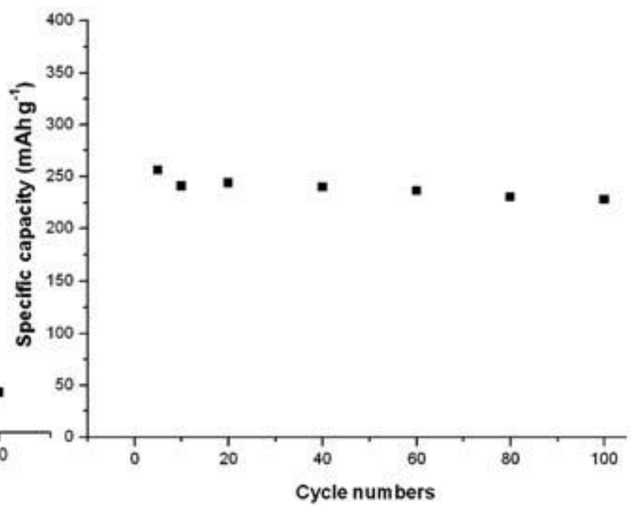
(a) IL-modified graphene, (b) KOH-exfoliated graphene, (c) polyelectrolyte-modified graphene, (d) PSS-modified graphene and (e) polyaniline-modified graphene.

Graphene ink for flexible batteries





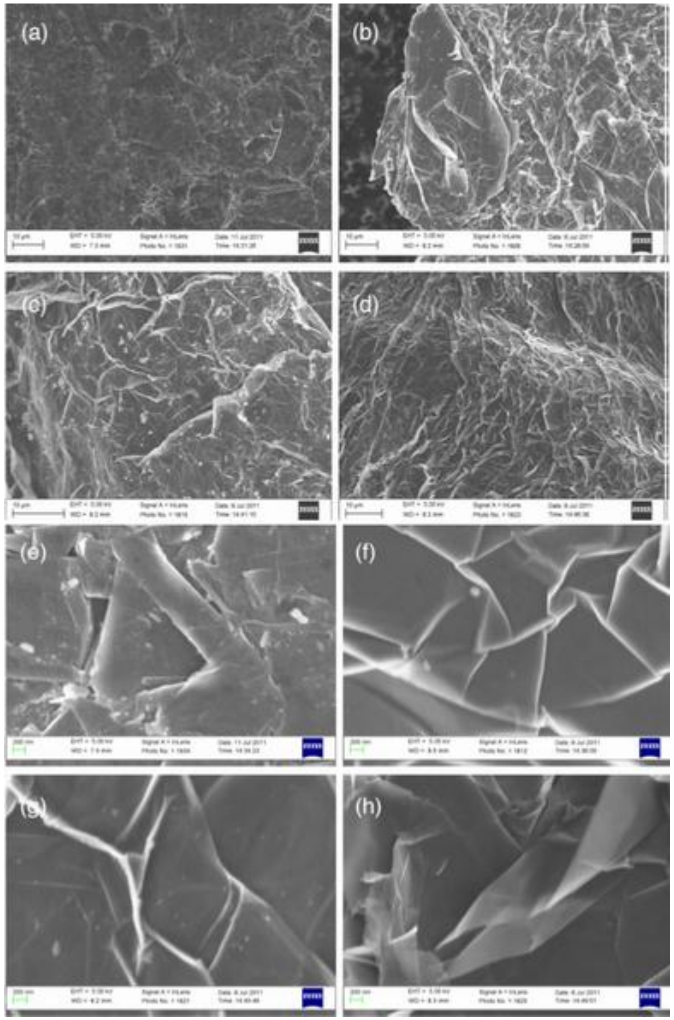


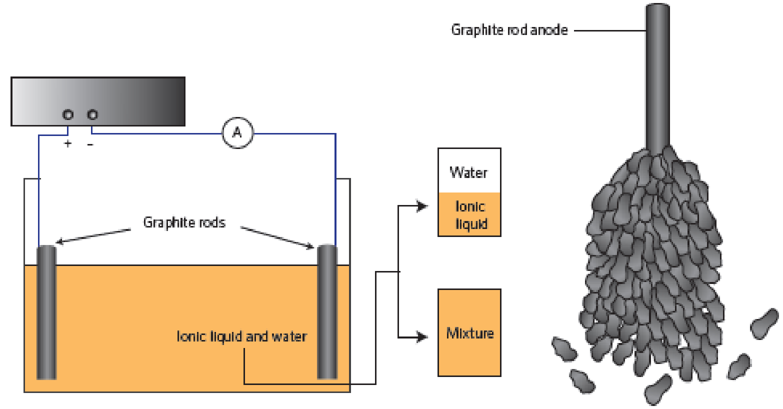


- Flexible
- Printable
- Low cost
- Scalable

Di Wei et al. *J. Mater. Chem.*, 2011, **21**, 9762-9767

Electrochemical exfoliation





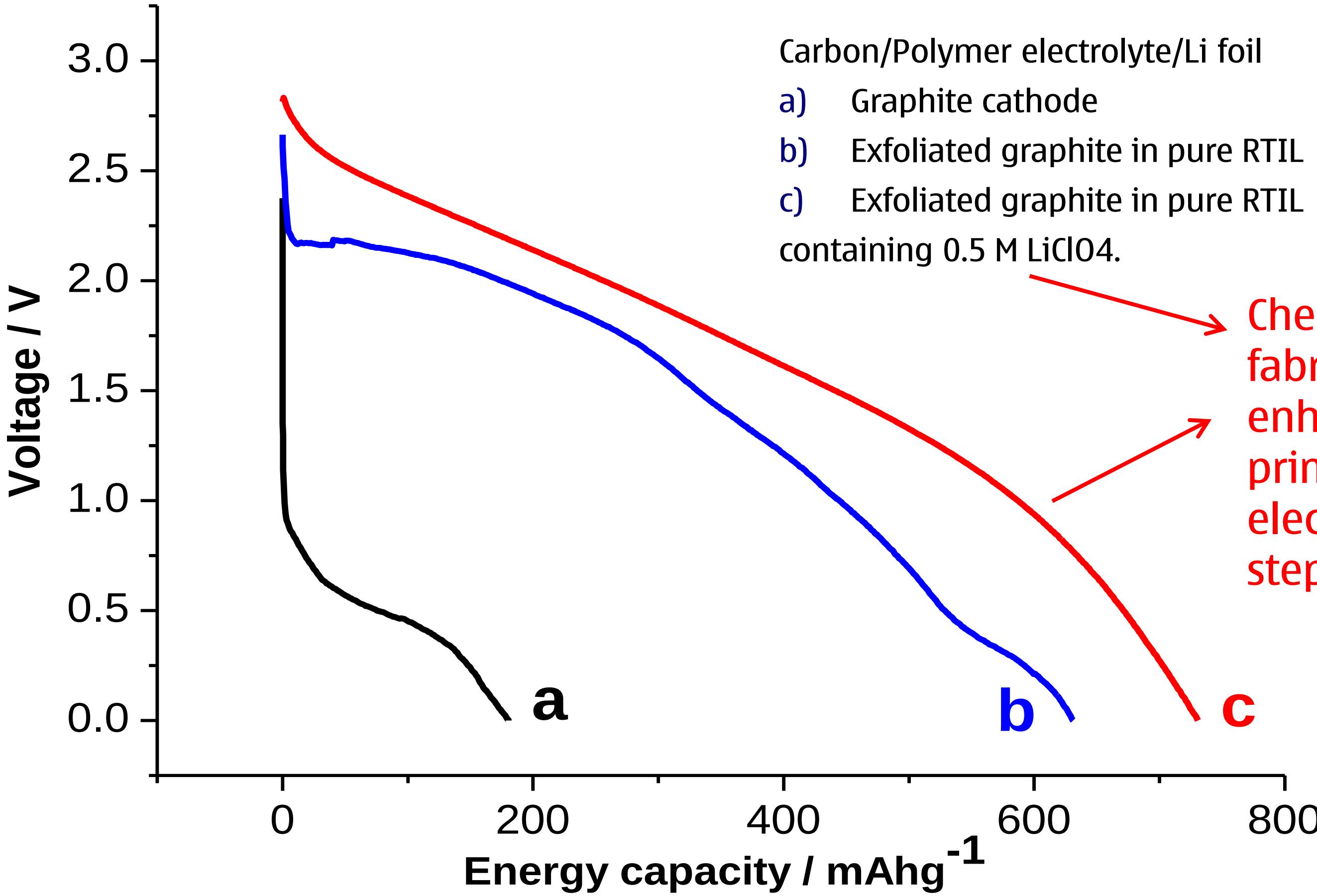
	Sheet Resistance (ohms/sq)	Transparency (%)
Chemical reduction of GO	1000-70,000 31,000-19M	<80% <95%
Liquid-phase exfoliation	520-3110 5000-8000	63-90
Electrochemical exfoliation of graphite	210-43000 (210 after thermal annealing at 450 C)	96

Improve graphene inks?

Electrochemical exfoliation: “green” method that allows easy tuneability of the obtained products by varying the applied potential and/or the IL content.

NOKIA

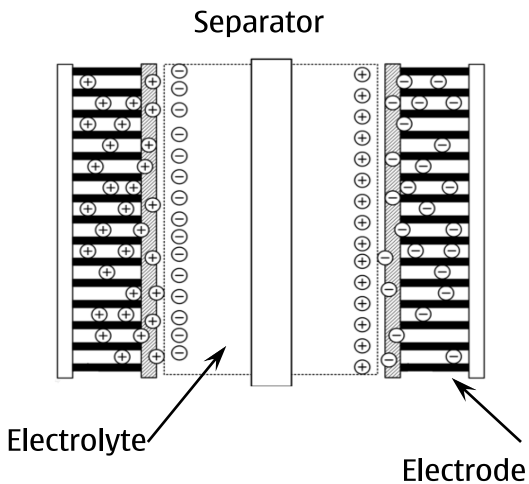
Electrochemically exfoliated graphene for enhanced primary battery electrodes

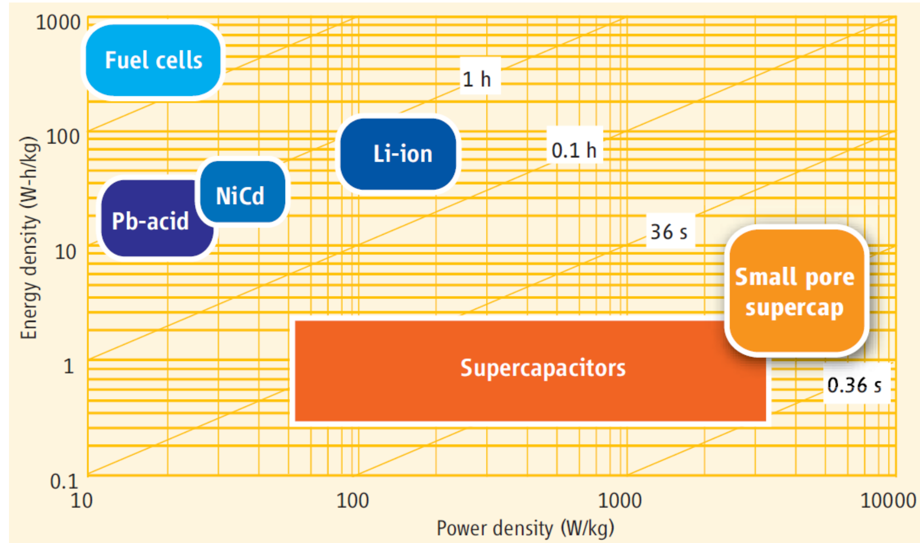


Cheap way to fabricate enhanced primary battery electrodes in one step

D.Wei et al., Chem. Commun., 2012, **48**, 1239–1241

Supercapacitors

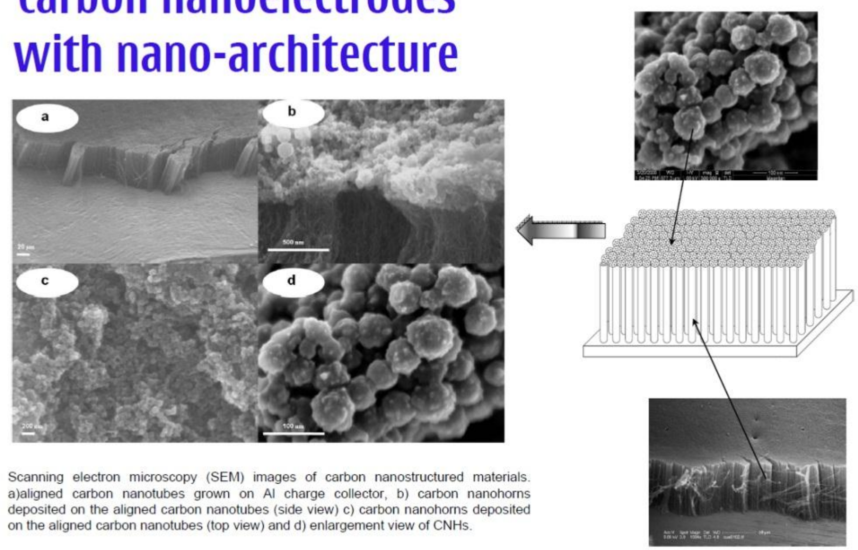




Electrochemical Double Layer Capacitors (EDLC)

- Carbon for electrodes in supercapacitors due to its electric conductivity, light and porous structure to absorb ions. The smaller the pores in the material the larger its surface area and the more charge the capacitor can hold.
- Carbon with 0.6 nm pores holds 50% more charge than powders from standard supercapacitors.
- Nanostructure electrodes for very low ESR energy sources.
- New electrolyte solutions for safe and high power batteries. Deformable and bendable structures.

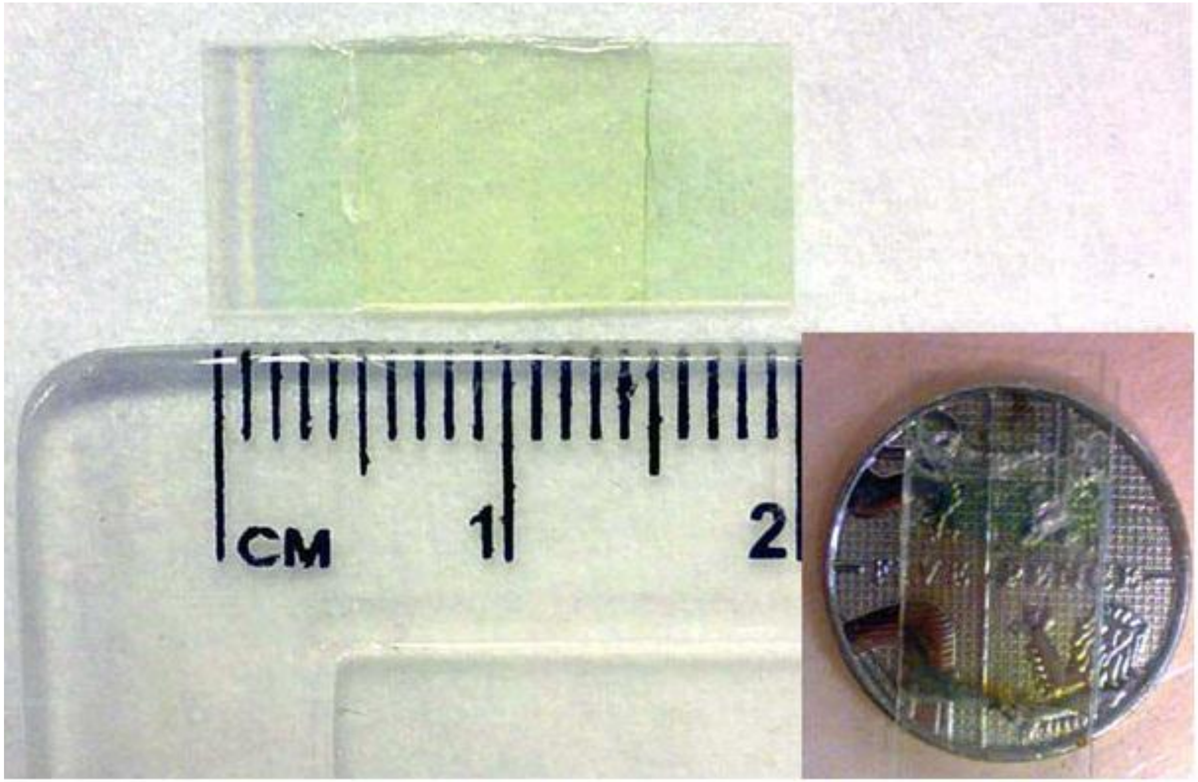
Carbon nanoelectrodes with nano-architecture



Scanning electron microscopy (SEM) images of carbon nanostructured materials. a)aligned carbon nanotubes grown on Al charge collector, b) carbon nanohorns deposited on the aligned carbon nanotubes (side view) c) carbon nanohorns deposited on the aligned carbon nanotubes (top view) and d) enlargement view of CNHs.

1 US/2010/0178531, WO/2010/081770A1 High efficiency energy conversion and storage systems using carbon nano-structured materials.
2 US/2010/0328845 WO/2010/149835 Nano-structured flexible electrodes, and energy storage devices using the same.

Supercapacitors at NRC



D. Wei et al. Electrochemistry Communications 11 (2009) 2285–2287

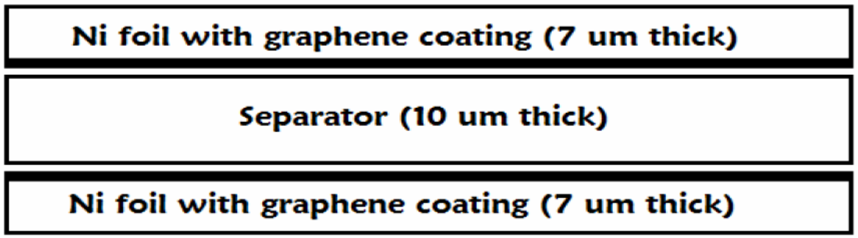
ITO coated transparent and flexible supercapacitor based on ionic liquid gel

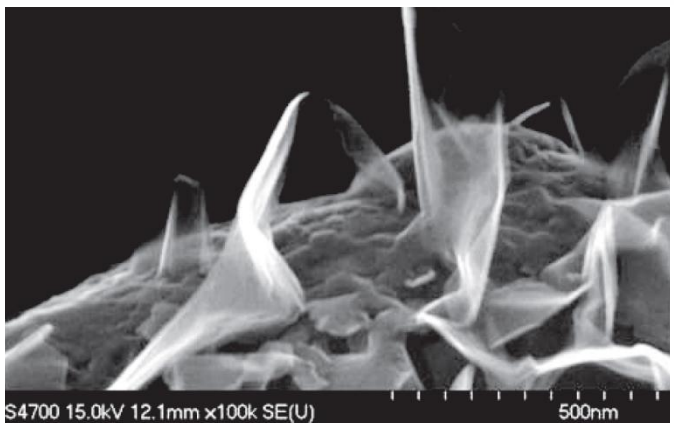
Graphene technology:

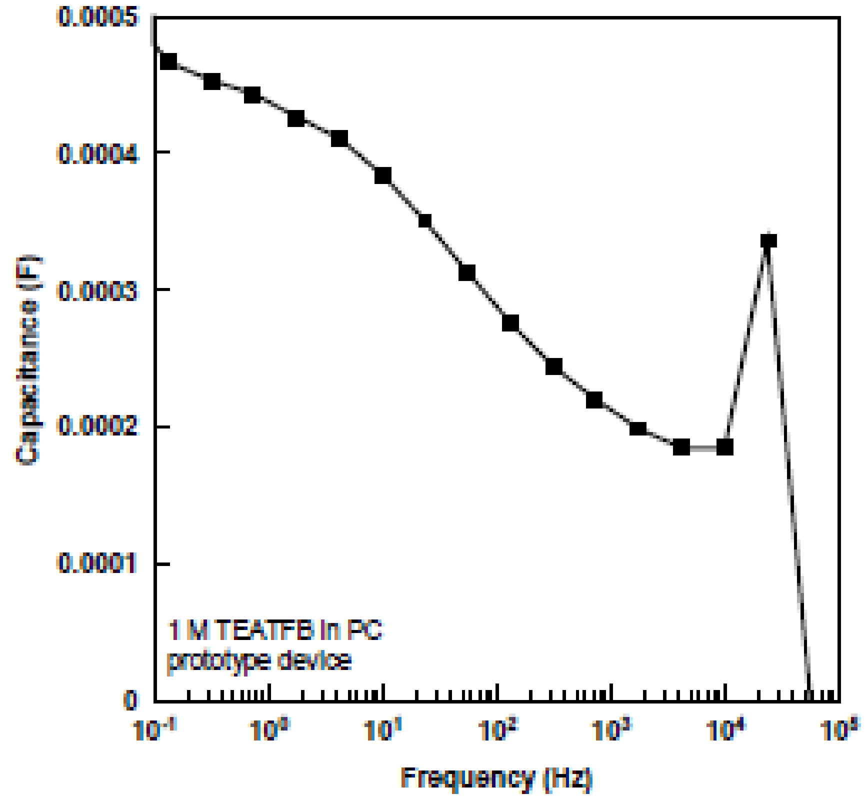
Replace ITO and...

Graphene: enabling supercapacitors in high frequency applications

Graphene in EDLCs can minimize electronic and ionic resistance and produce capacitors with RC time constant of less than 200 μs, in contrast with ~ 1s for typical EDLCs.







Science AAAS

Graphene Double-Layer Capacitor with ac Line-Filtering Performance
John R. Miller, *et al.*
Science **329**, 1637 (2010);
DOI: 10.1126/science.1194372

First high-frequency AC "supercapacitors" containing graphene electrodes.

Mass production of graphene

	Sheet Resistance (ohms/sq)	Transparency (%)
Chemical reduction of GO	1000-70,000 31,000-19M	<80% <95%
Liquid-phase exfoliation	520-3110 5000-8000	63-90
Electrochemical exfoliation of graphite	210-43000 (210 after thermal annealing at 450 C)	96
CVD graphene	30-2000	90

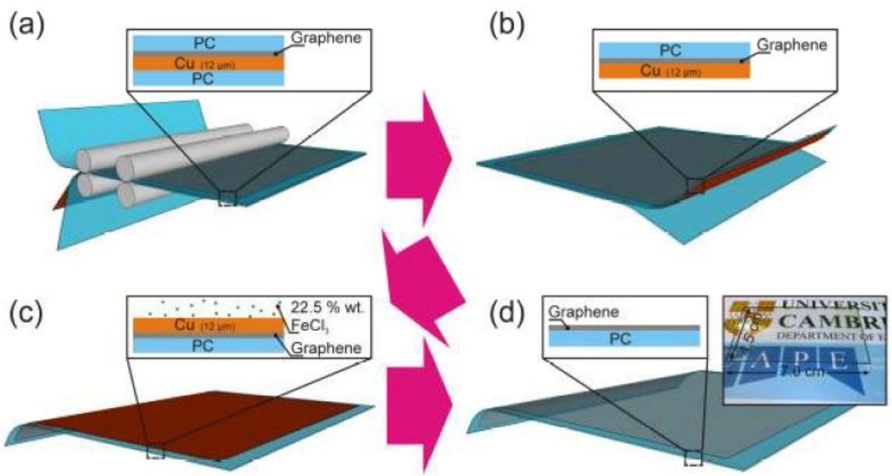
Chemical / electrochemical route:

Graphene solutions, functionalised graphene

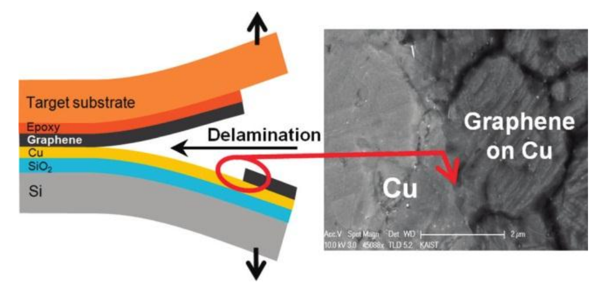
Graphene sheets:

Suitable for electronic devices

Work in progress on large area R2R production techniques: Graphene laminates



NRC cooperation with Cambridge Univ. and AIXTRON

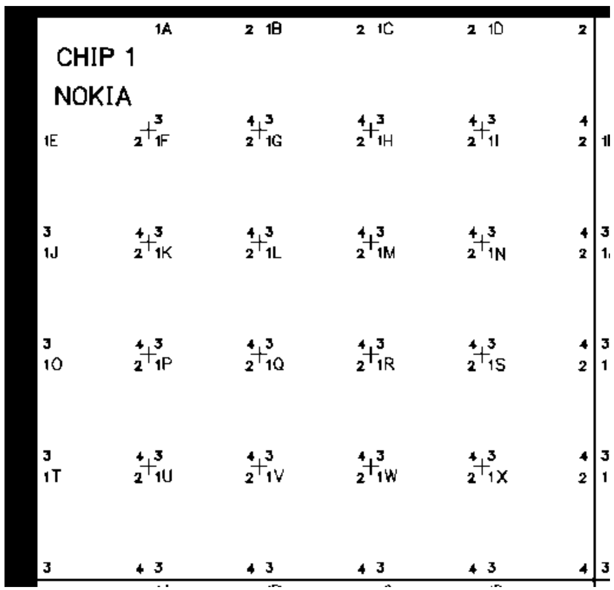


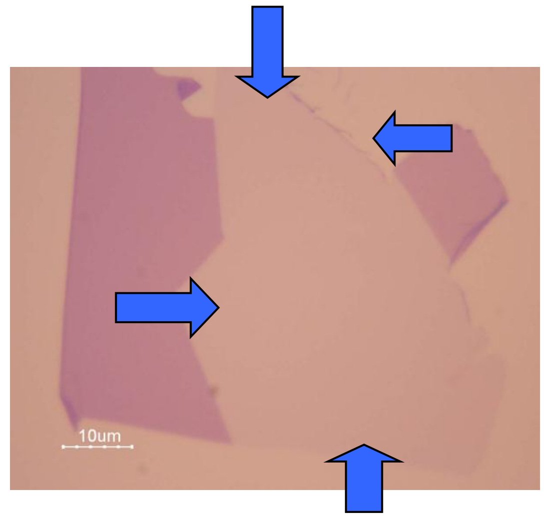
T. Yoon et al., Nano Lett. 2012

Graphene for electronics and optoelectronics

Graphene-based electronic / optoelectronic devices

Started in 2008: preliminary work on mechanically exfoliated graphene





Useful to gain knowledge about some main technological issues of graphene devices:

Contact resistance; top gate dielectrics; etc...

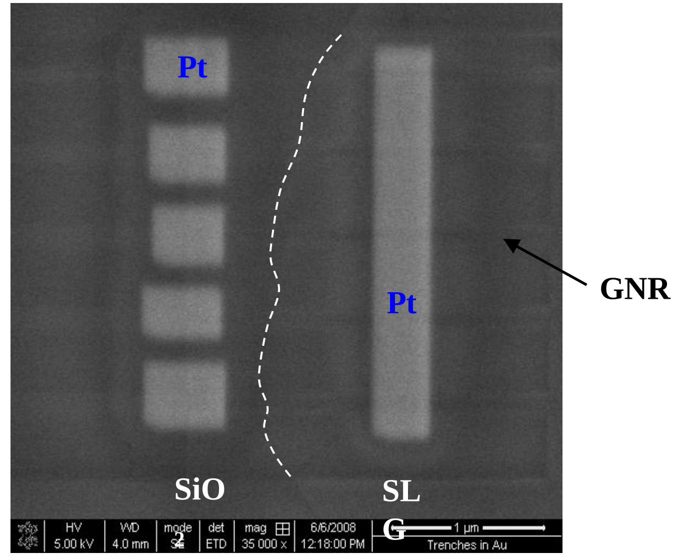
Graphene nanoribbons

Dual Beam:

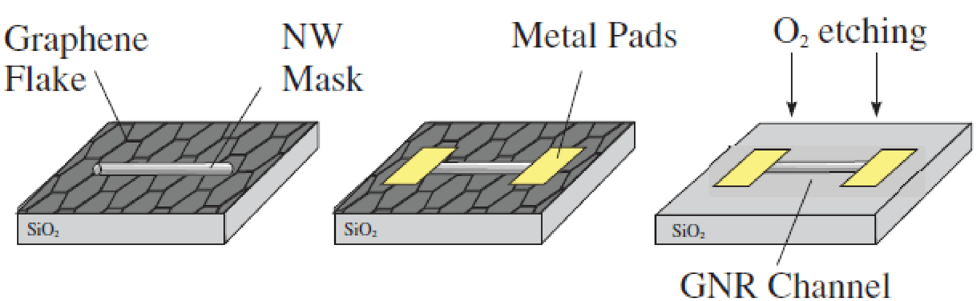
- Monolayer graphene directly patterned by FIB. The width of ribbons is varied from 50 - 70 nm.
- Platinum (Pt) pads/contacts deposited *in situ*.

S. Haque et al. Patent US2010/0272917 A1

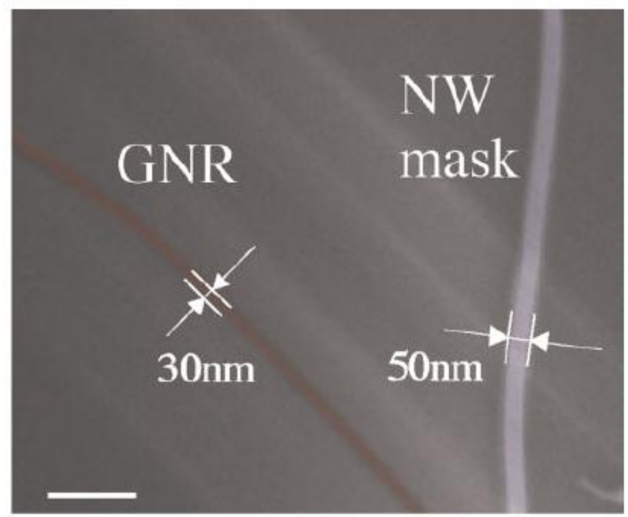
SEM image of GNR patterned by FIB. Around 50nm wide parallel GNRs were directly patterned using ion milling technique and Pt pads were formed by deposition function. (Collaboration with TKK Finland)



SiNW mask:

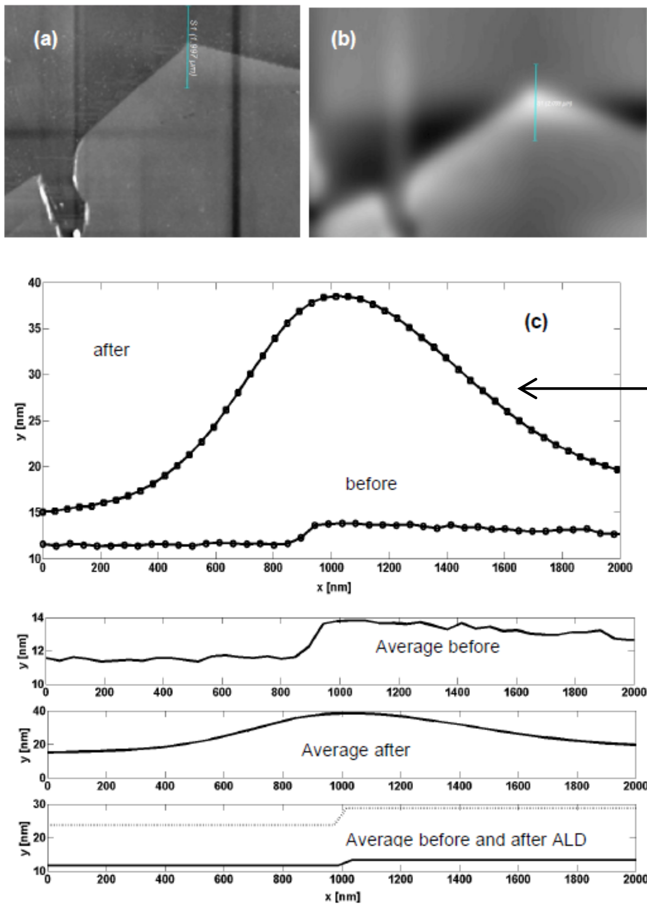


A. Fasoli et al., Phys. Status Solidi B (2009)

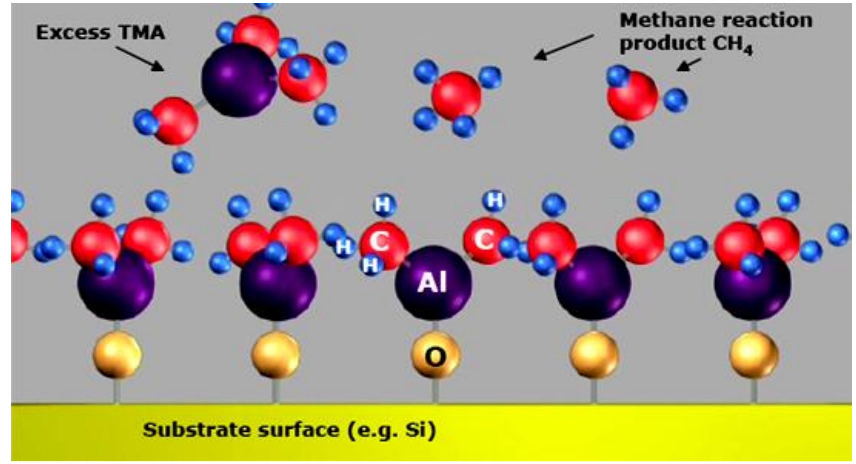


Top-gate dielectrics: Atomic Layer Deposition

ALD deposition of Al_2O_3 on graphene:



S. Haque et al., “ALD methods for fabricating graphene devices: theory and experiment”, APS March Meeting 2009
(cooperation with TKK Finland and Cambridge Univ.)



Preferential growth at graphene edges, due to reactive sites (dangling bonds).

Difficult growth on graphene surface , due to hydrophobicity.

Solution: Preliminary Al thin film deposition and oxidation [S. Kim et al., APL **94**, 062107 (2009)]

- ✓ Seed layer: evaporation of Al:

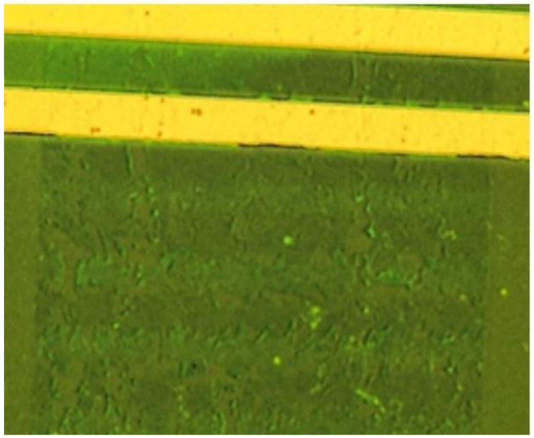
  Al boat: 2 nm evaporation @ 0.1nm/s
  (fully oxidized upon exposure to air)

- ✓ Deposition of Al_2O_3 by ALD:

  Temperature = 200°C
  Deposition/purge time = 250/500 ms (both for TMA and Water)
  8 nm deposition @ 0.1 nm/cycle (80 full cycles)

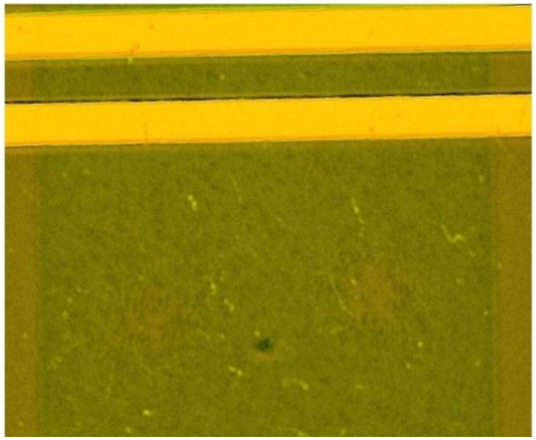
CVD graphene

Assessing the quality of commercially available CVD graphene:



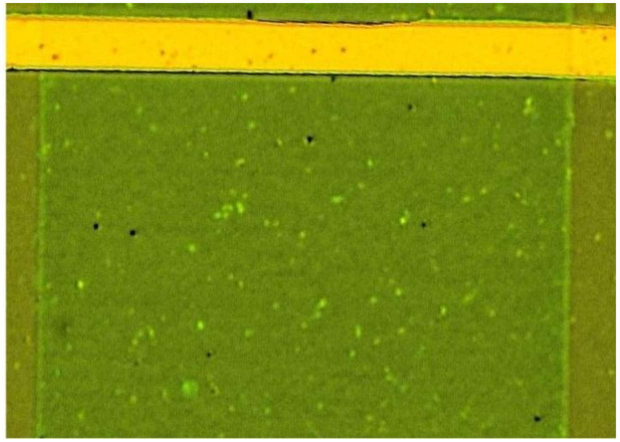
Heavily damaged and discontinuos

(R_{sheet} ~ 50 kOhm/sq)



Few defects and gaps

(R_{sheet} ~ 3-6 kOhm/sq)



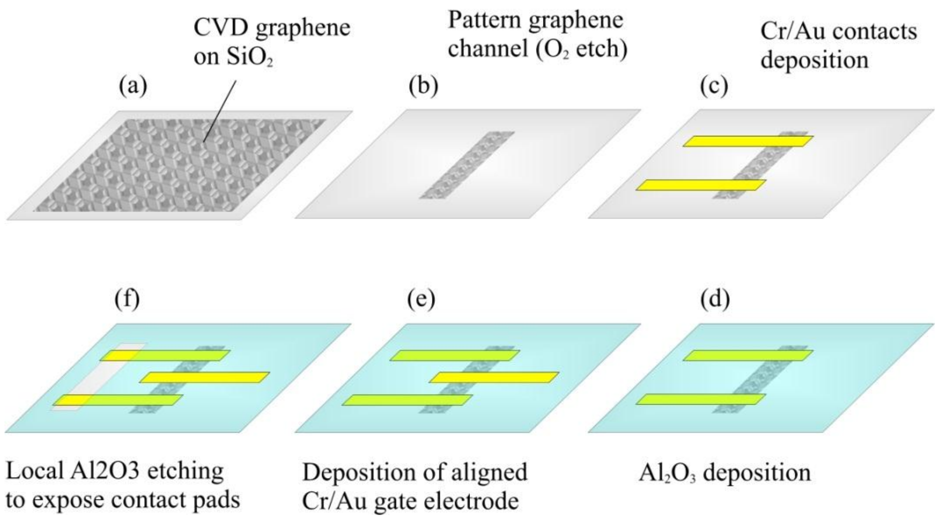
Largely uniform

(R_{sheet} ~ 600 Ohm/sq)

Same batch of CVD graphene grown on Cu.

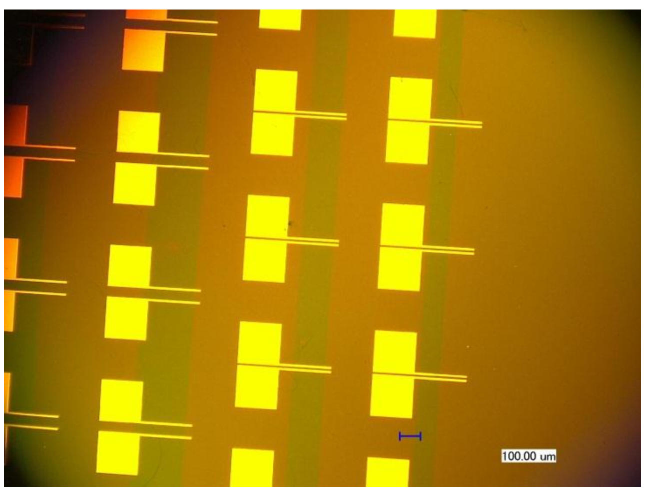
Critical parameters (such as sheet resistance) defining the electrical performance were found to strongly depend on the quality of the transfer process on SiO_2, plus the reliability of the following fabrication steps.

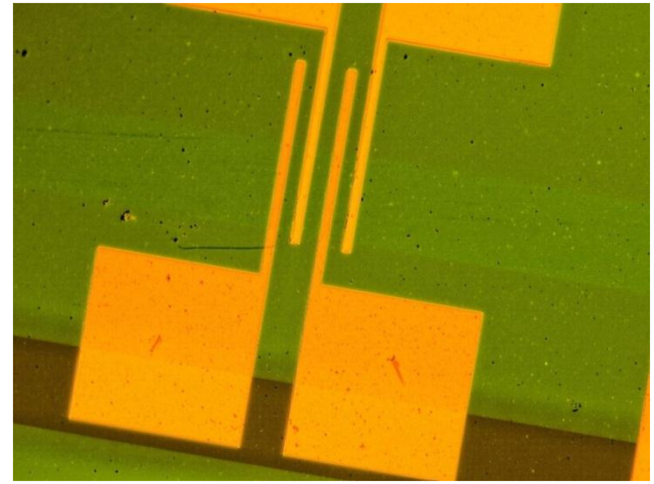
CVD graphene devices

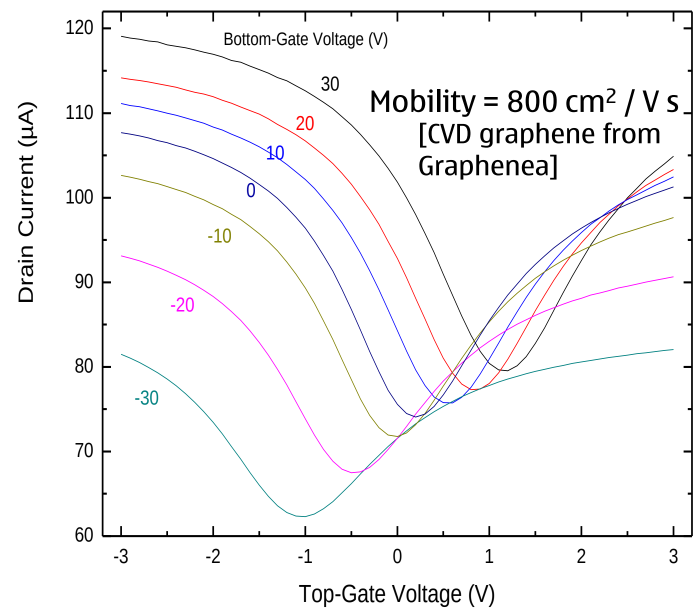


Final process: Annealing in furnace reactor to remove native p-type doping

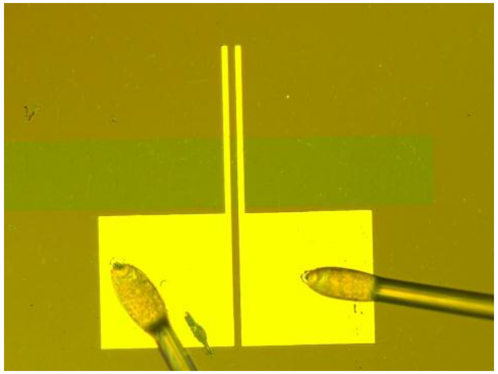
Arrays:

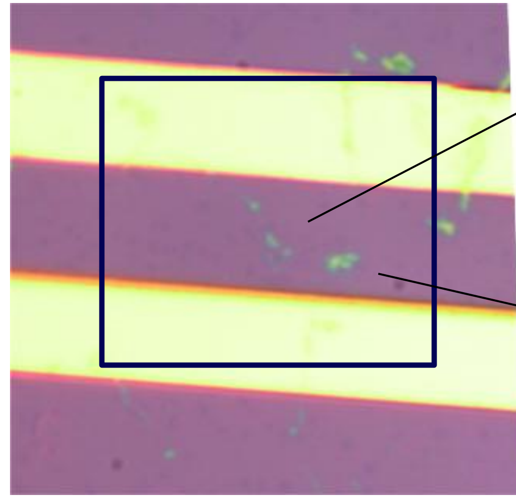






Photoresponse of CVD graphene





Graphene

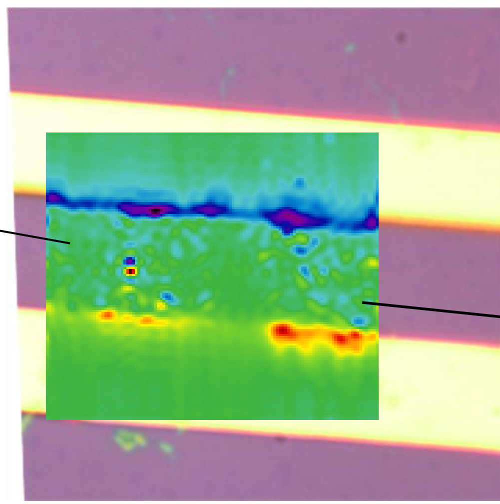
Area scanned by the laser beam.

(Area: 30x30 µm)

(Spot size ~ 1µm)

(Power ~ 500µW)

Photovoltage measurements on doped CVD graphene

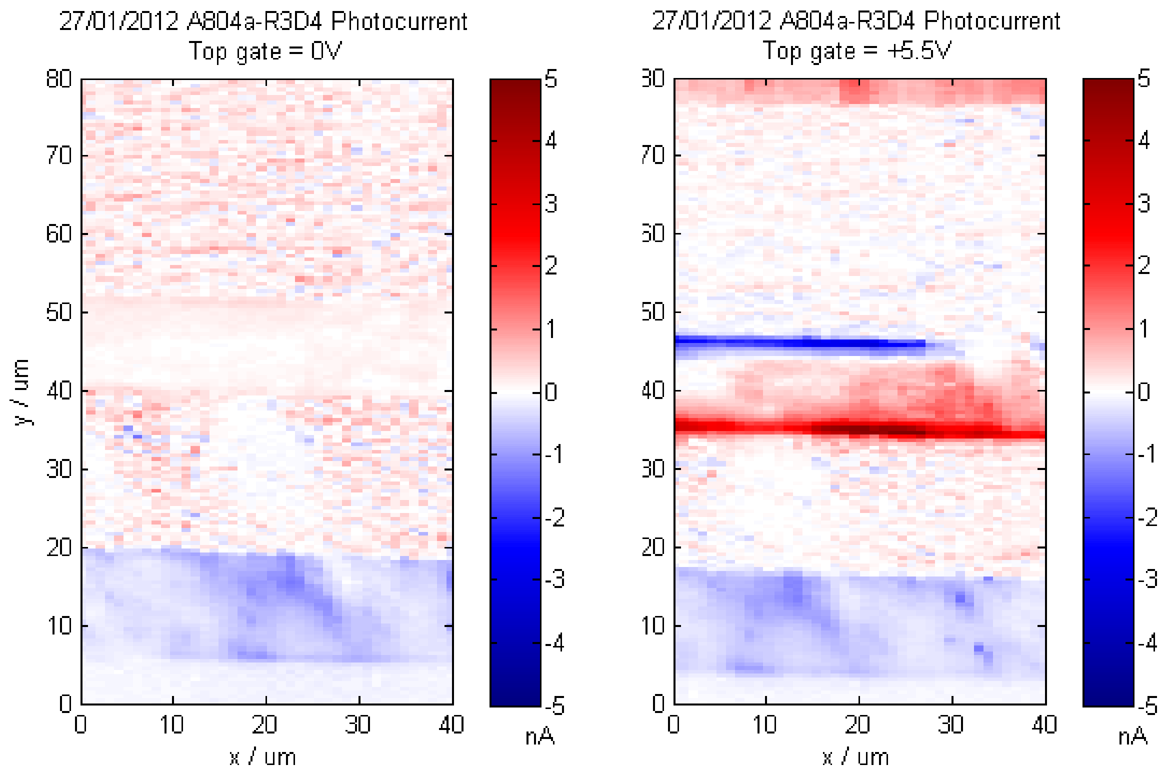


Good quality ⟺ long charge carrier lifetime

Photoresponse 10 times smaller than in exfoliated graphene, but still measurable

CVD graphene optoelectronic devices

Photomapping of top-gated devices:



Opportunities:

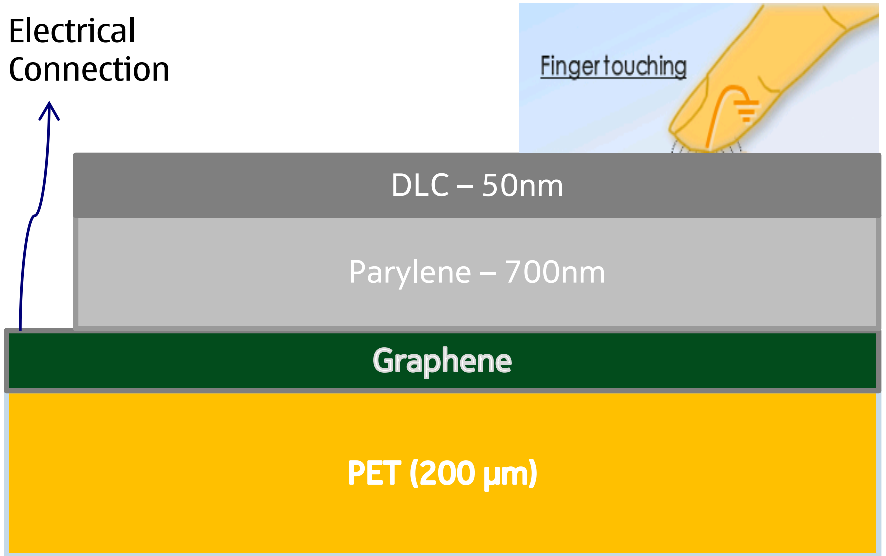
- Photodetectors
- Energy harvesting:

N. M. Gabor et al., "Hot Carrier–Assisted Intrinsic Photoresponse in Graphene", Science 2011

Further applications under study

Electrotactile devices (haptic feedback):

Feel the image on the screen



Diamond Like Carbon (DLC) for improving scratch resistance, moisture repelling properties.

Parylene polymer soft flexible dielectric.

Graphene (chemically exfoliated and coated uniformly – 200nm thick

PET (plastic sheet) - 200 µm

TYPE	ITO	Copper Mesh	Silver Nanowires	Graphene	CNTs
Sheet Resistance	350Ω/□	1.5 Ω/□	30-50 Ω/□	30 Ω/□ - few kΩ/□	400 Ω/□
Transmittance	88%	88%	90%	90%	88%
Colour	Colourless	Colourless	Colourless	Colourless	Almost colourless
Bending Durability	Inferior	Superior	Superior	Good	Good
Environment	Good	Good	OK	Good	Good
ET Effect	Very Good	-	Very Good	Very Good	Very Good

Furthermore: Multi-functional sensing surfaces (physical sensors + chemical sensors)

Graphene opportunities

- Large scale; mass production; planar / thin film technology
- Easy implementation into existing industrial processes
- Co-existence of various outstanding properties
- New **unique technological platform**
- Enabling new concept devices based on new materials and technologies

"The principal applications of any sufficiently new and innovative technology always have been – and will continue to be – applications ***created*** *by that technology".*

[Lemma of New Technology, H. Kroemer]