Graphene electronics

Johannes Svensson

Nanoelectronics EITP05

Outline

- Graphene production
  - Mechanical exfoliation
  - Epitaxial growth
  - Chemical vapor deposition
- Transport characteristics
- High frequency performance
- Inducing a band gap
  - Nanoribbon
  - Bilayer graphene
  - Chemical modification
- Performance comparison (graphene / CNTs)
- Other electronic CNT/graphene devices

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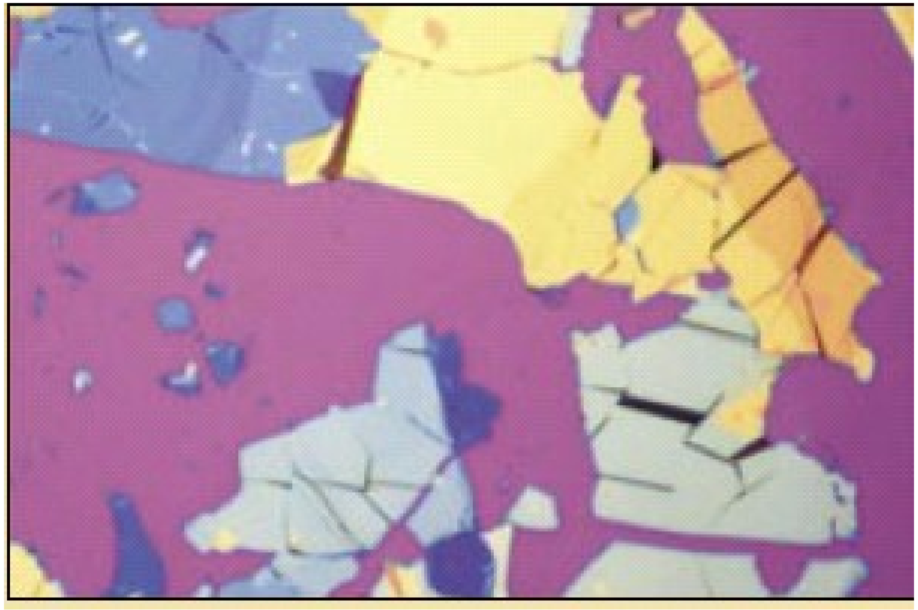
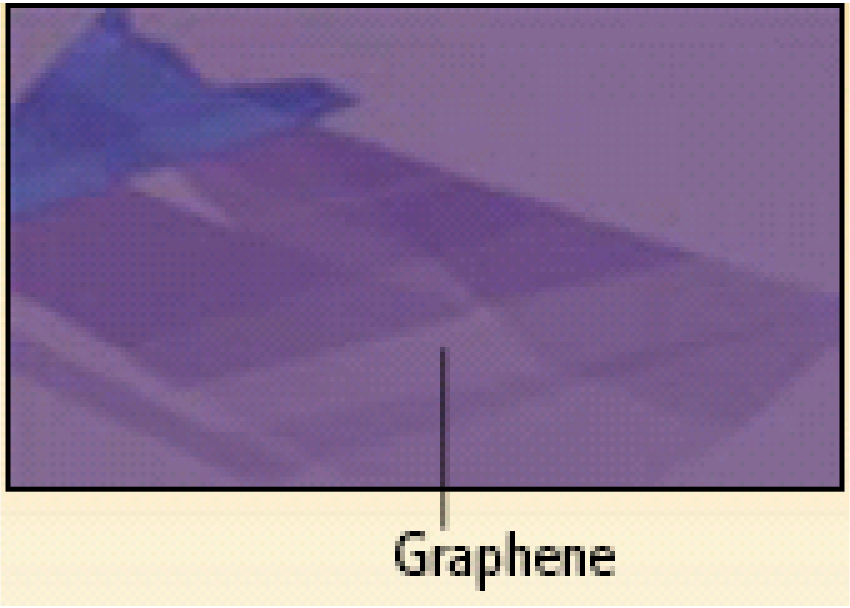
Mechanical exfoliation

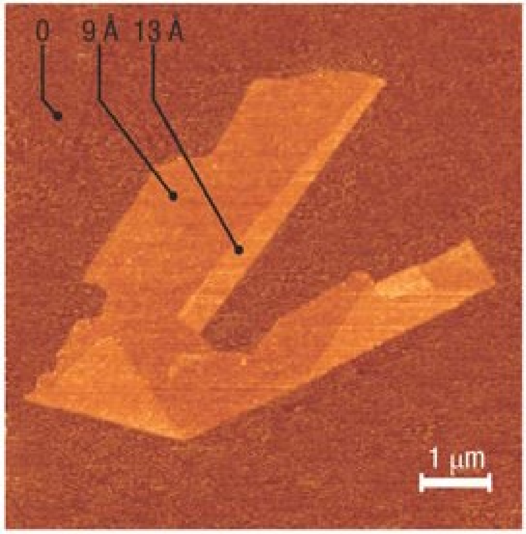
- Rub graphite on substrate
- Use adhesive tape to peel off layers
- 100x100 µm flakes -> mainly for research
- Visible in optical microscope

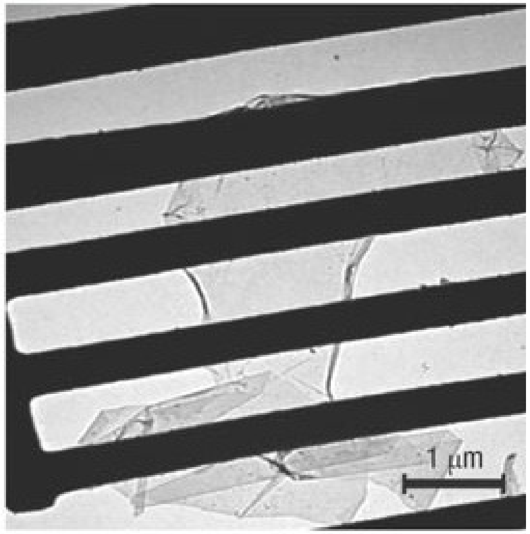


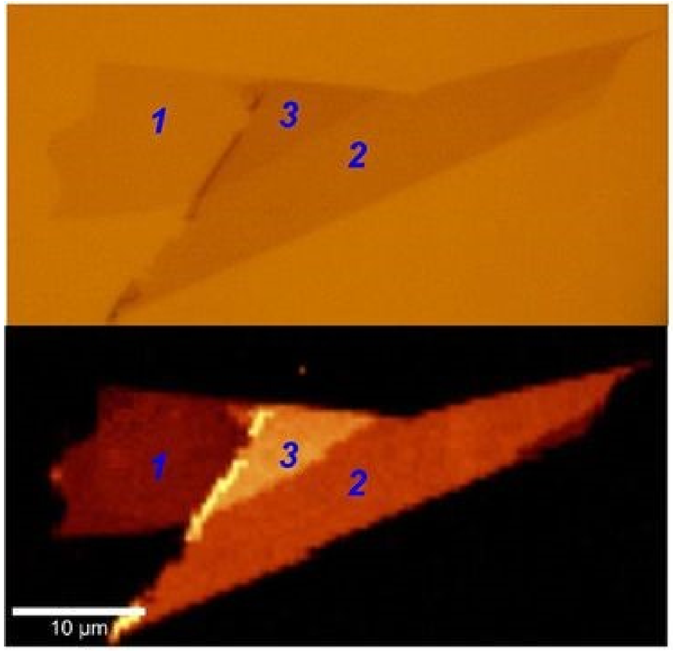


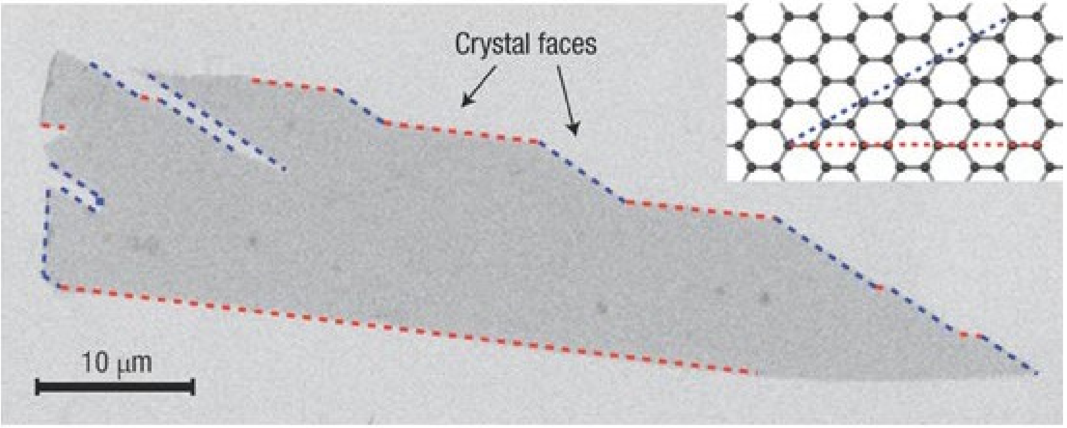
Observing graphene

- Optical microscope
- Atomic force microscopy
- TEM
- SEM
- Raman spectroscopy





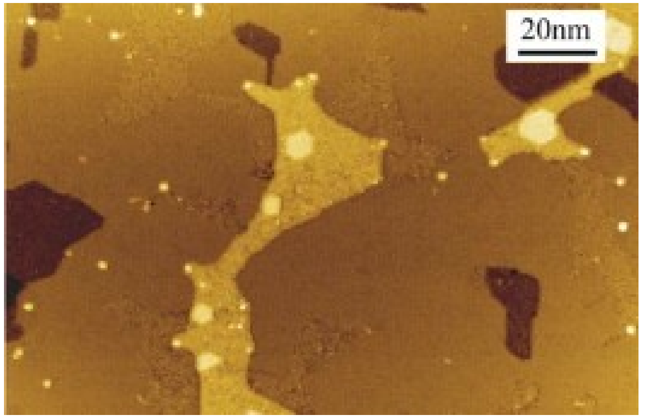


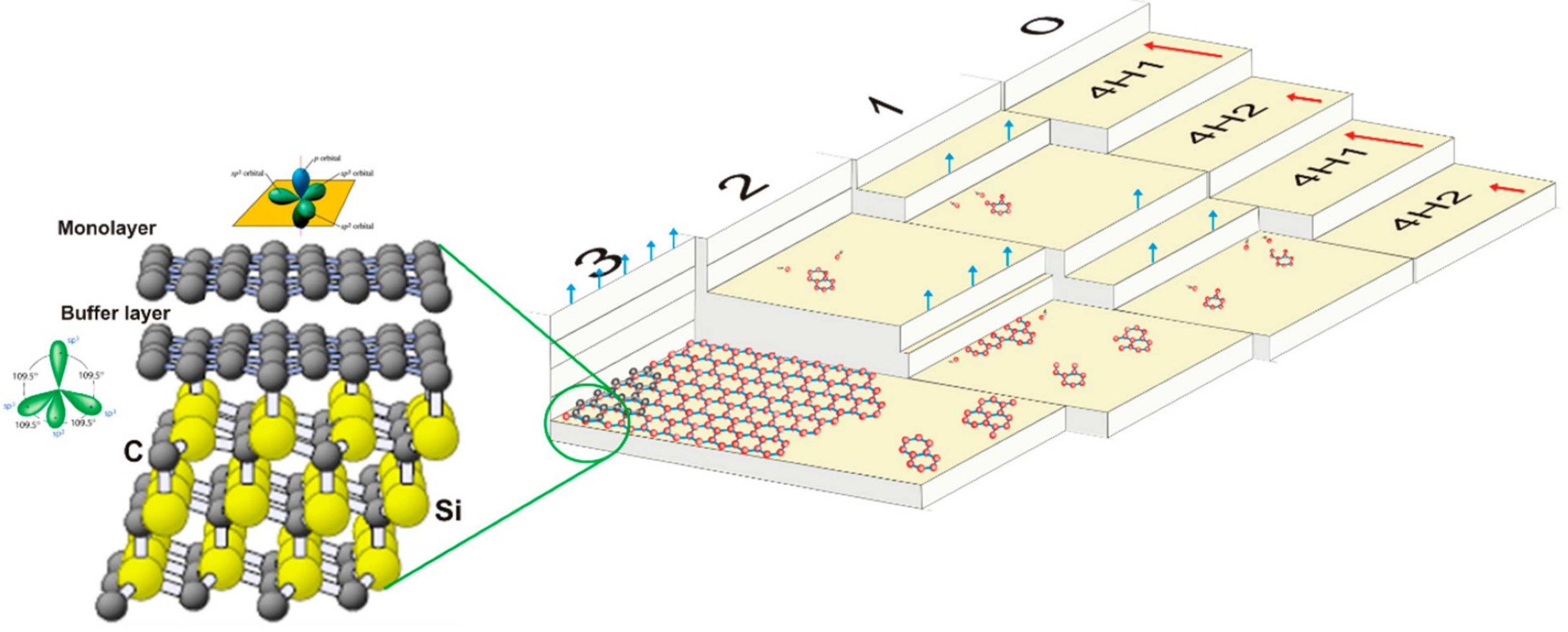


Epitaxial growth on SiC

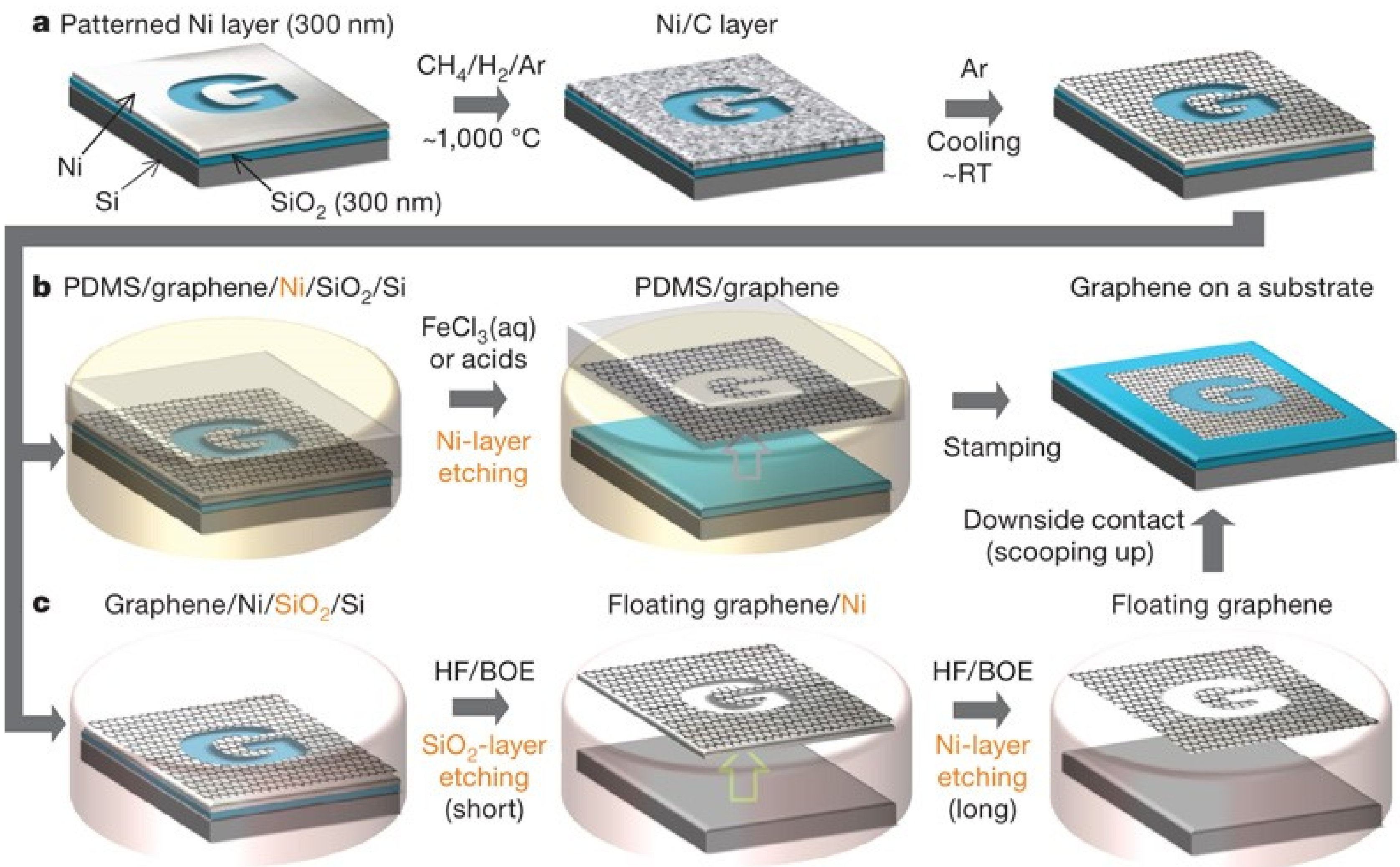
-Heat to 1550 °C to remove Si which will expose a graphene layer

-Need to remove "coupling" to substrate by e.g. hydrogen treatment





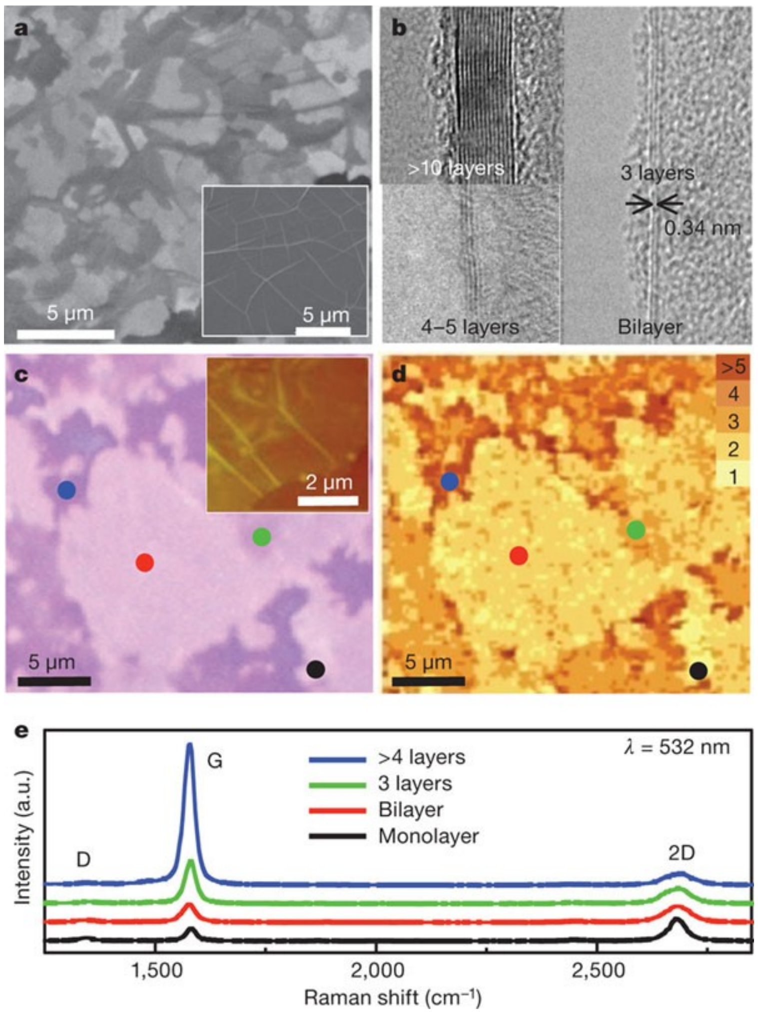
Chemical vapor deposition

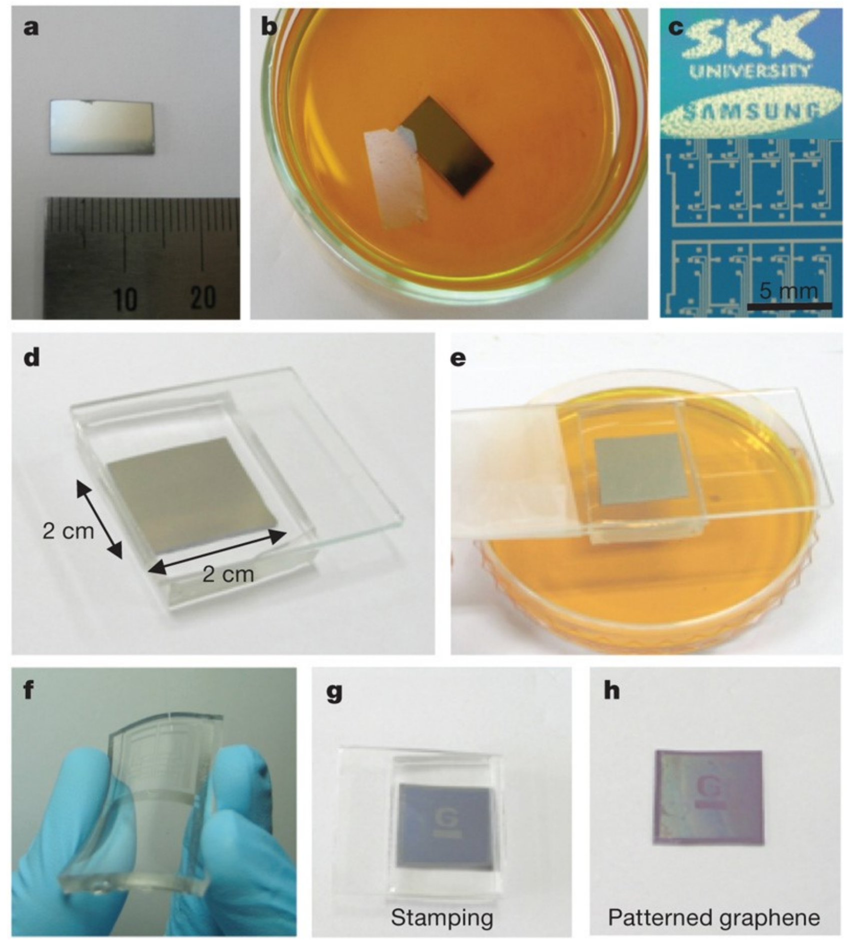


Kim et al. *Nature* **457**, 706-710 (2009)

Chemical vapor deposition - result

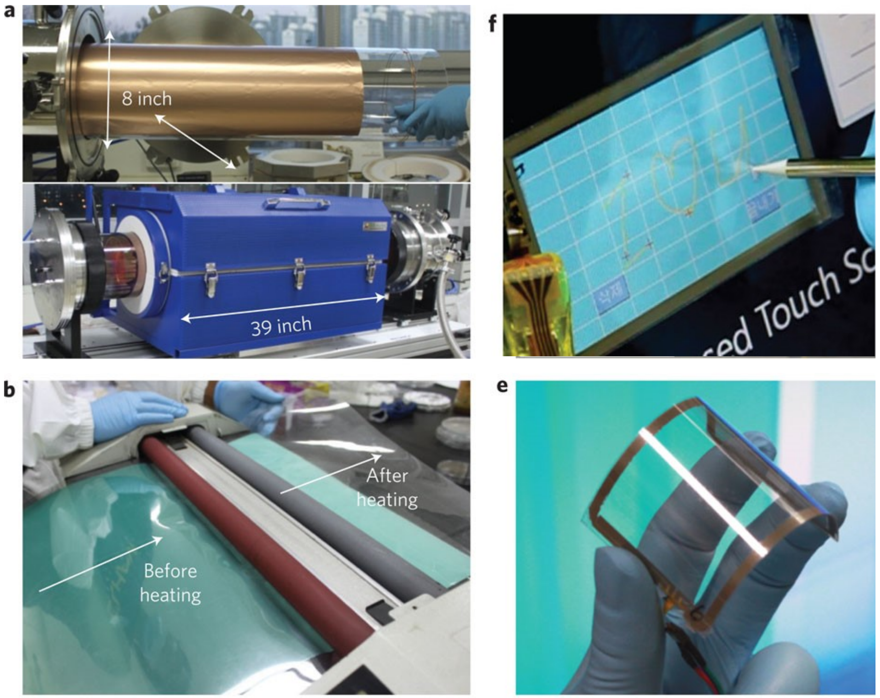
- Mix of single and multilayered
- μ_e=3,700 cm^2/Vs after transfer

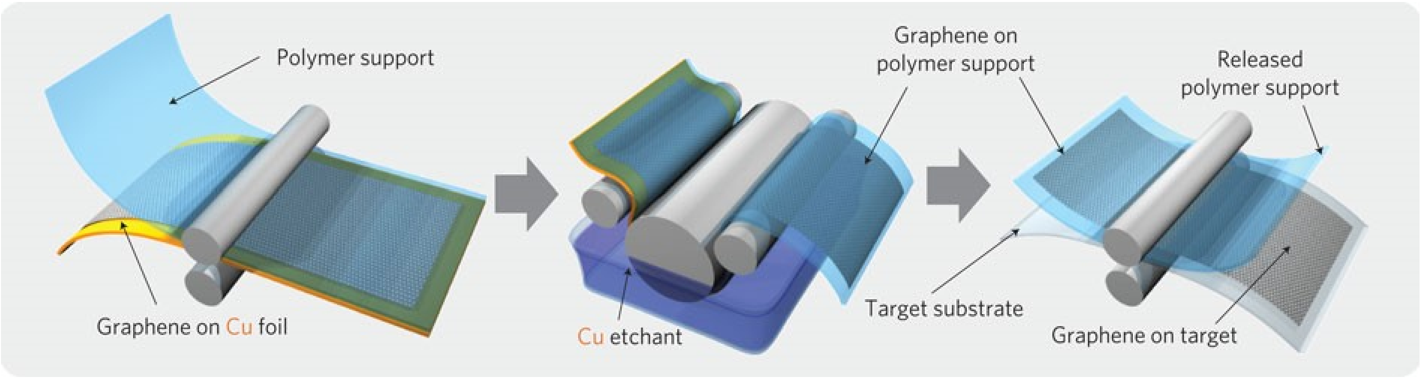




Large scale CVD production

- CVD on Cu foil
- 30 inch multilayer flake
- 30 Ω/□ at 90% transparency
- Better than ITO





Bae et al. *Nature Nanotech*. **5**, 574–578 (2010)

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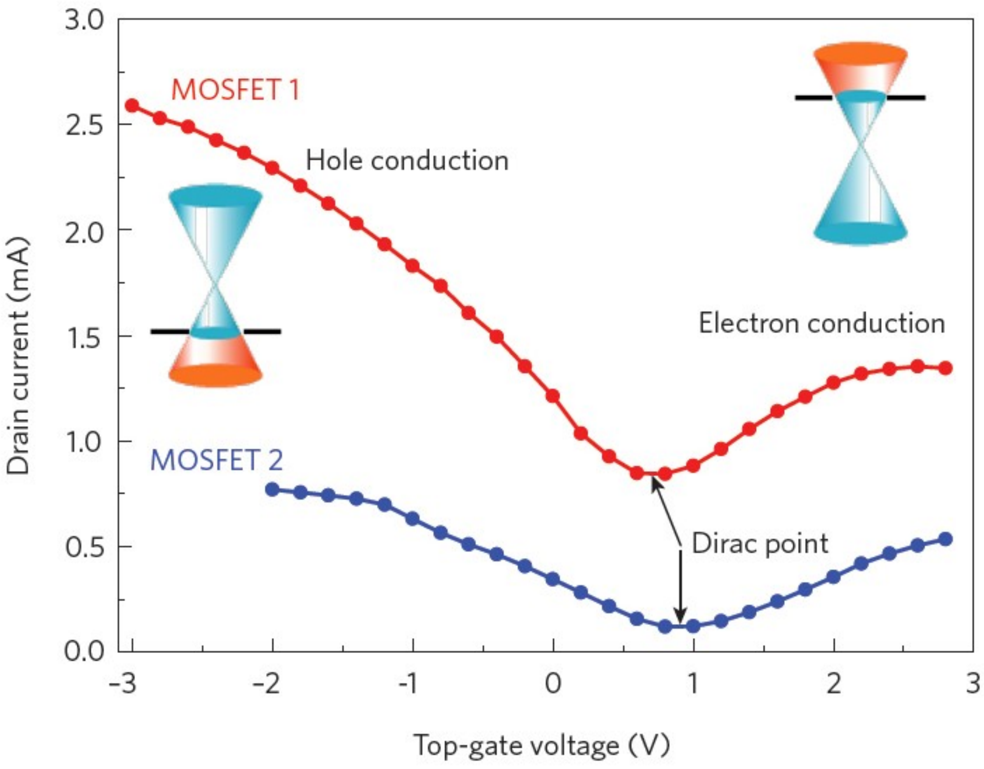
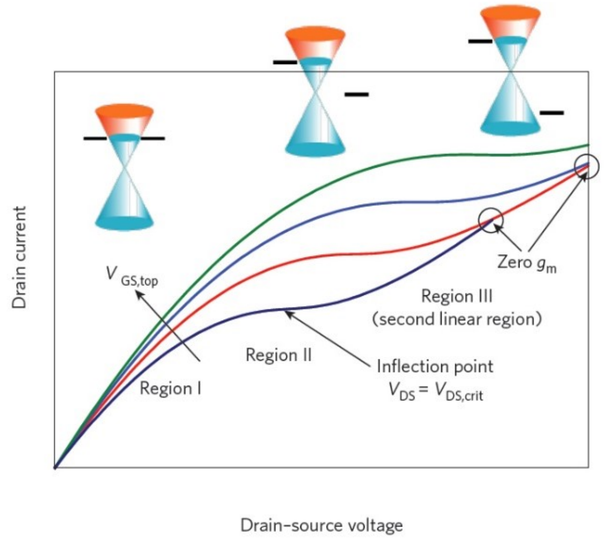
Transfer characteristics

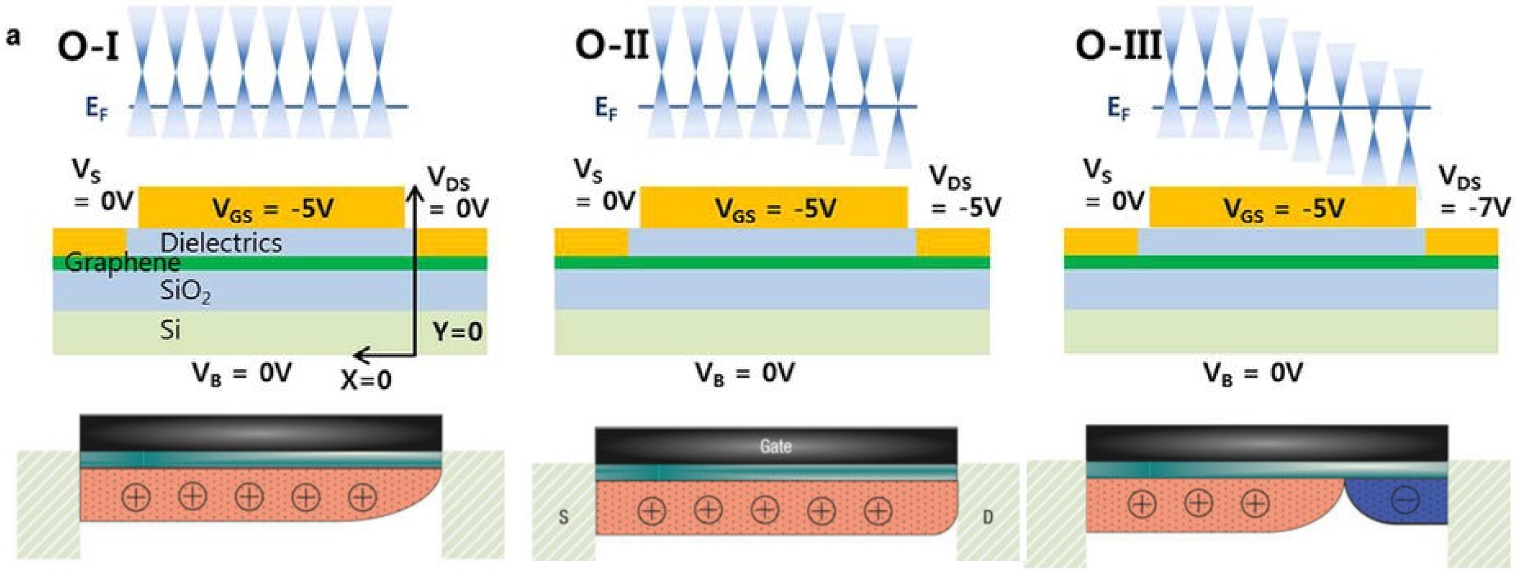
- DOS decreases towards ”Dirac” point.
- Finite conductance due to corrugations, charge impurities, disorder etc.
- No band gap -> poor on/off ratio
- Logic requires on/off > 3000 i.e. can not make digital circuits.



Output characteristics

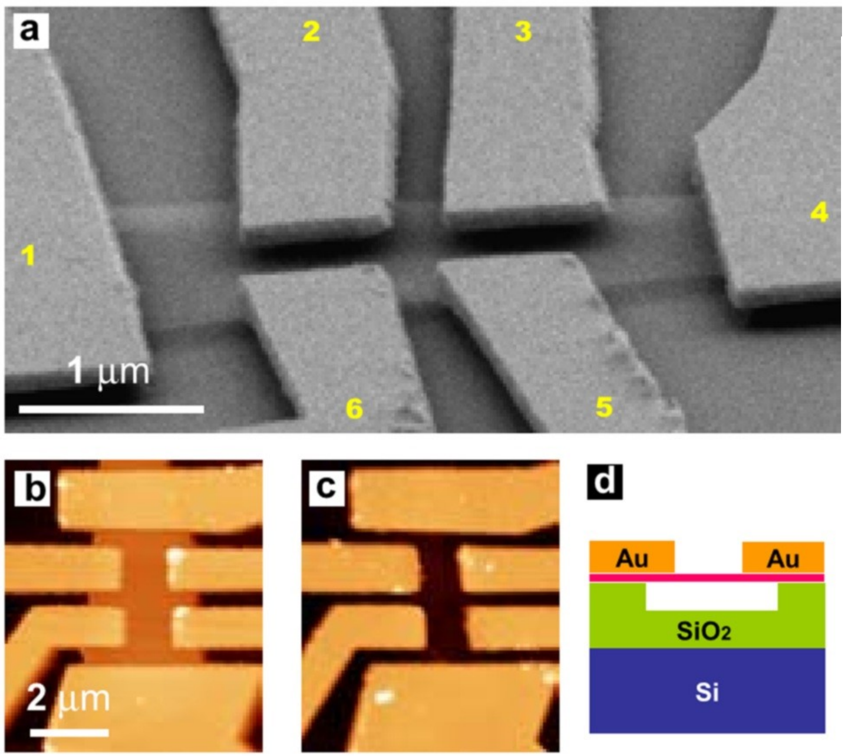
- Low V_{DS}: only holes in channel
- Intermediate V_{DS}: channel pinched off at drain.
- High V_{DS}: electrons close to drain. e/h crossover point moves into channel with increasing V_{DS}

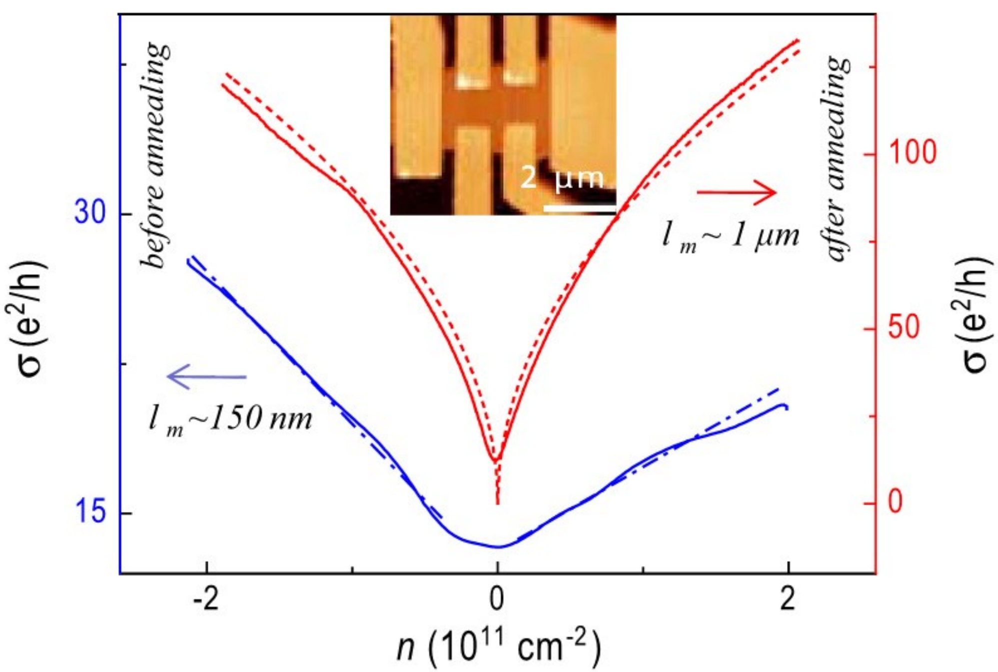




High mobility

- Exfoliated graphene
- Unsuspended flakes: μ_e=2 000 - 30 000 cm^2/Vs (substrate phonons)
- Supended and annealed flakes: μ_e=230 000 cm^2/Vs
- Scattering due to, phonons, impurities and edges





Bolotin et al. *PRL* 101, 096802 (2008)

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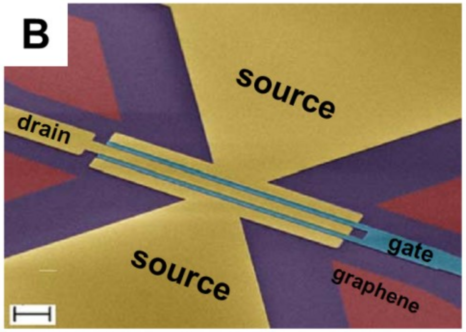
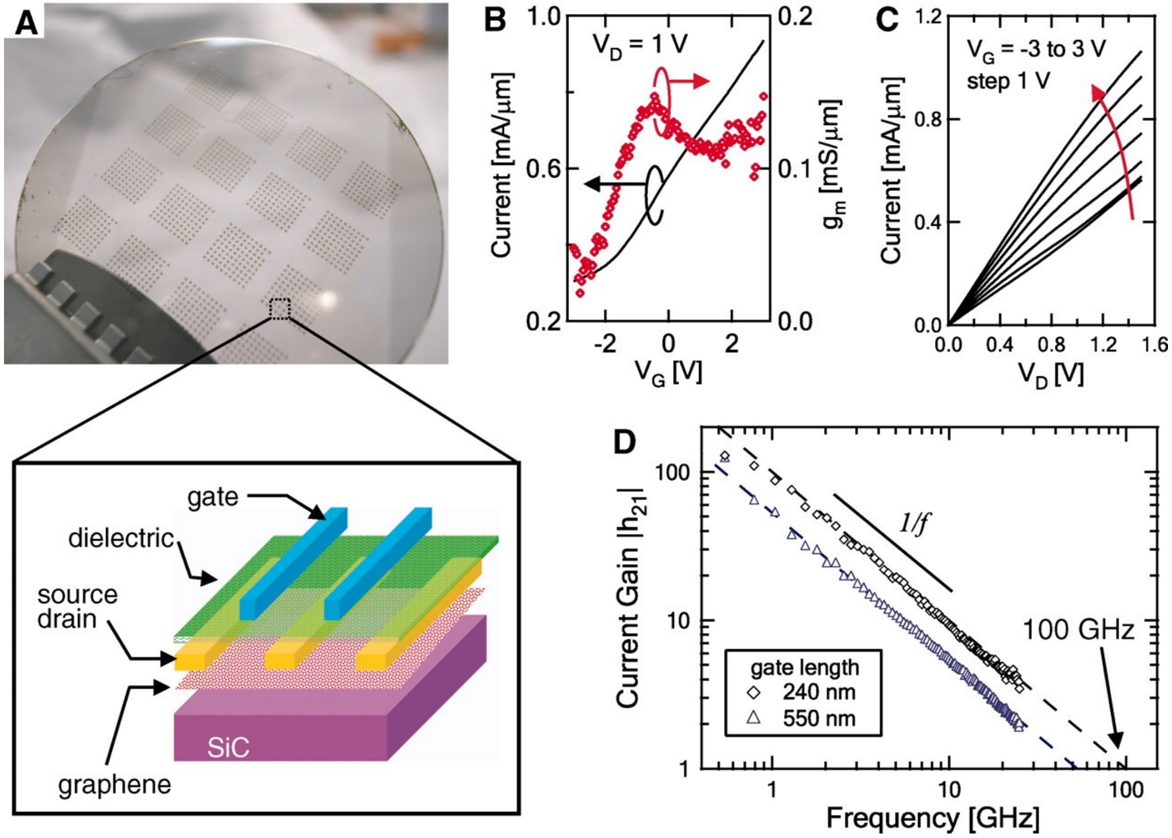
High frequency device

- SiC grown graphene
- f_T=100 GHz for L_g=240 nm
- Large output conductance -> low f_{max}

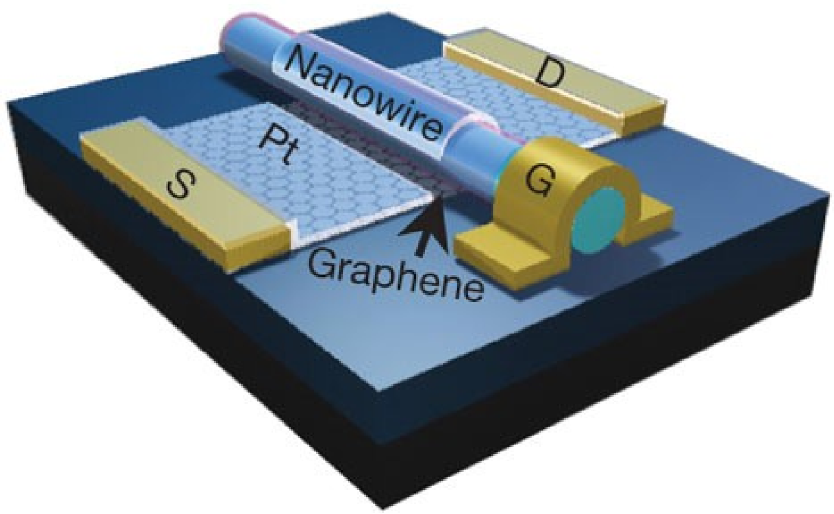


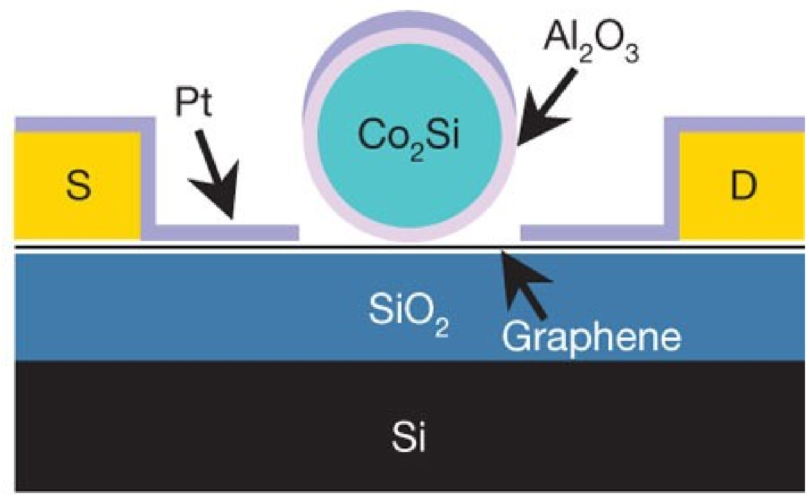


Lin et al. *Science*, **327** , 662 (2010)

Graphene - nanowire device

- Dielectric lowers mobility
- Gate underlap: high source/drain access resistance reduce g_m
- Gate overlap: increased paracitic capacitances
- Silicide nanowires with Al_2O_3 shell on exfoliated graphene
- Self-aligned Pt contacts

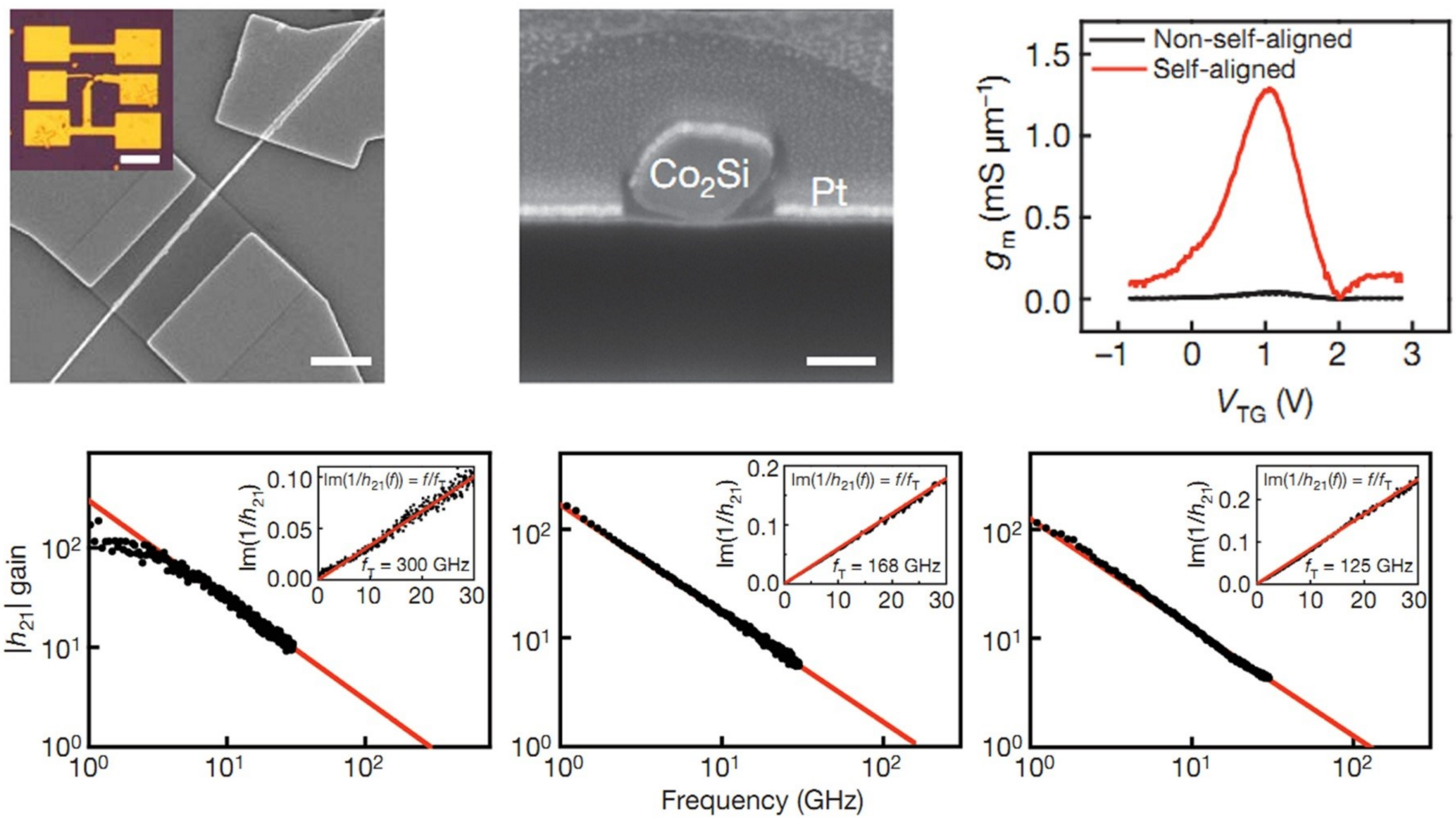




Liao et al. *Nature* , **467**, 305–308 (2010)

Graphene - nanowire device performance

- g_m improves after Pt
- f_T=300 GHz for L_g=144 nm
- Better than Si MOSFETs, similar to InP and GaAs HEMTs



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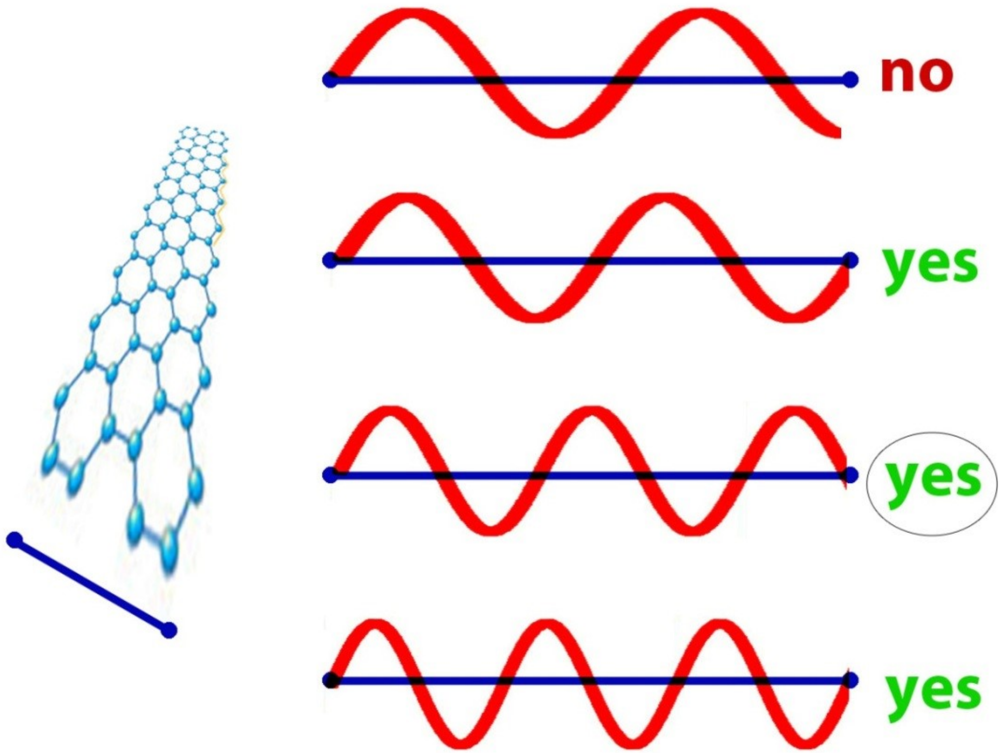
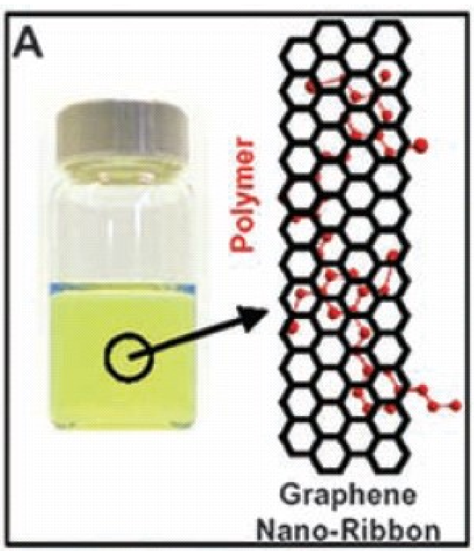
Confinement of electron wavefunctions

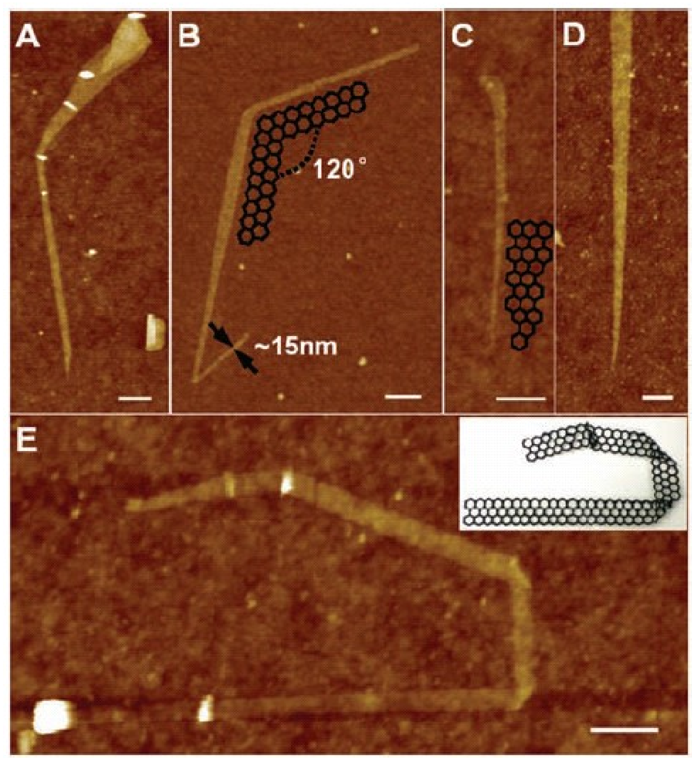
- Make narrow ribbon to introduce band gap
- Fixed boundary conditions instead of periodic (CNT)
- Wavevectors $k_{\perp} = n\pi/C$ with n=1,2,3... allowed
- Need width = CNT circumference / 2 to get same band gap

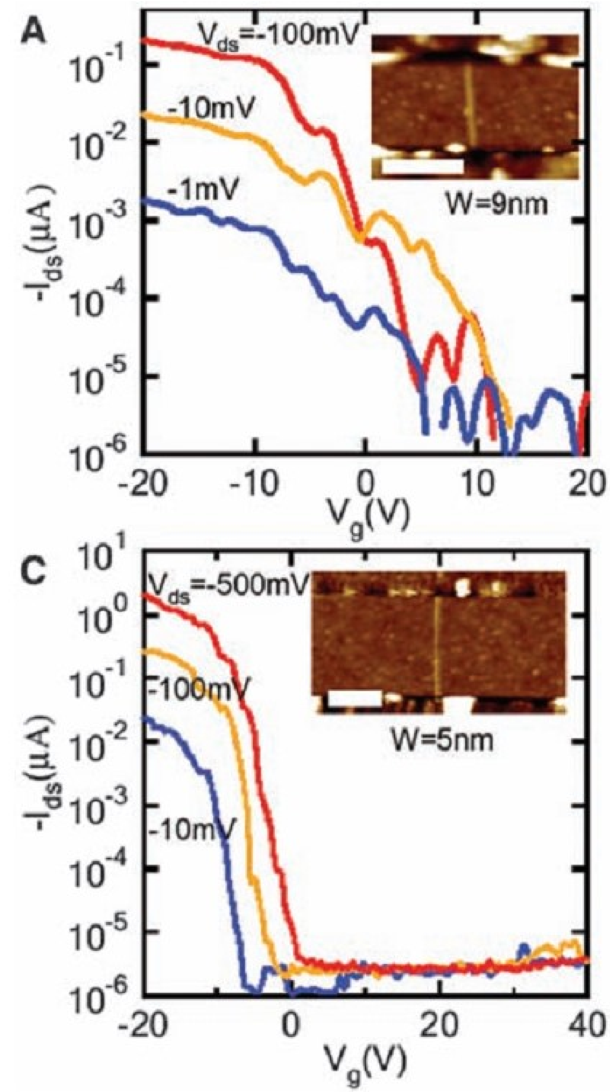


Chemical exfoliation

- Intercalate sulfuric acid and nitric acid in graphite
- Heat to 1000°C -> few-layered graphene sheets.
- Sonication with polymer -> graphene nanoribbons



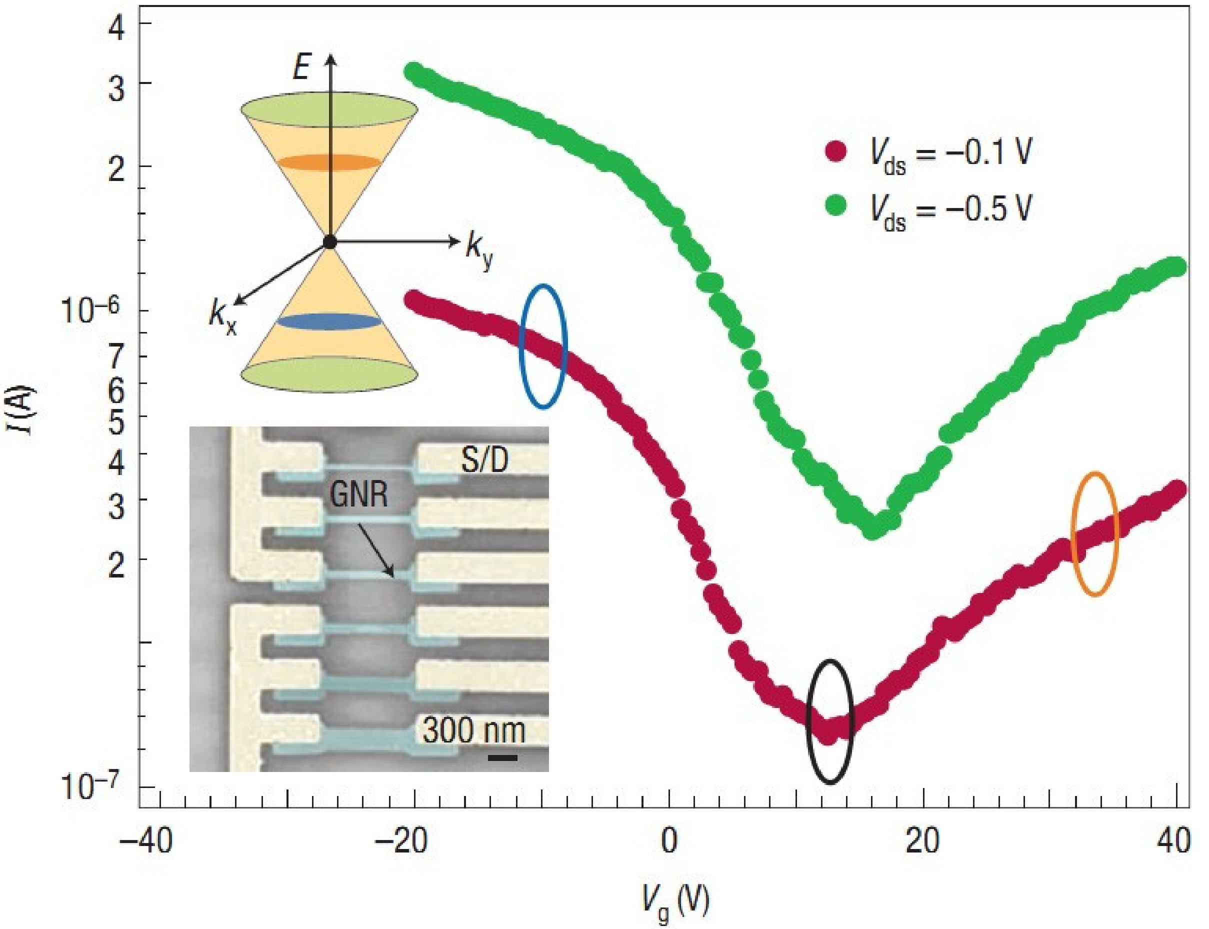




Li et al. *Science,* **319 (**2008)

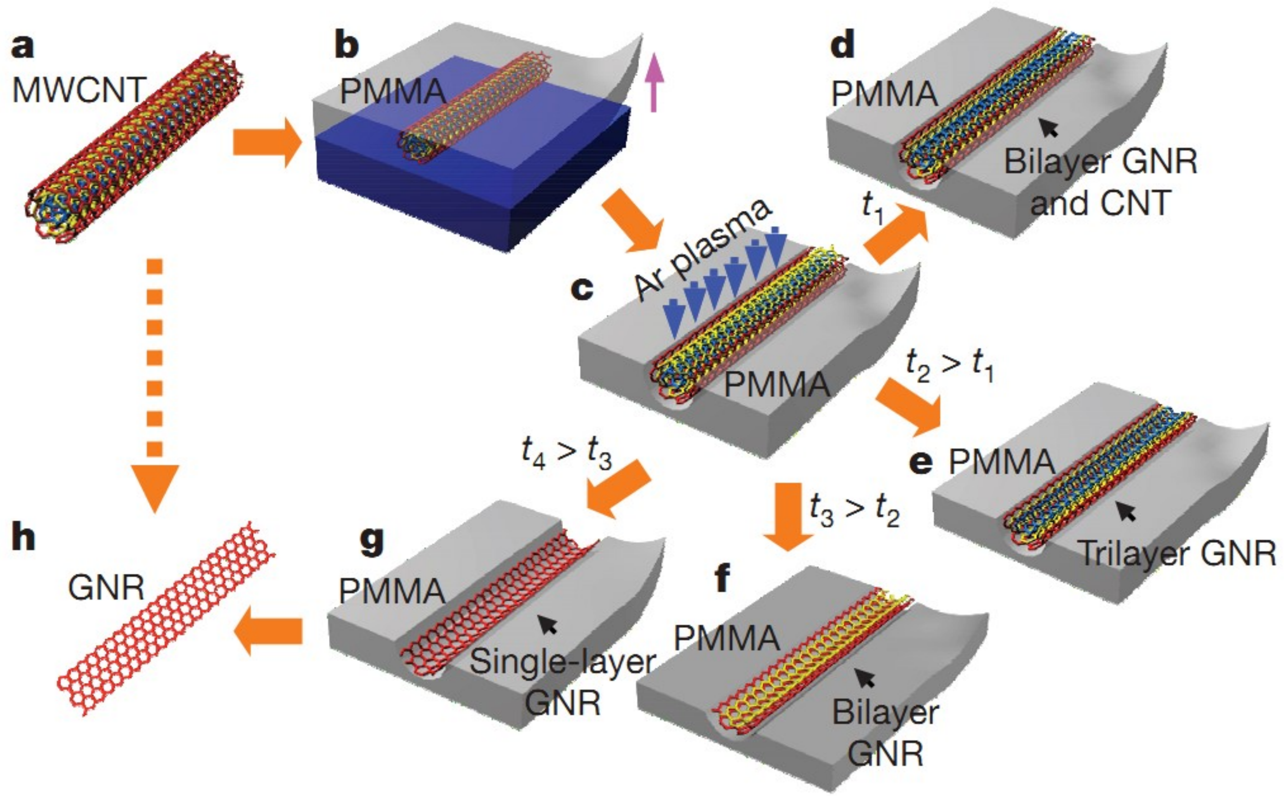
Etching

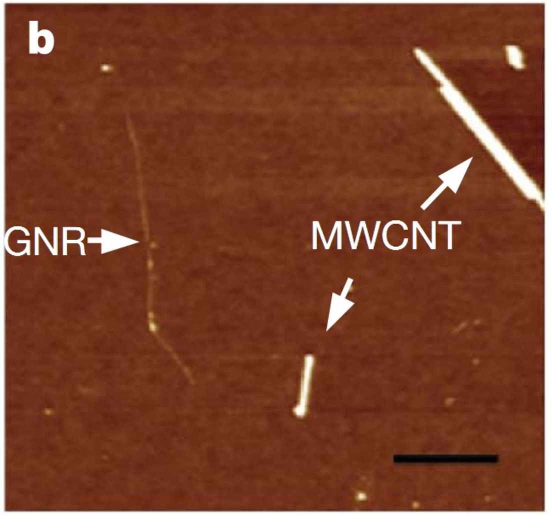
- E-beam lithography and oxygen plasma etching
- Not narrow enough
- Diffcult to control edges



Unzipping a CNT

- Use oxygen plasma to remove layers of CNTs
- Very delicate process -> no mass production

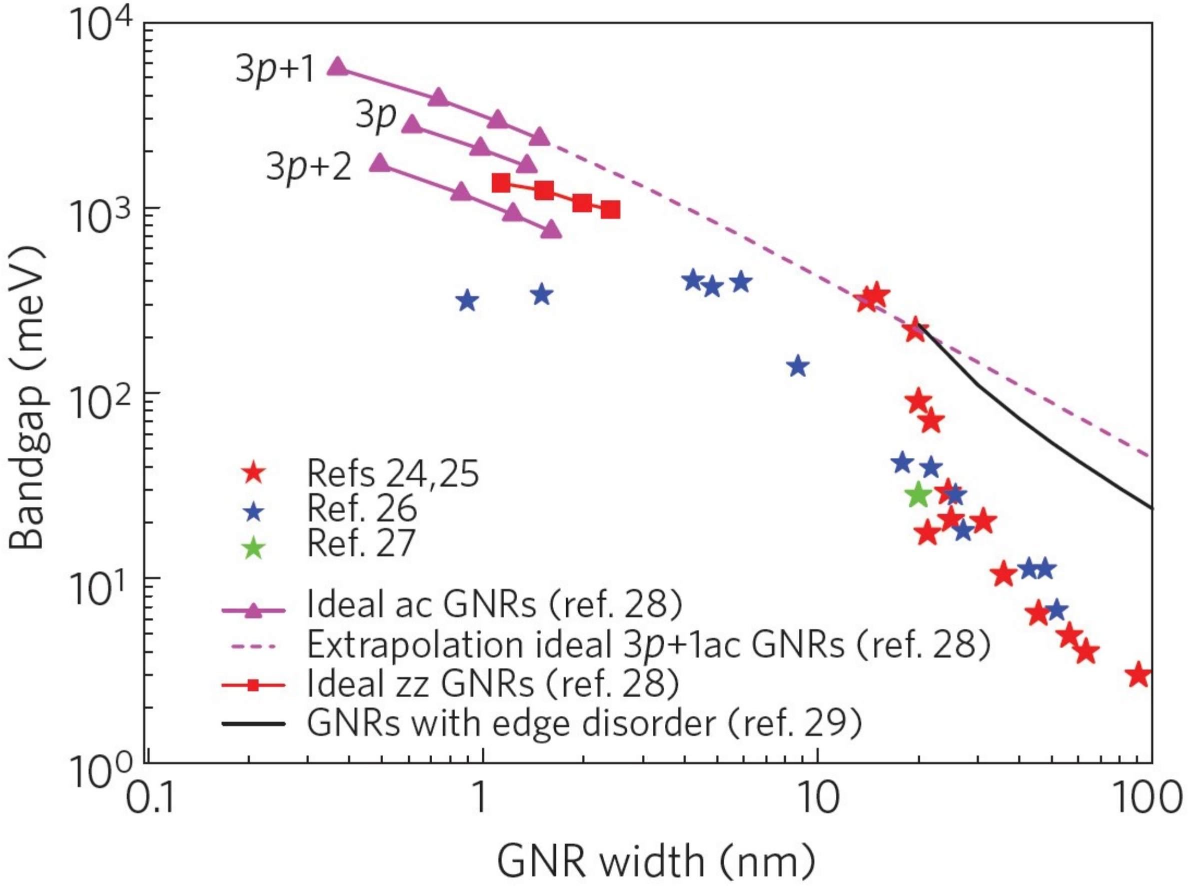




Jiao et al. *Nature*, **458**, 877-880 (2009)

Band gap vs GNR width

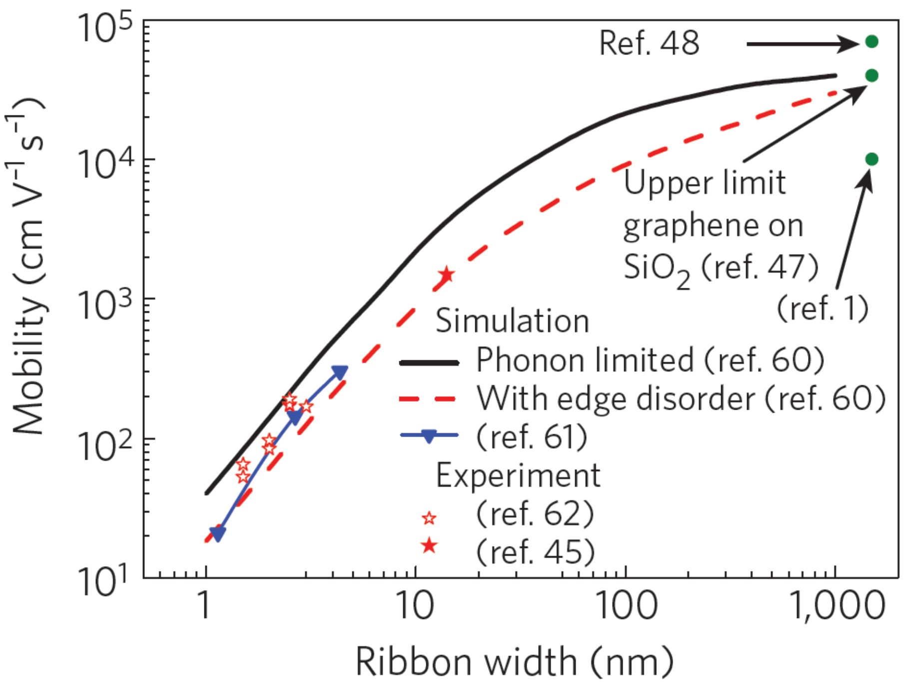
- Need 1 nm wide ribbons to get E_g=1 eV
- Gap depends on edge structure

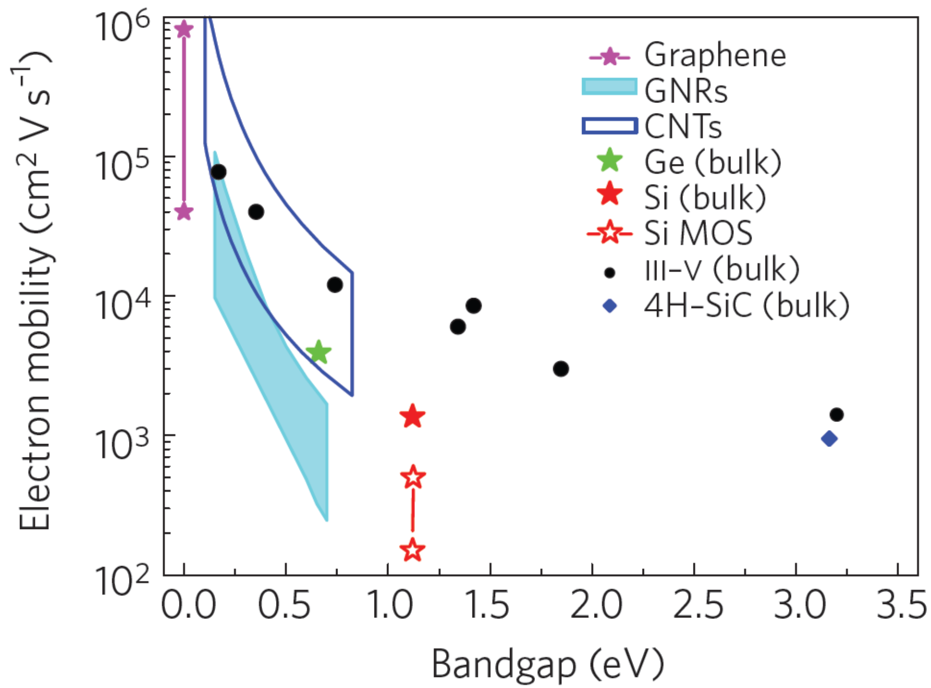


Schwierz, *Nature Nanotech.* **5**, 487 (2010)

Mobility degradation

- Narrower -> Larger E_g -> higher m^* -> lower mobility (as for CNTs)
- Graphene ribbons are worse than III-V materials

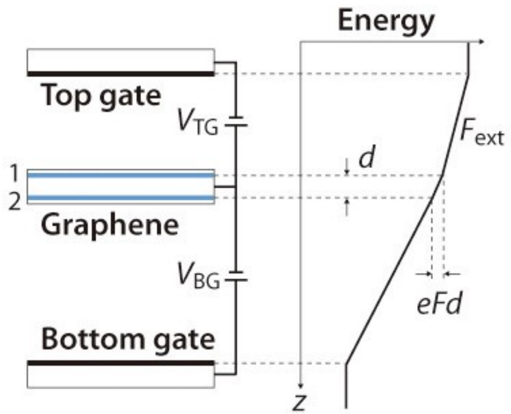


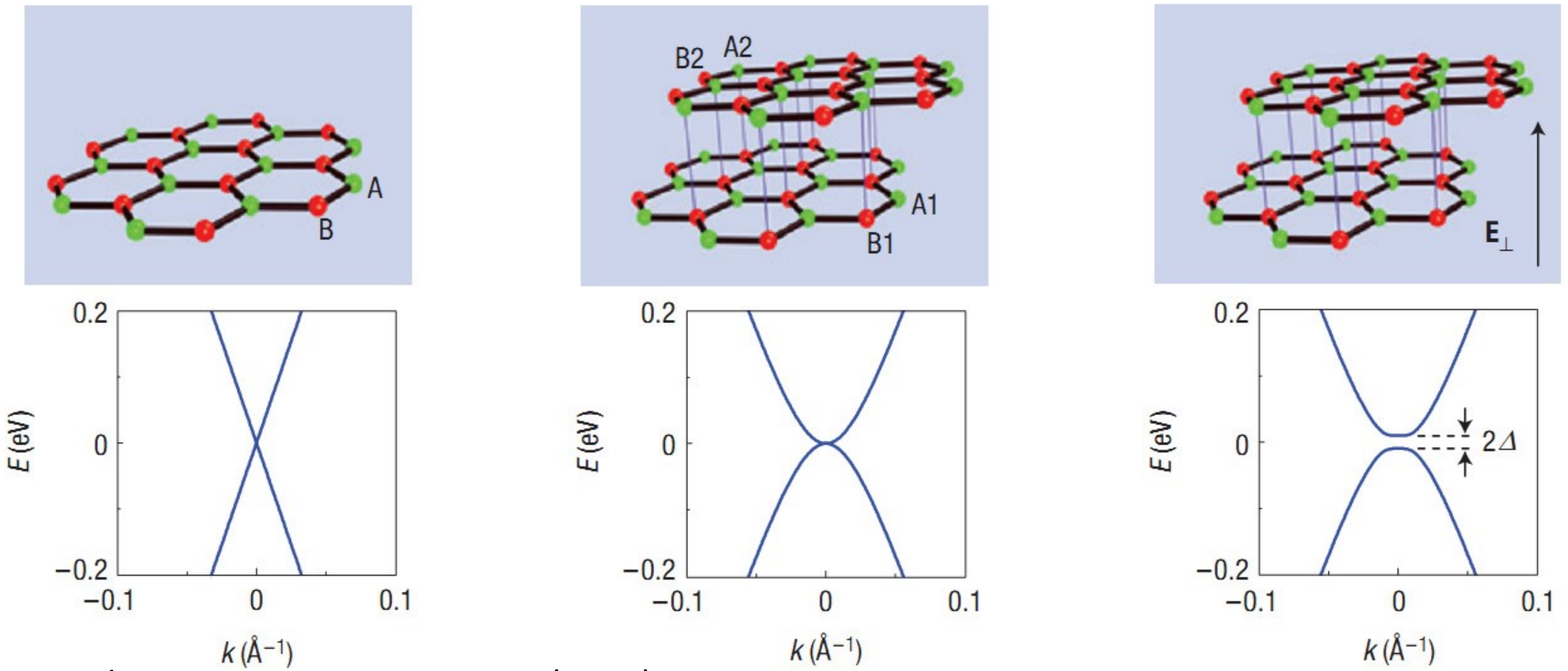


Bilayer graphene

- Perpendicular electric field breaks symmetry in bilayer graphene.

- Band gap proportional to E-field.

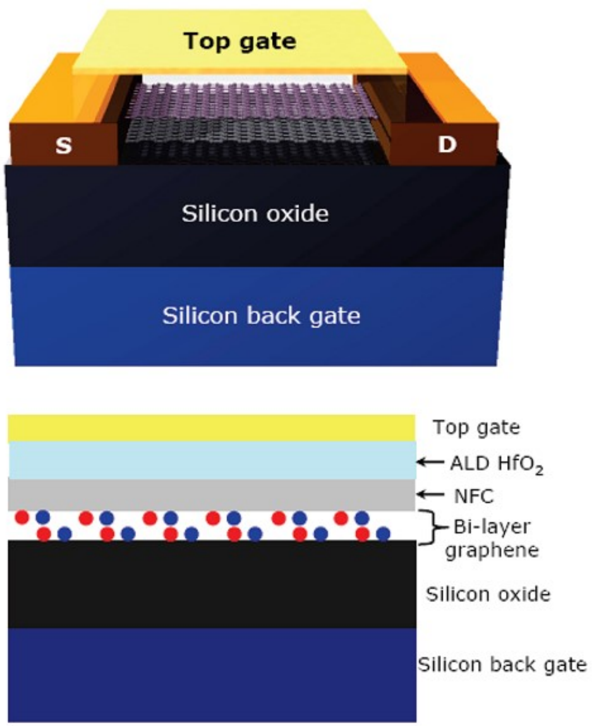


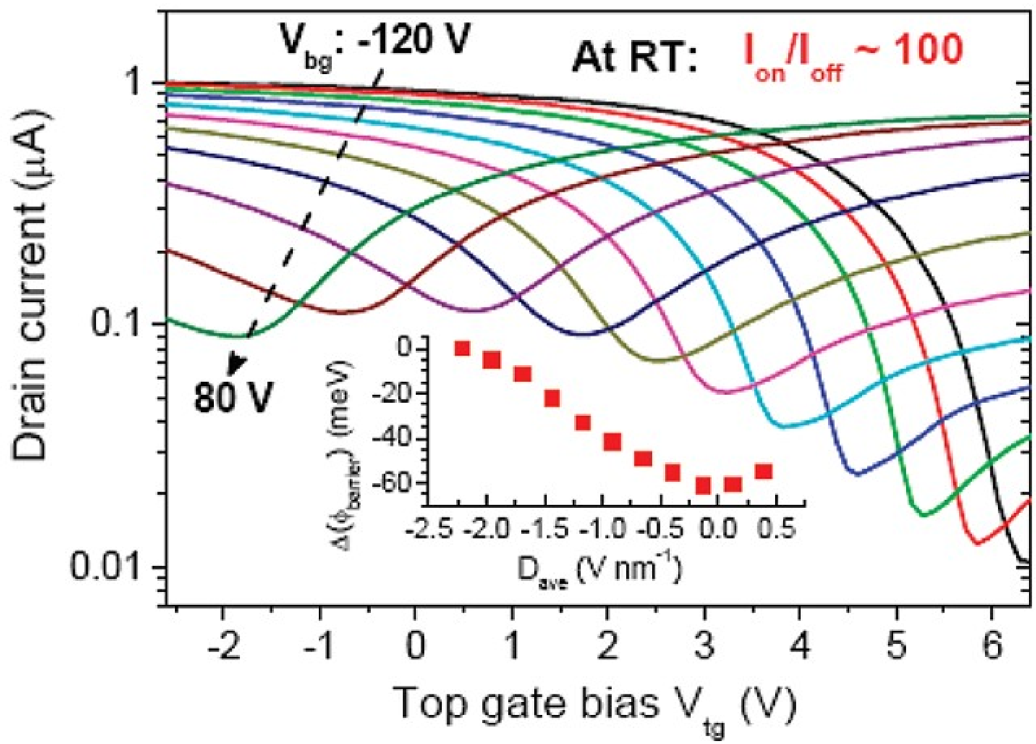


Oostinga et al. *Nature Mat.* **7**, 151 - 157 (2007)

Double gated bilayer device

- Need to apply 120 V to get on/off = 100
- Difficult to use for integrated circuits
- Mobility is probably degraded

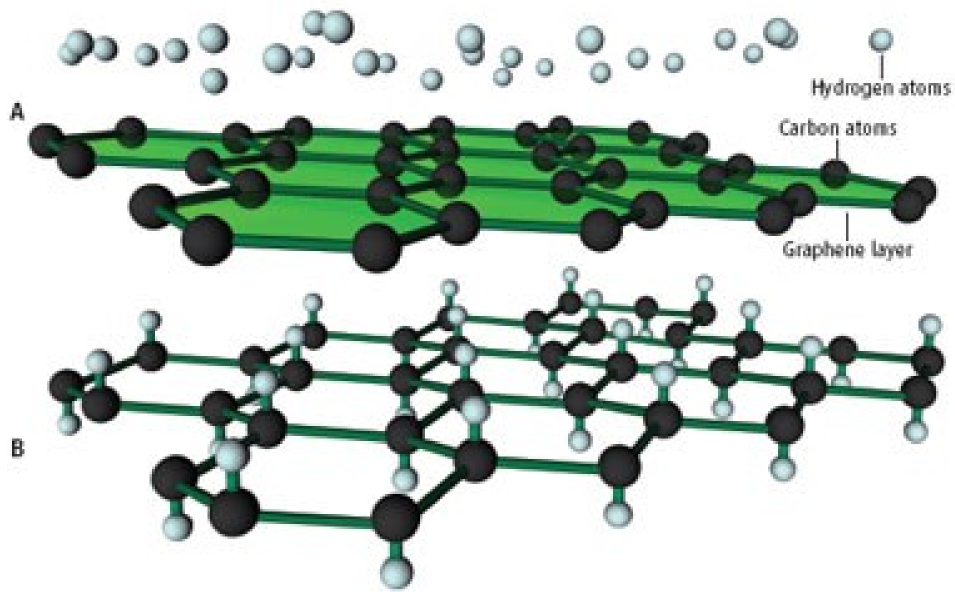


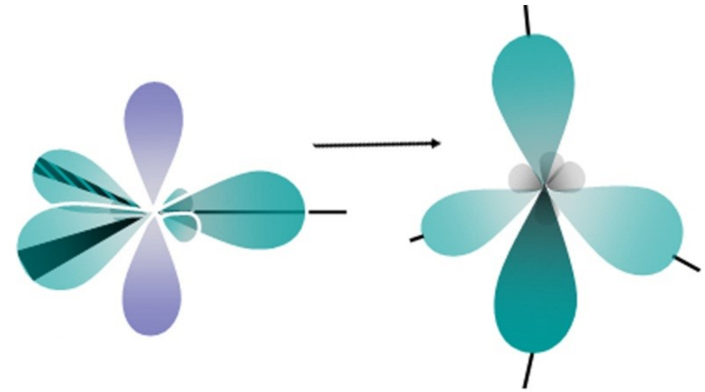


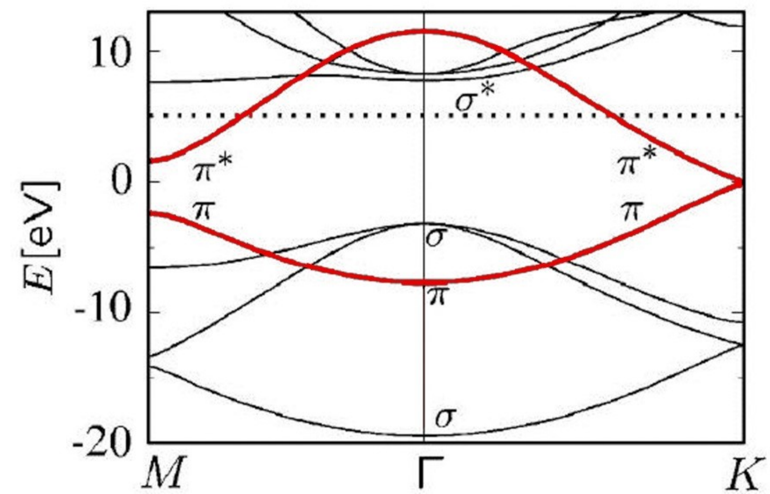
Xia et al. *Nano Lett.* **10**, 715–718 (2010)

Graphane

- Heat graphene in hydrogen -> graphane
- sp^2 -> sp^3 -> remove conducting π-bonds and opening an energy gap
- Lose the linear band dispersion of graphene







Elias et al. *Science*, **323**, 610-613 (2009)

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Comparing CNT and graphene FETs

Graphene FETs	Carbon nanotubes FETs
No band gap gives poor on/off ratio, not for logic, maybe RF	Sufficient band gap for logic
Difficult to control edges which gives mobility degradation	No dangling bonds
Large area production possible	Need parallel CNTs to obtain high on-current and g_m
Only one type of device	No control of metallic / semiconducting type

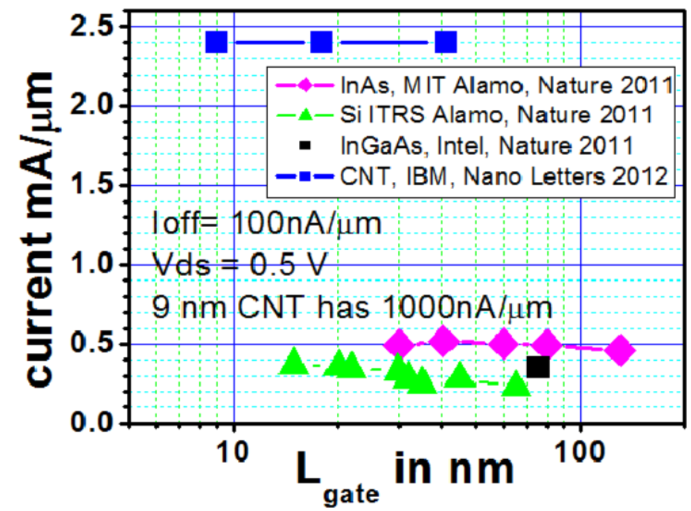
NanoElectronics Roadmap for Europe

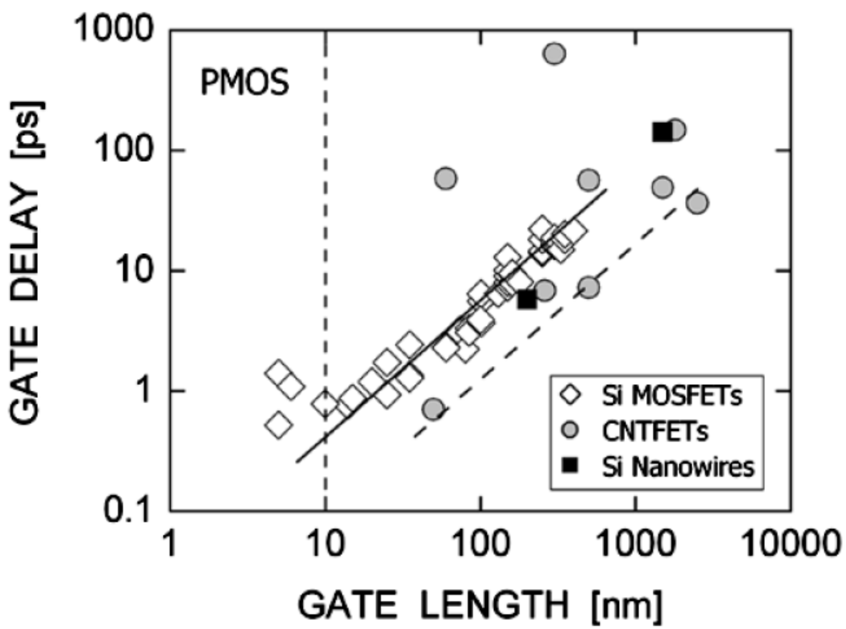
Recommendations for Carbon Nanotubes

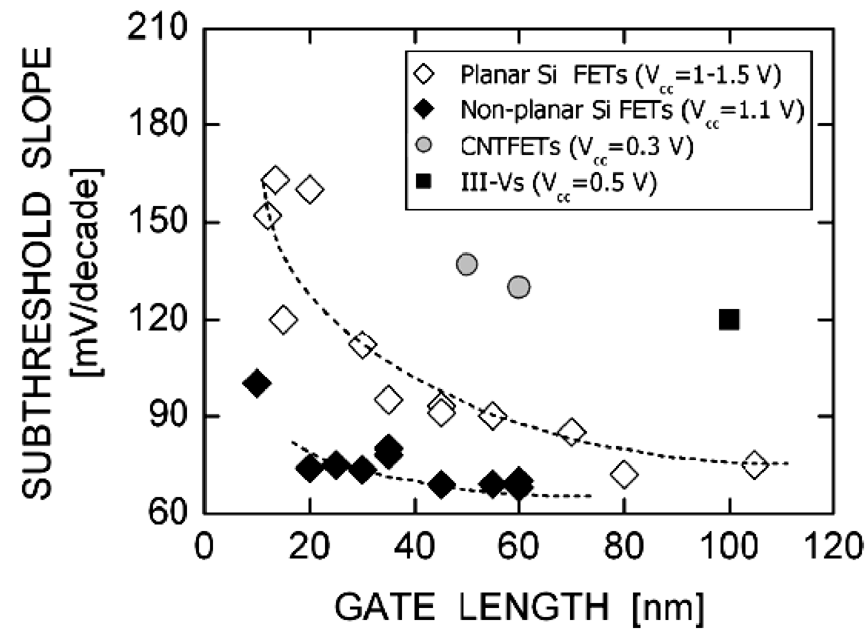
- Develop solutions to at source/drain
- Develop solutions to
  Develop faster growing process
-
  induced by m-CNTs and doping fluctuation
- Develop compact models and design tools and evaluate the power-performance on real design contexts taking into account the physics of the device (quantum capacitance) and its parasitics.

Benchmarking

- DC measurements: gate delay, energy delay product, subthreshold slope
- Large spread in results for CNTs
- Gate delay (CV/I) may be quite incorrect

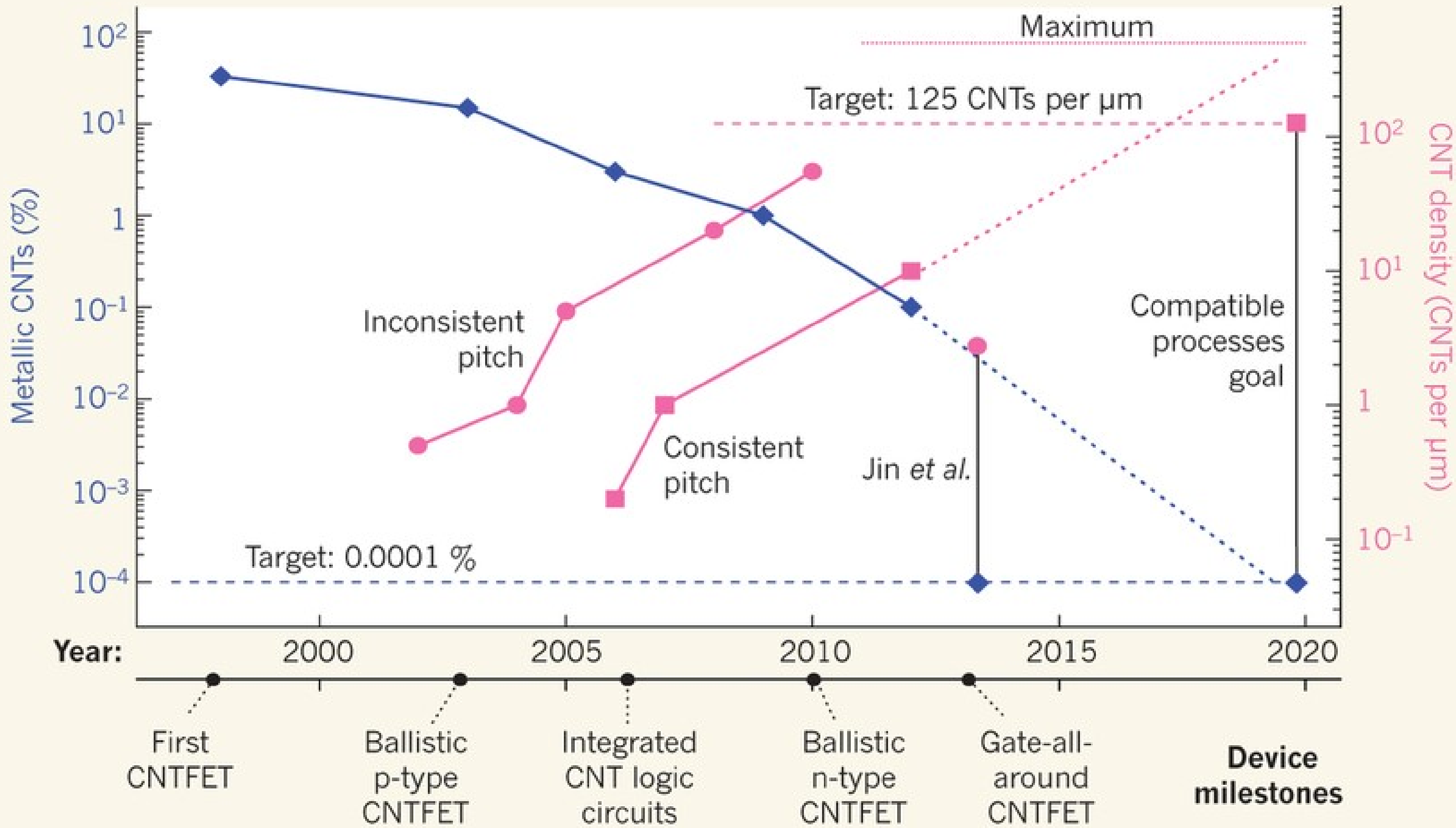






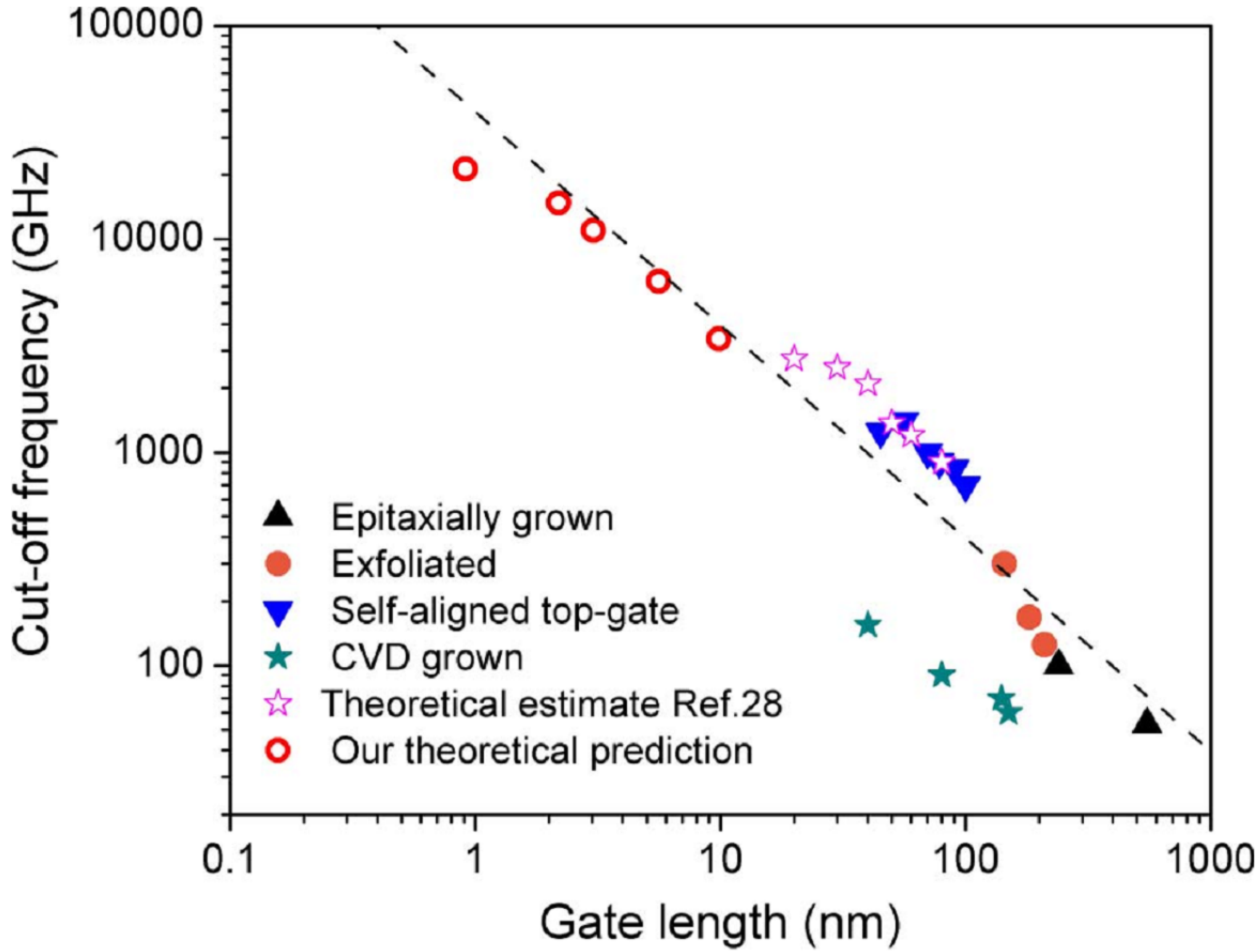
Chau et al. *IEEE Trans. Nanotechnol.* **4** (2005)

CNT density and purity



Franklin, *Nature* **498**, 443 (2013)

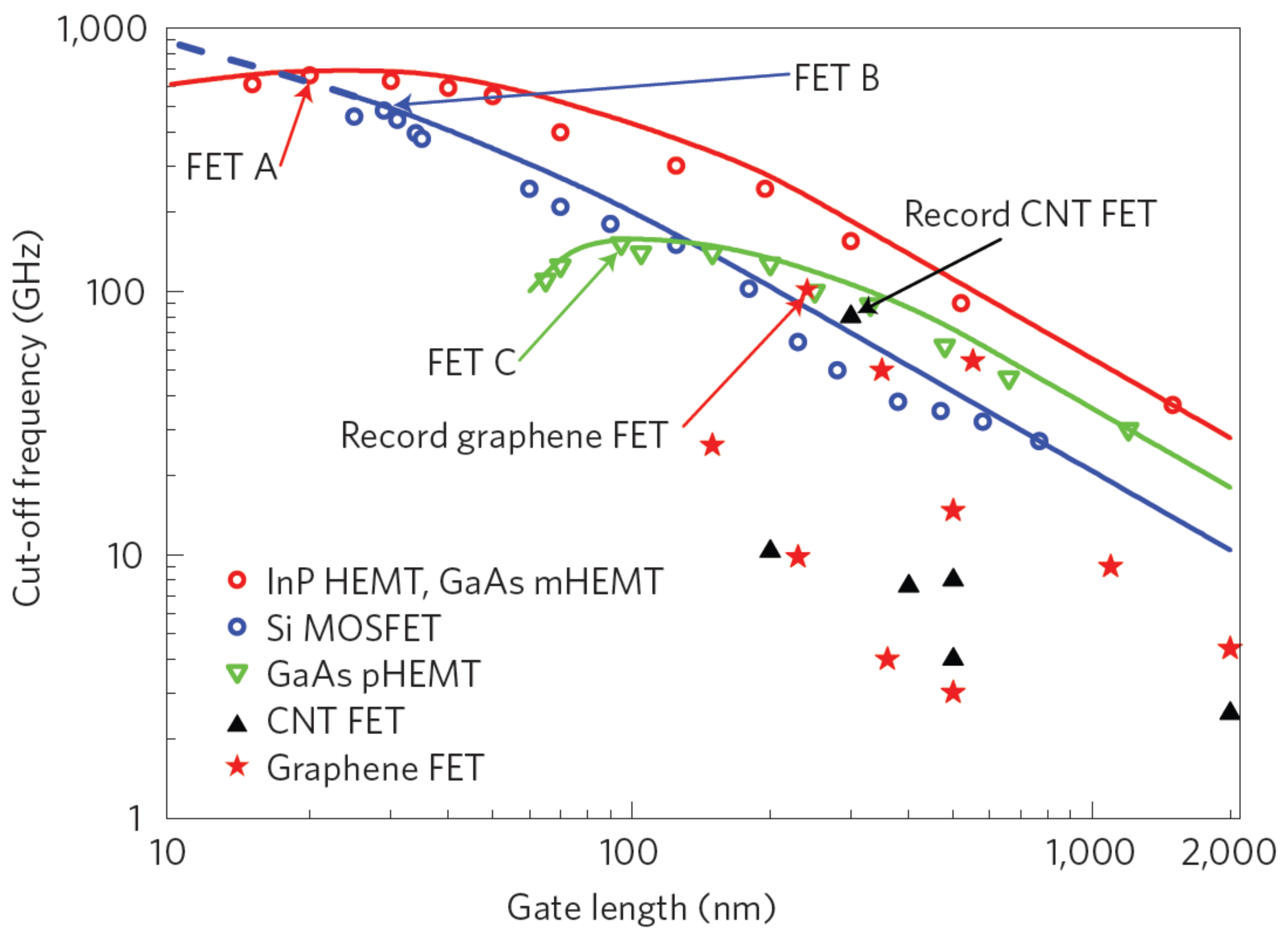
Graphene gate length scaling



Zheng et al. *Scientific Reports* **3**, 1314 (2013)

Comparing high frequency performance

- III-V materials are still better
- Need to reduce L_g of CNT/graphene FET
- Need good saturation (low g_d) to get high f_{max}



Why carbon electronics?

+ High mobility (long mfp, no surface roughness scattering, high carrier velocity)

+ High current density

+ Good electrostatics

+ Compatible with high-k dielectrics

+ Same electron/hole band structure

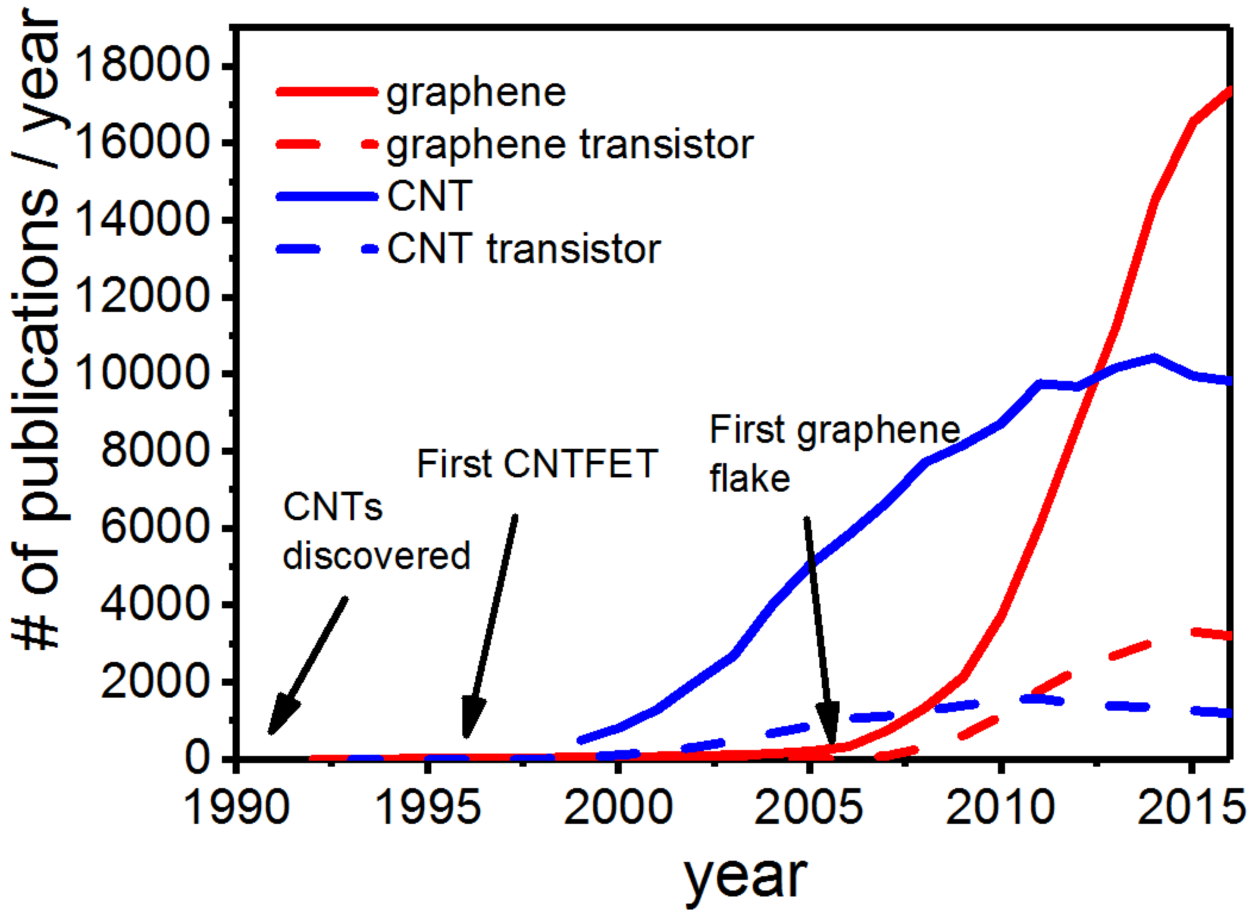
+ ”cheap” starting materials

Why not?

- Uncontrolled band gap
- Poor position control
- Unstable doping
- Difficult to mass produce

Research Activity

- Rapidly increasing # of publications
- Graphene > CNTs in 2011



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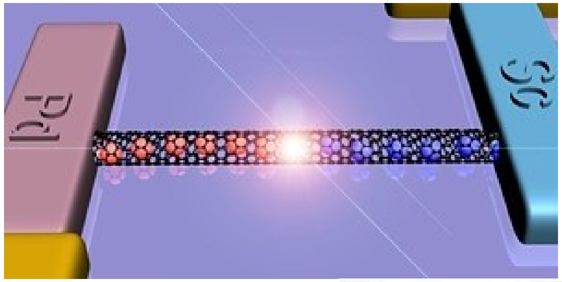
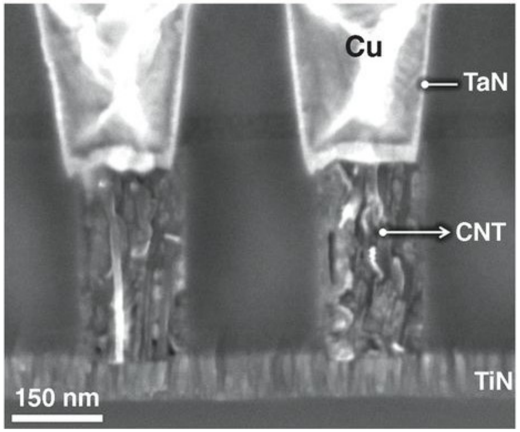
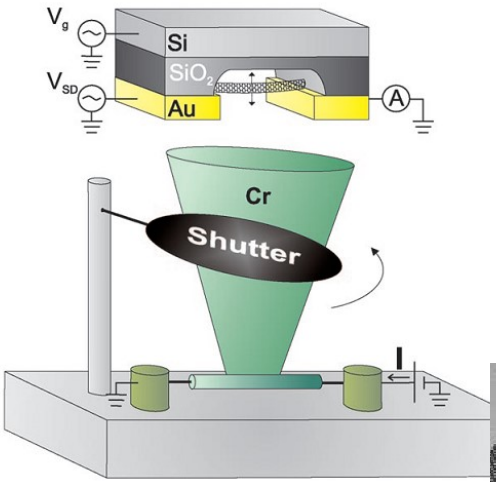
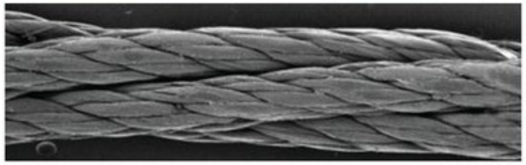
Other applications

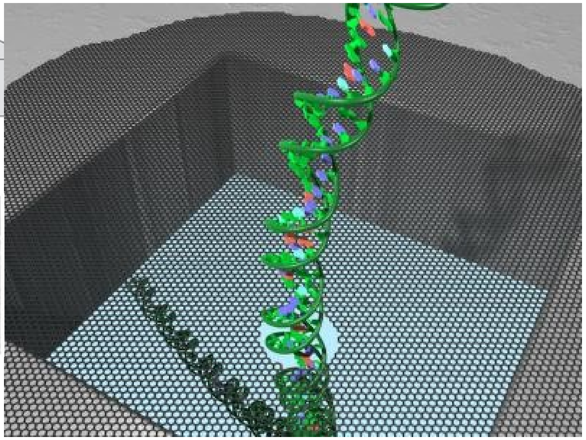
- supercapacitor electrodes
- memories
- LEDs
- photodiodes
- solar cells
- interconnects
- transparent electrodes
- NEMS for mass sensing
- DNA sequencing
- quantum computing
- spintronics
- Conductive materials











Space elevator