Graphene electronics

Johannes Svensson

Nanoelectronics FFF160

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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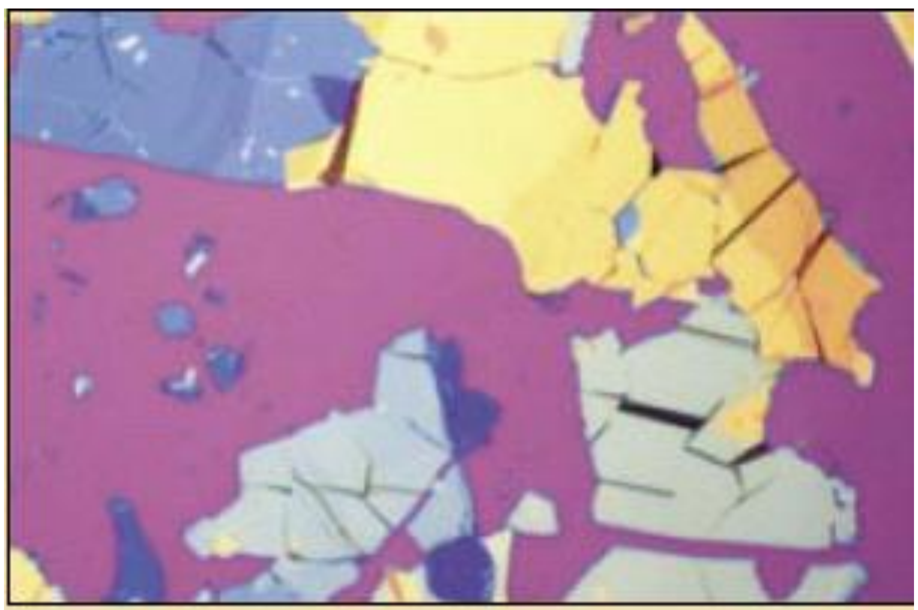
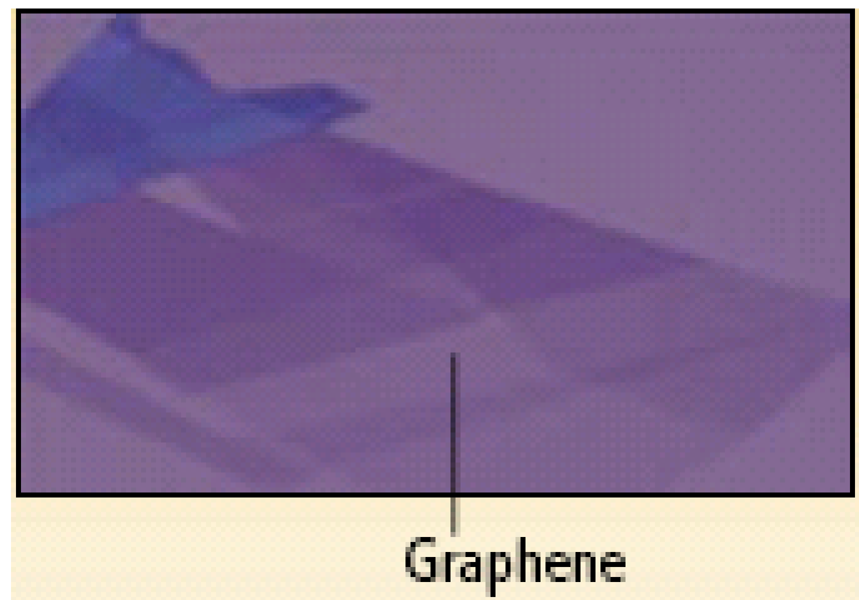
Mechanical exfoliation

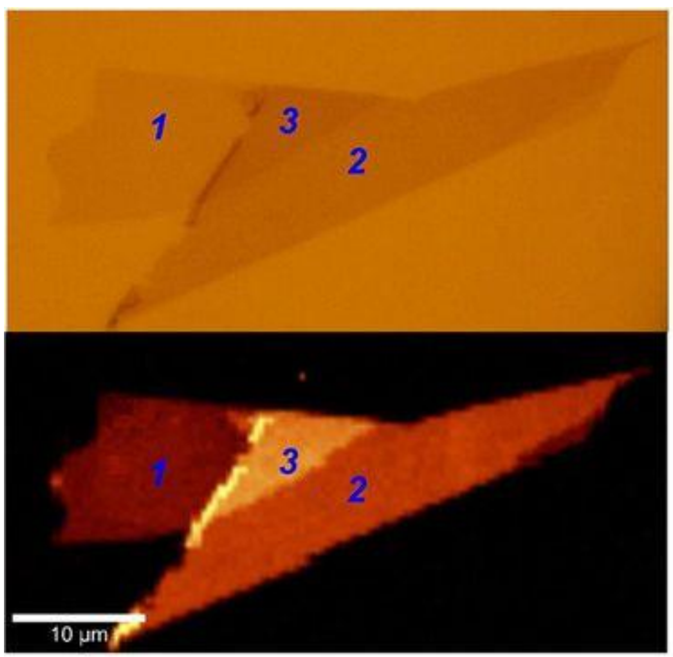
- Rub graphite on substrate
- Use adhesive tape to peel off layers
- 100x100 µm flakes -> mainly for research
- Visible in optical microscope

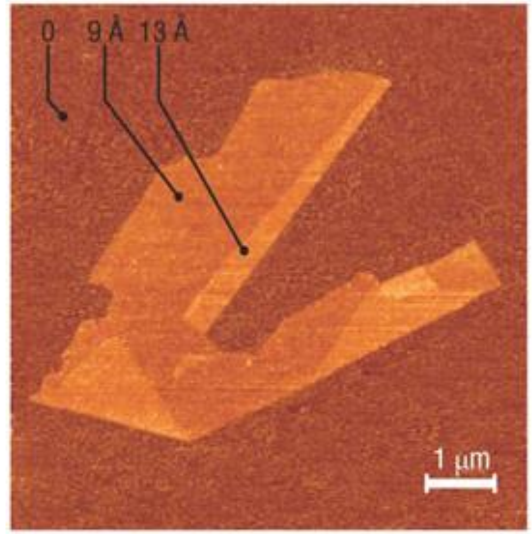


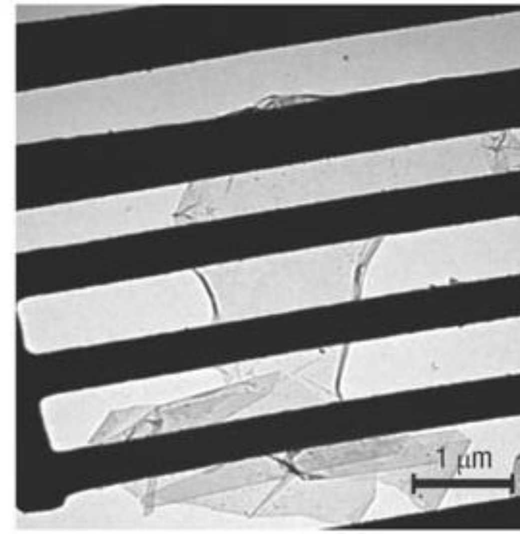


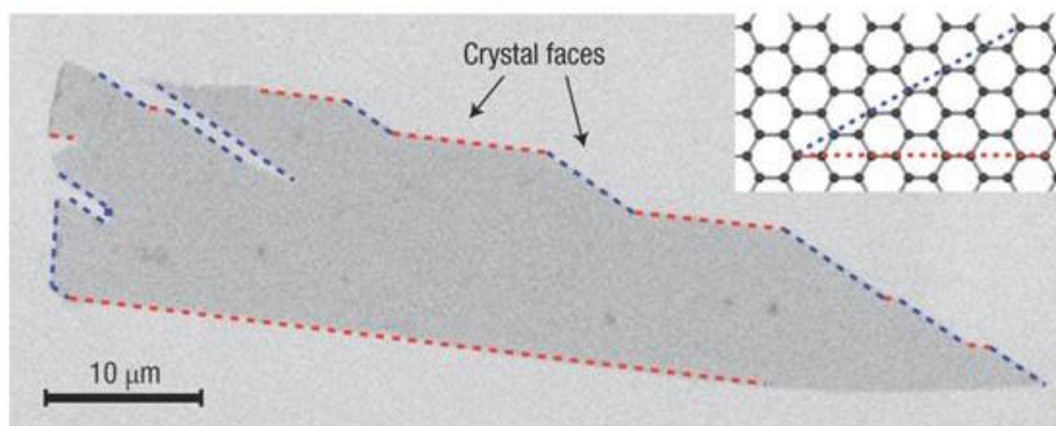
Observing graphene

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







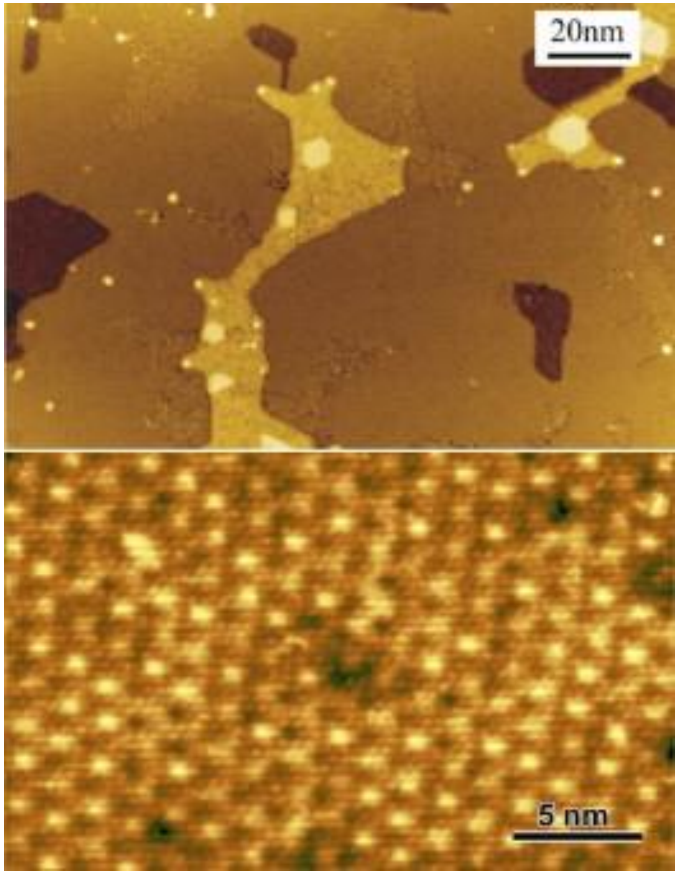


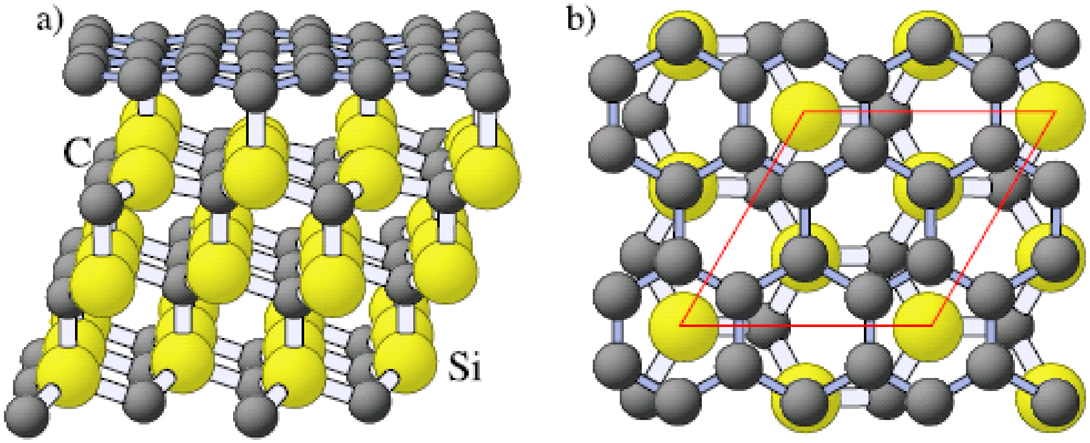
Epitaxial growth

- Prepare SiC surface by H_2 etching and heat to 1000°C by electron bombardment to remove native oxide

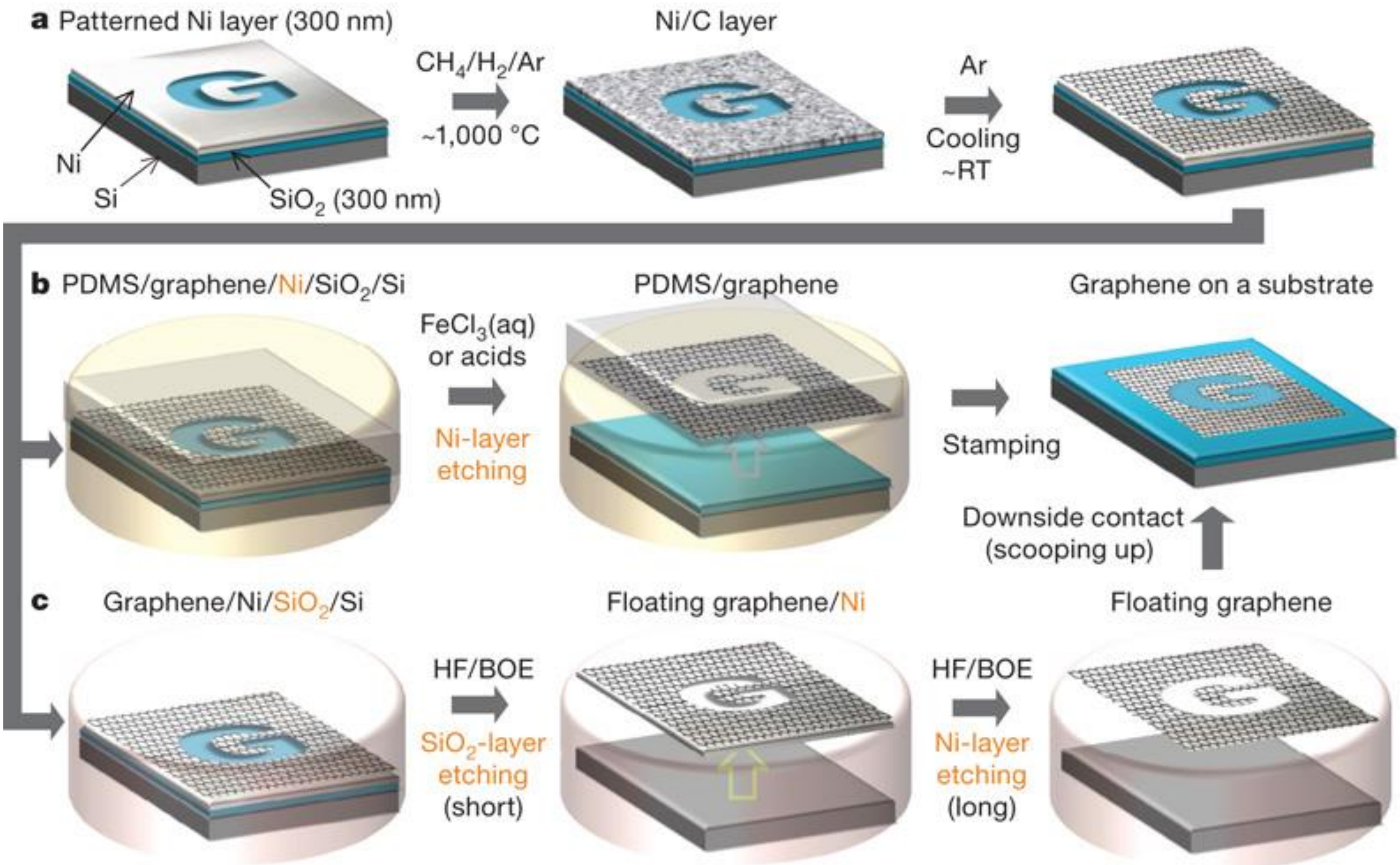
- Heat to 1250 °C to remove Si 1450 °C which will expose a graphene layer

- Often bi or trilayer graphene is formed





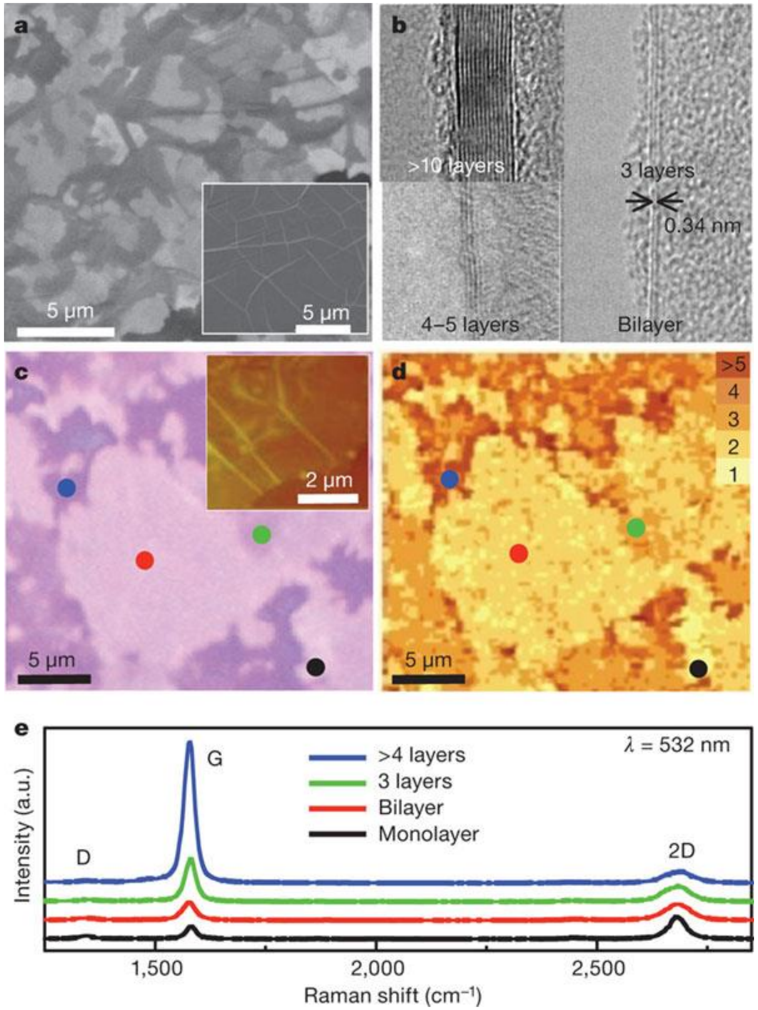
Chemical vapor deposition

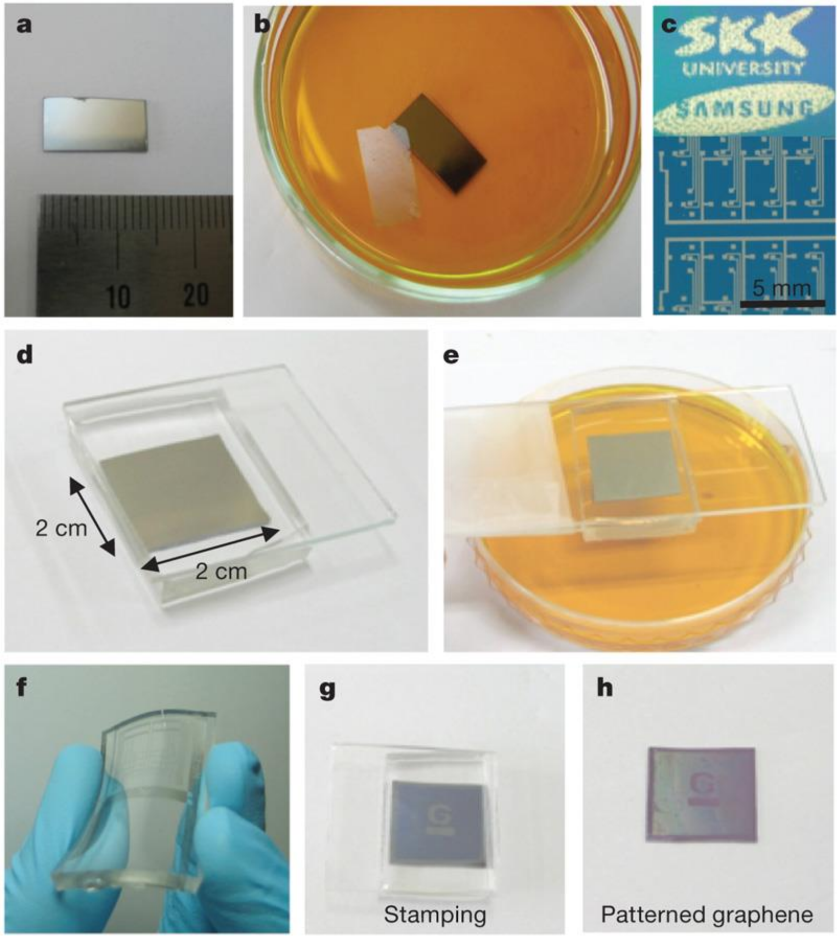


Kim et al. *Nature* **457**, 706-710 (2009)

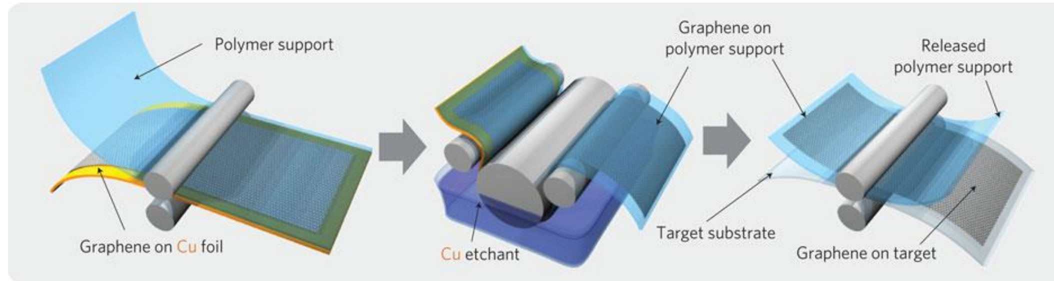
Chemical vapor deposition - result

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

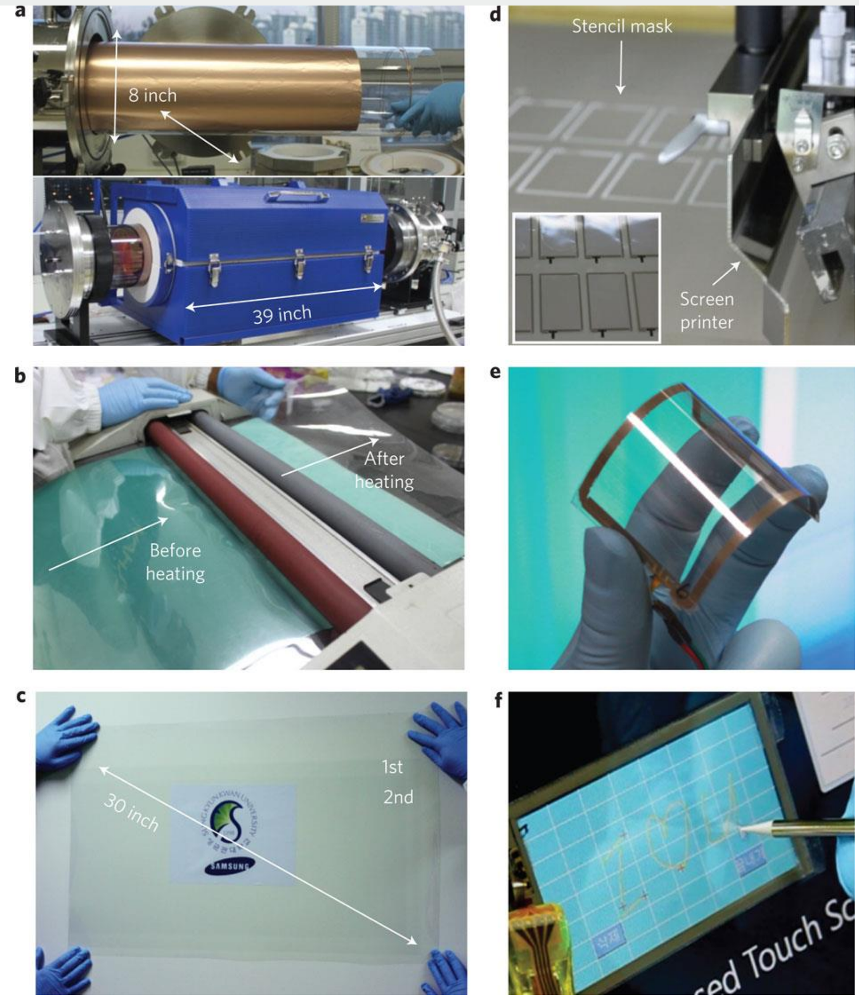




Large scale CVD production



- 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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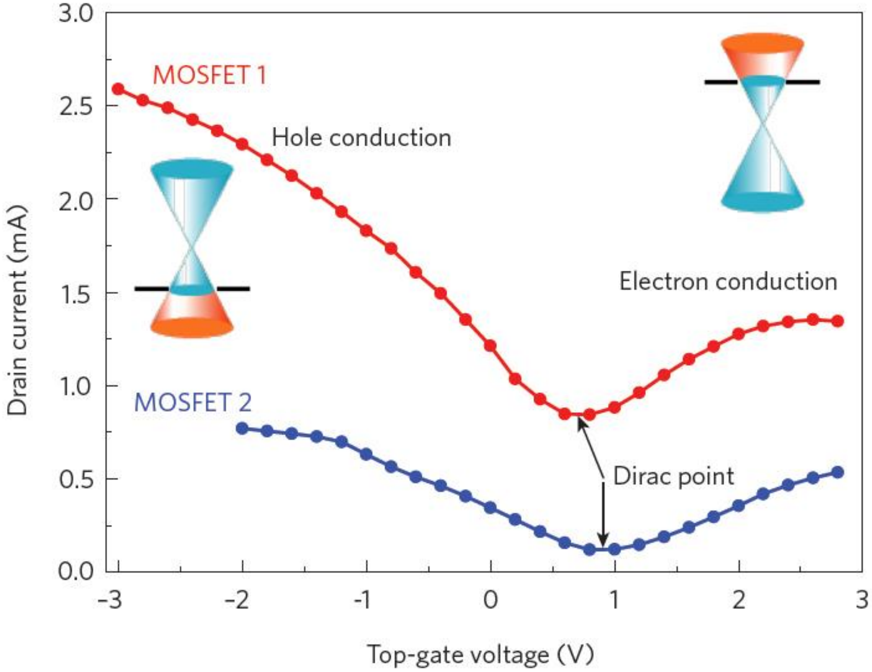
Graphene properties

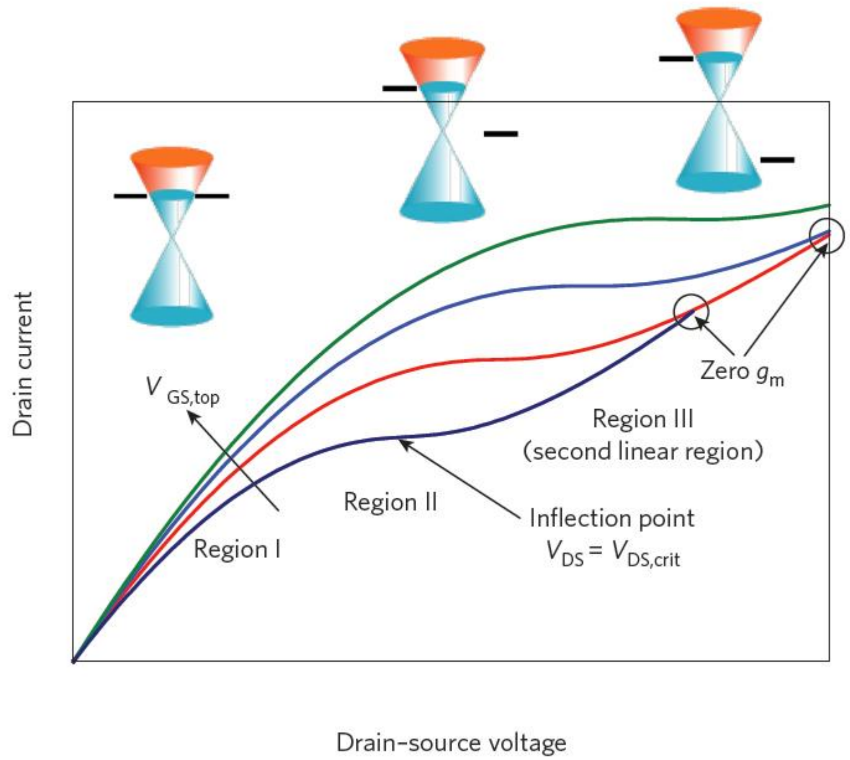
- Thinnest material
- Largest surface area (3000 m^2 / gram)
- Strongest
- Stiffest
- Most stretchable (20%)

- Highest thermal conductivity
- Highest current density (1000 x Cu)
- Highest mobility (100 x Si)
- Longest mean free path (~ µm)

Transistor characteristics

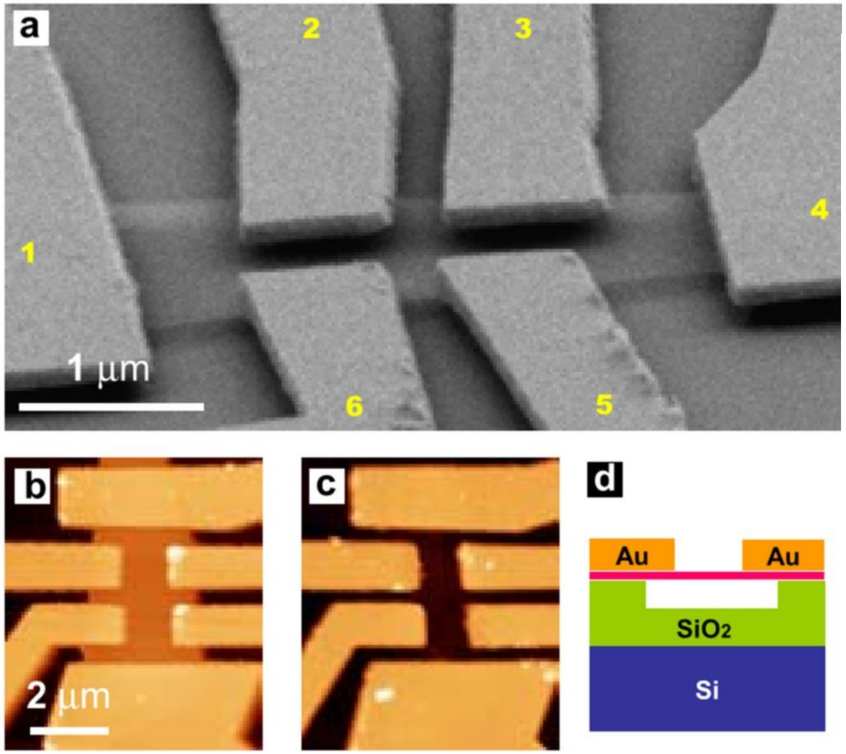
- No band gap -> poor on/off ratio
- Poor saturation
- Plateau at some gate voltages

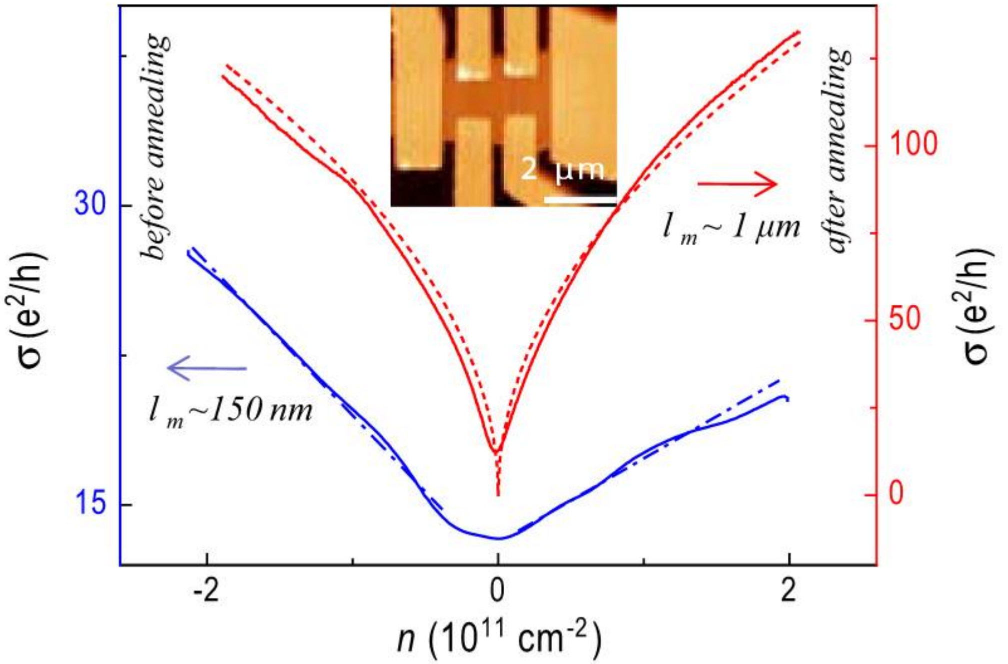




Highest mobility

- Exfoliated graphene
- No band gap –> poor on/off ratio
- Unsuspended flakes: μ_e=2 000 - 30 000 cm^2/Vs
- Supended and annealed flakes: μ_e=230 000 cm^2/Vs
- Scattering due to impurities and edges





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

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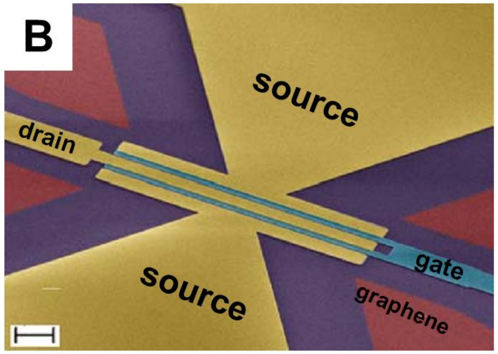
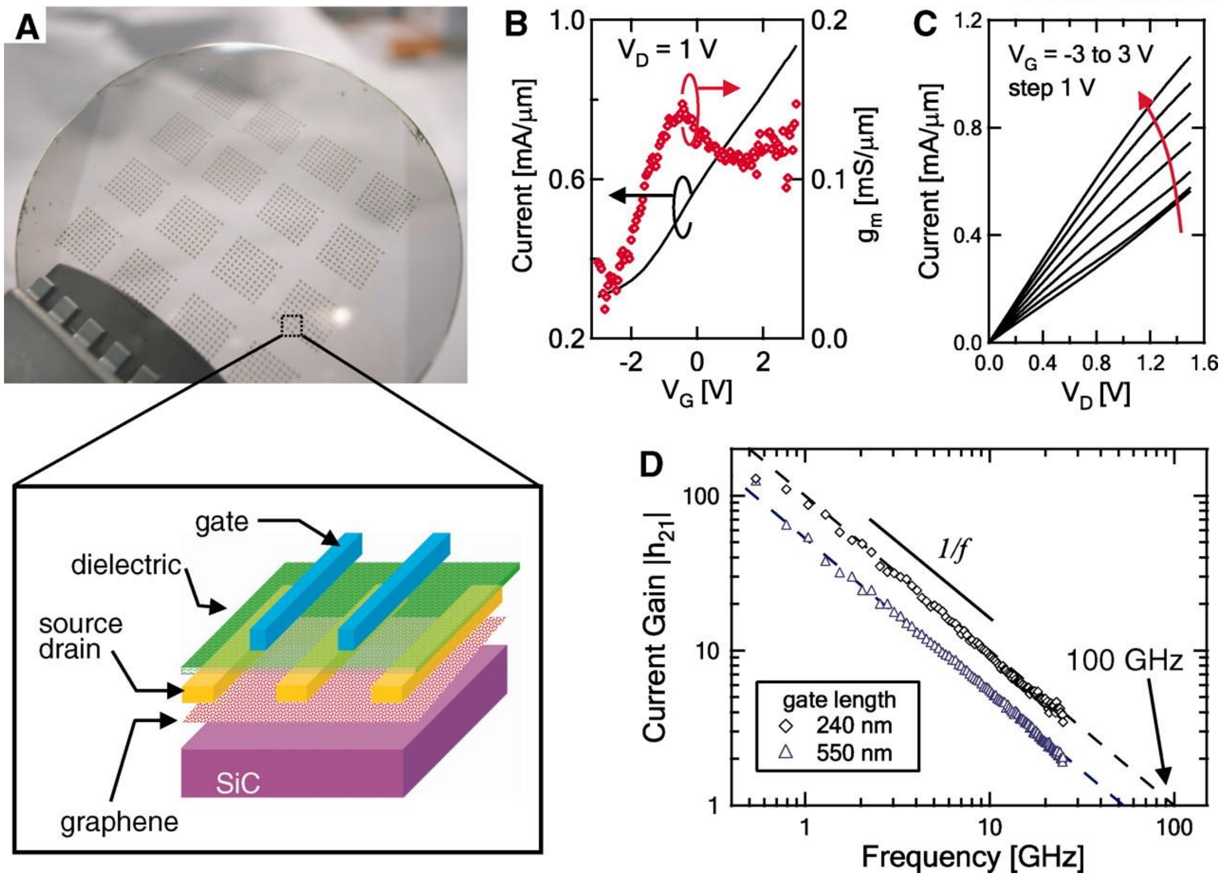
High frequency device

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

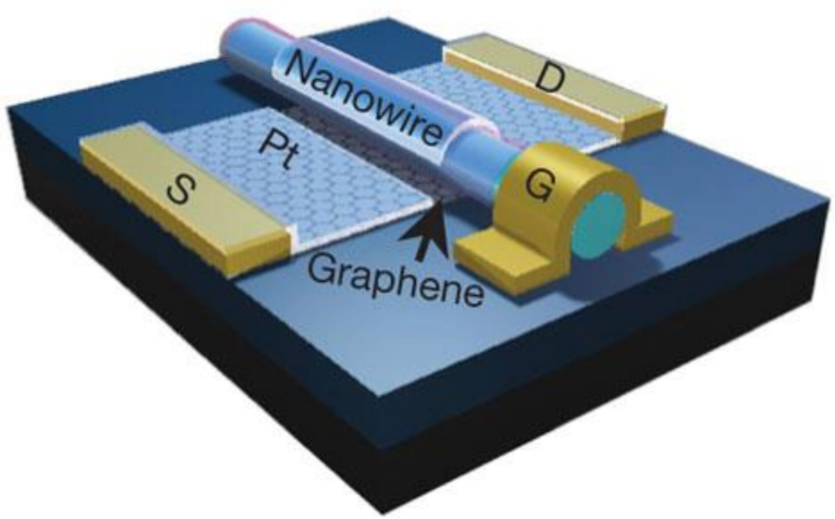


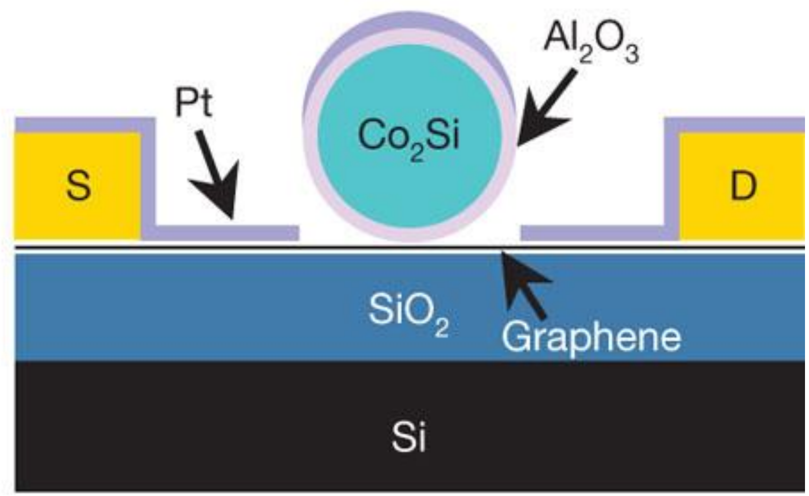


Lin et al. *Science*, **327** , 662 (2010)

Graphene - nanowire device

- Mobility degrades when depositing dielectric
- Gate underlap: high source/drain access resistance reduce g_m
- Gate overlap: increased paracitic capacitances
- Deposit silicide nanowires with Al_2O_3 shell on exfoliated graphene
- Evaporate self-aligned Pt source/drain contacts

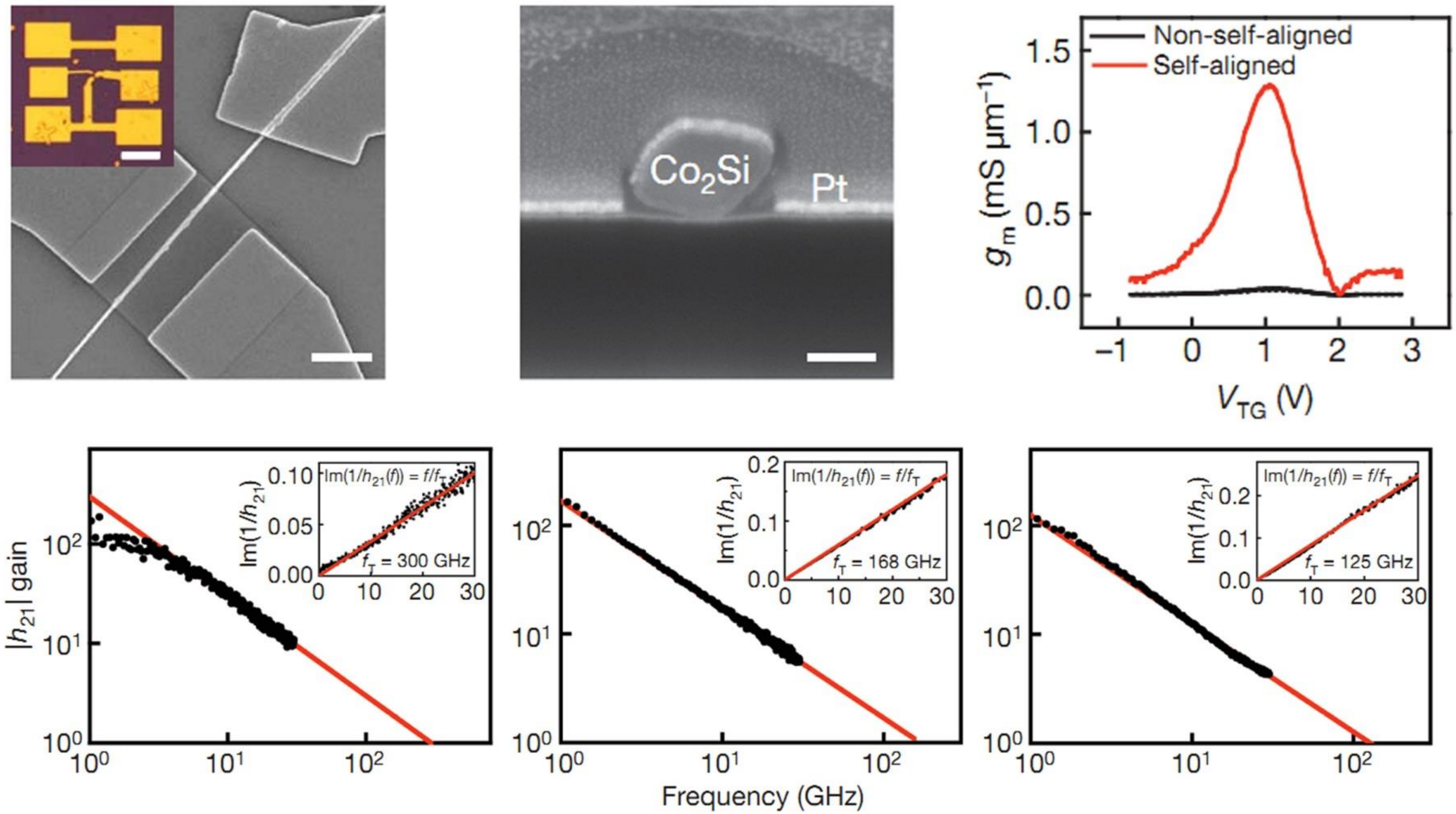




Liao et al. *Nature* , **467**, 305–308 (2010)

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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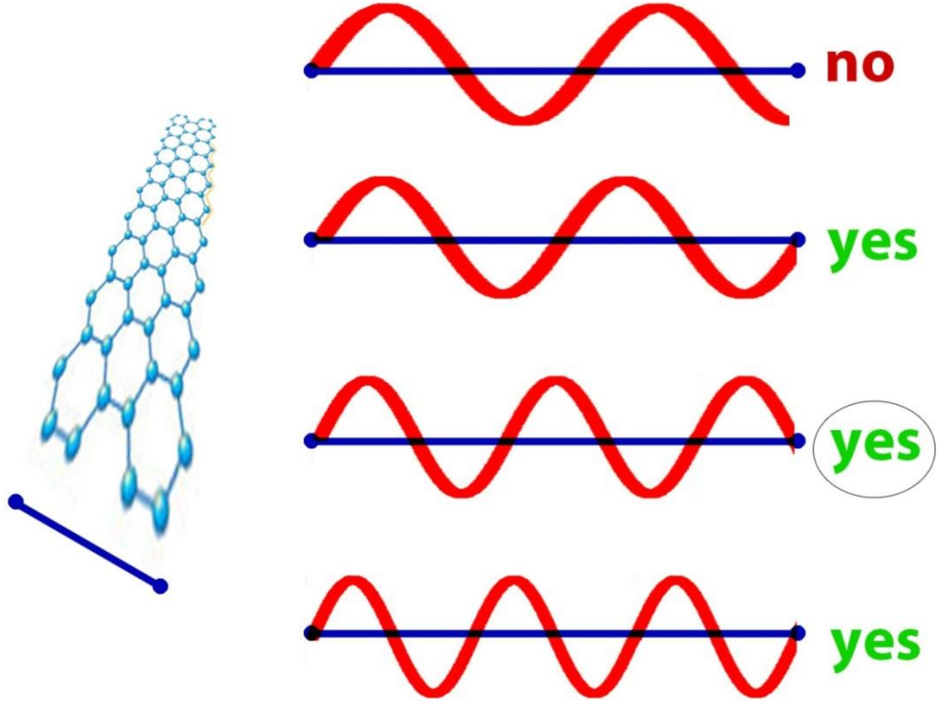
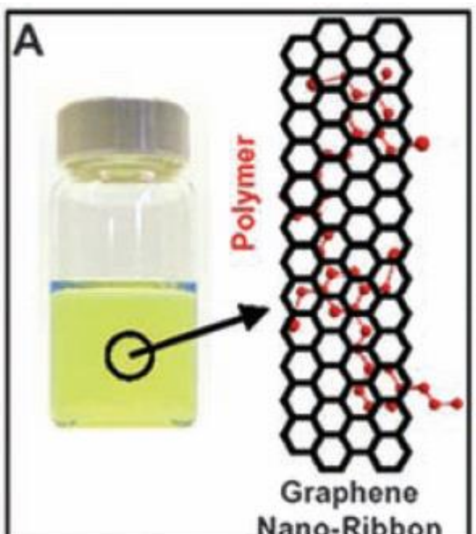
Confinement of electron wavefunctions

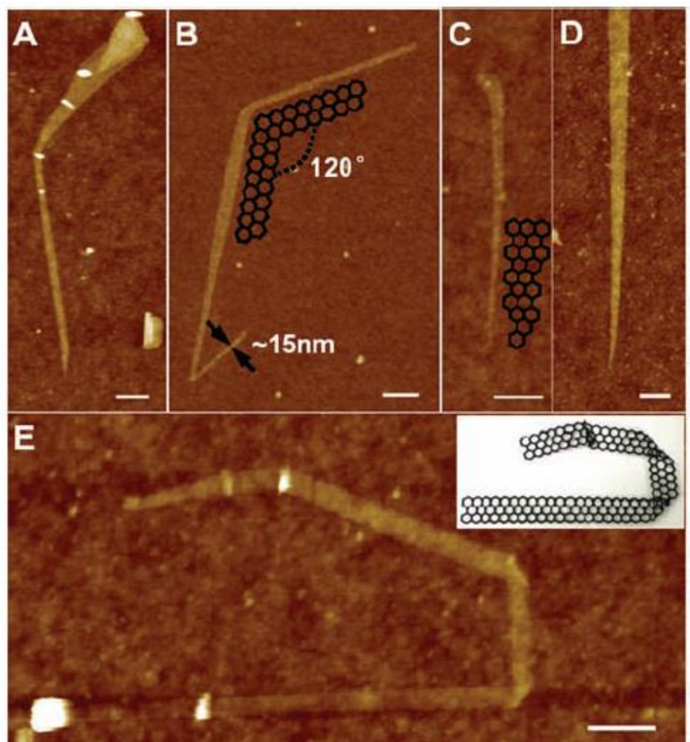
- Make narrow ribbon to introduce band gap
- Fixed boundary conditions instead of periodic (CNT)
- Wavevectors $k_{\perp} = n\pi/C$ with n=1,2,3... allowed
- Need width = CNT circumference / 2 to get same band gap

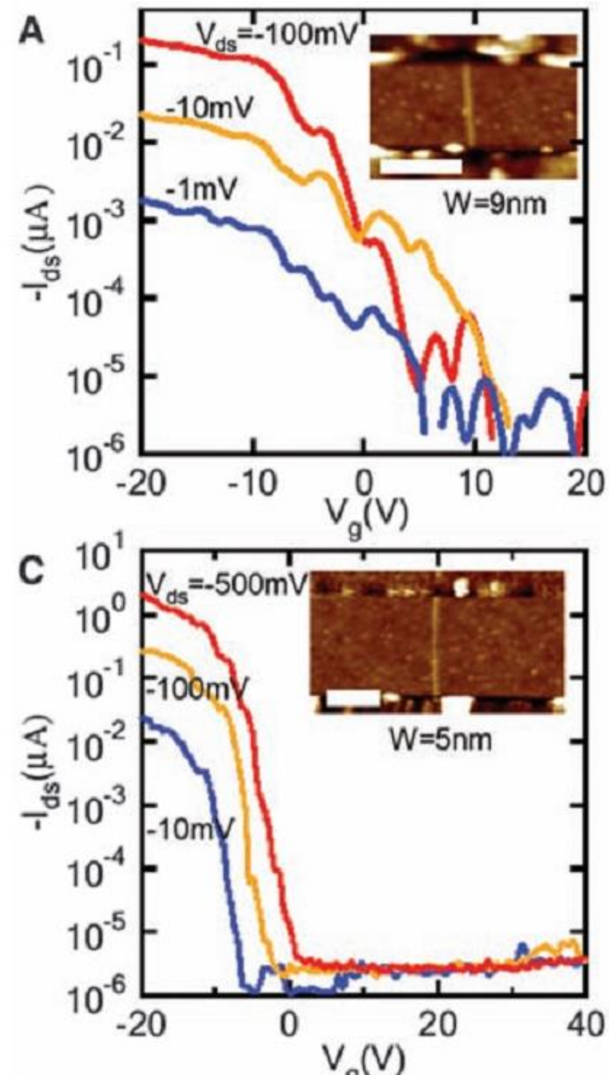


Chemical exfoliation

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



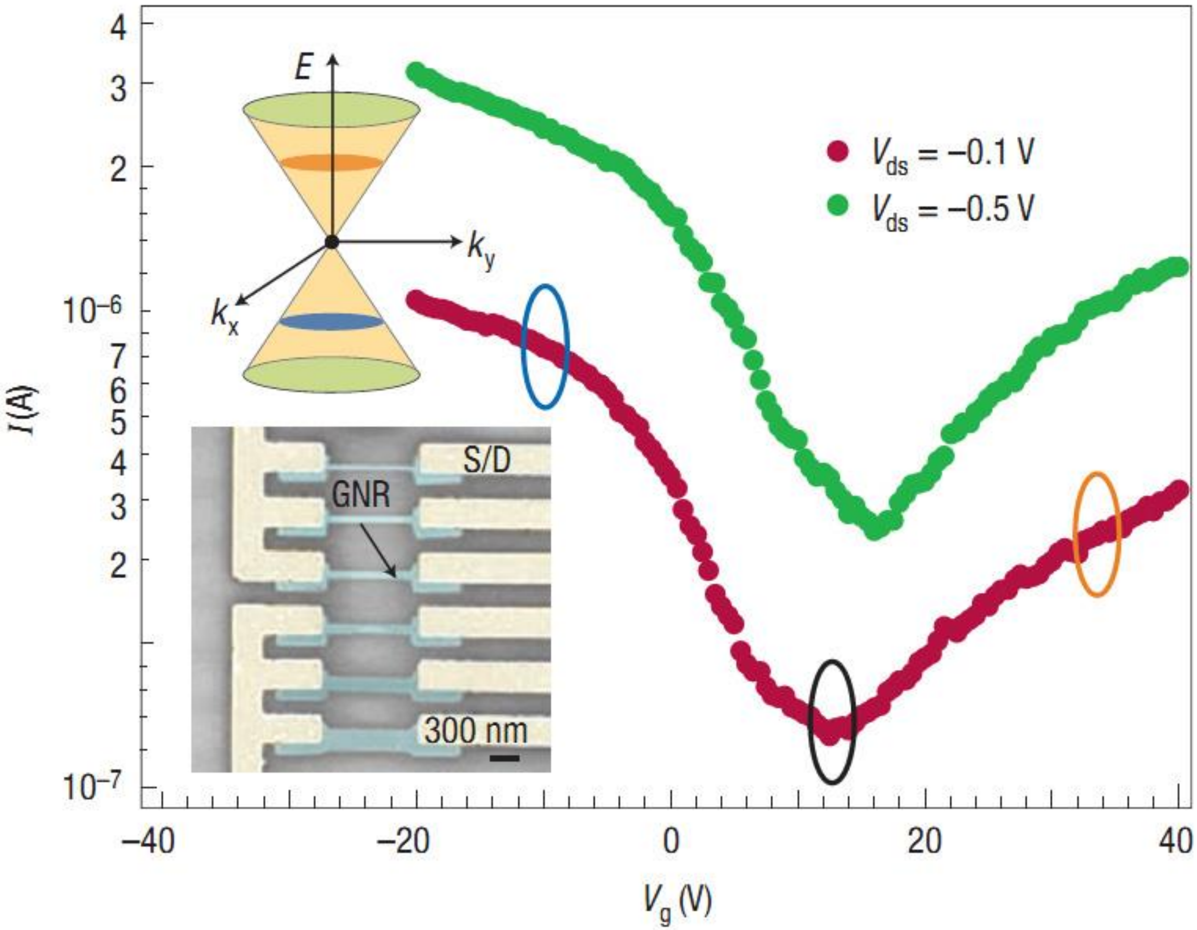




Li et al. *Science,* **319 (**2008)

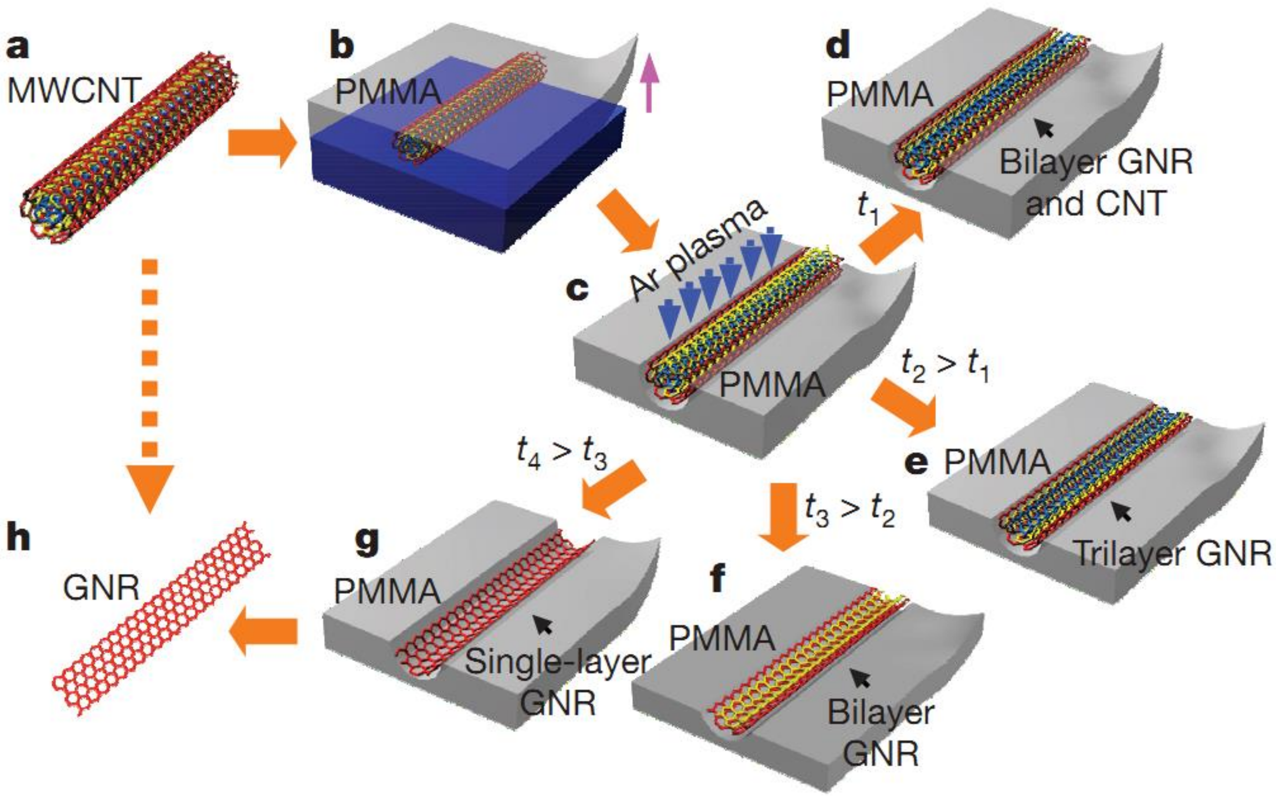
Etching

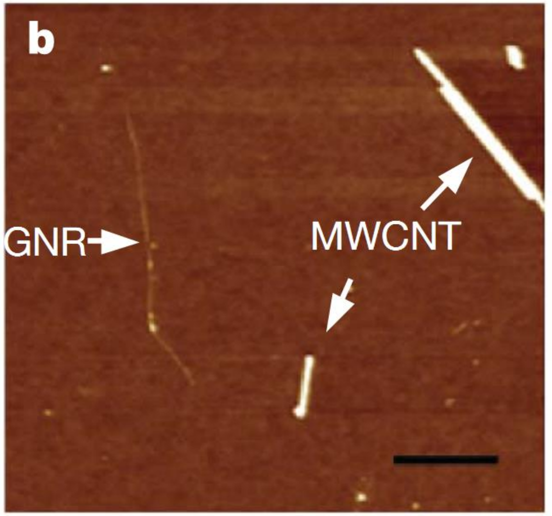
- Use e-beam lithography and oxygen plasma etching to etch flakes
- Not narrow enough
- Diffcult to control edges



Unzipping a CNT

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

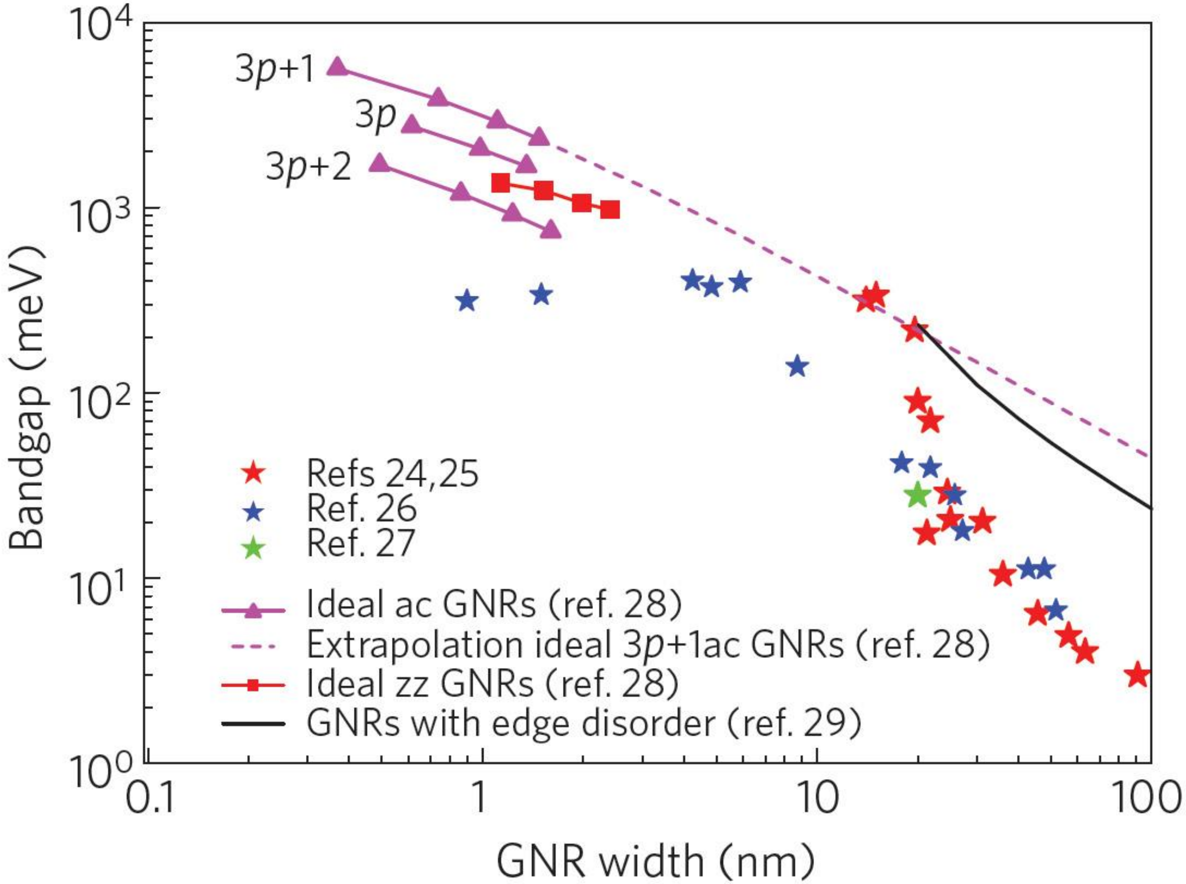




Jiao et al. *Nature*, **458**, 877-880 (2009)

Band gap vs GNR width

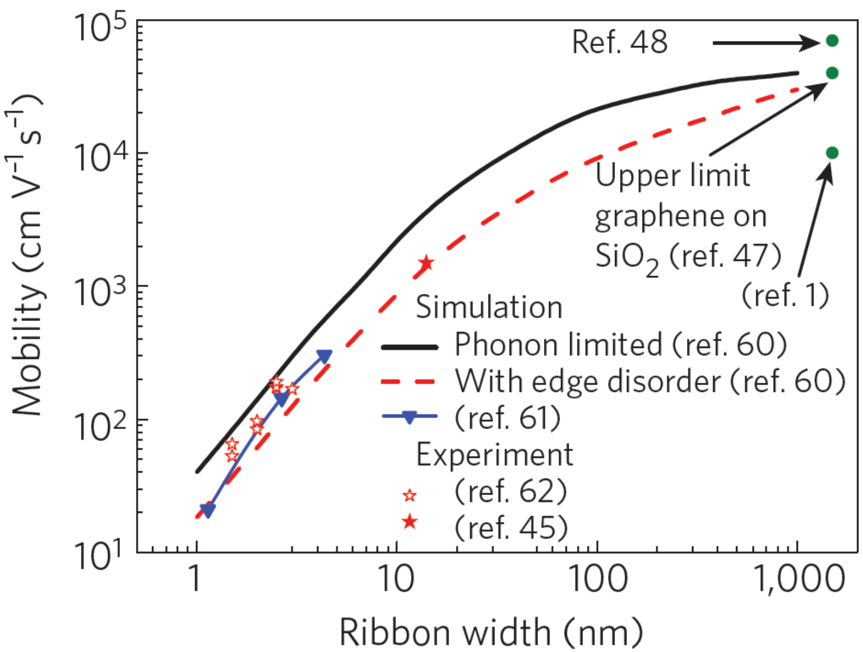
- Need 1 nm wide ribbons to get E_g=1 eV
- Gap depends on edge structure

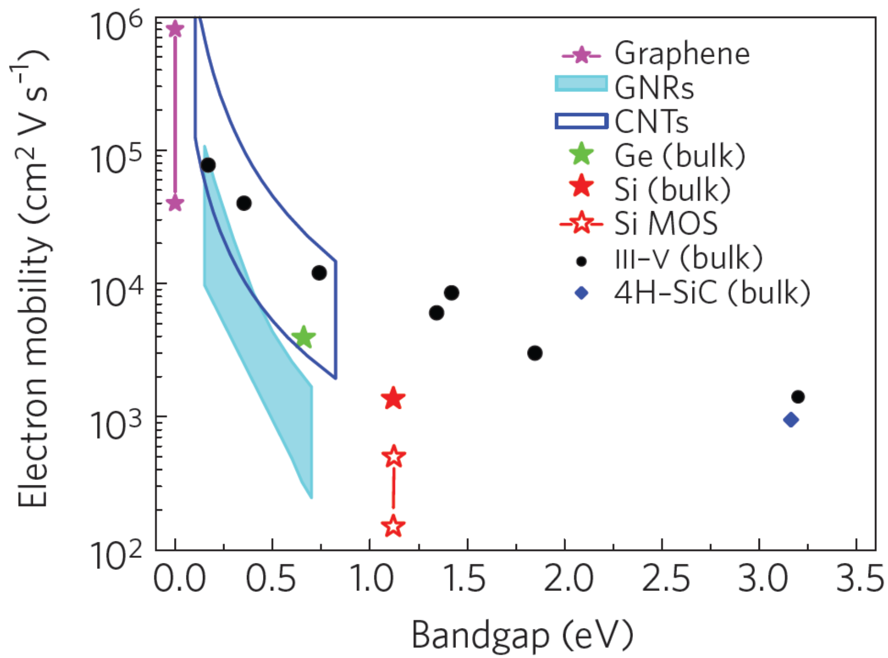


Schwierz, *Nature Nanotech.* **5**, 487 (2010)

Mobility degradation

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

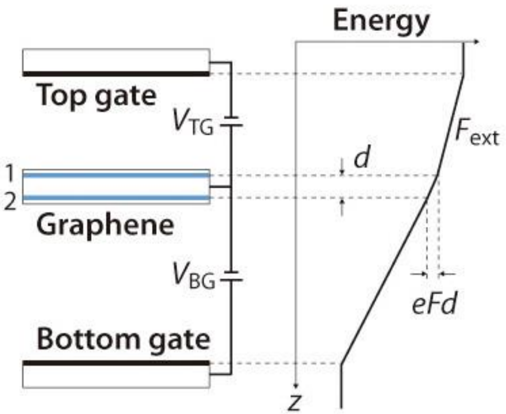


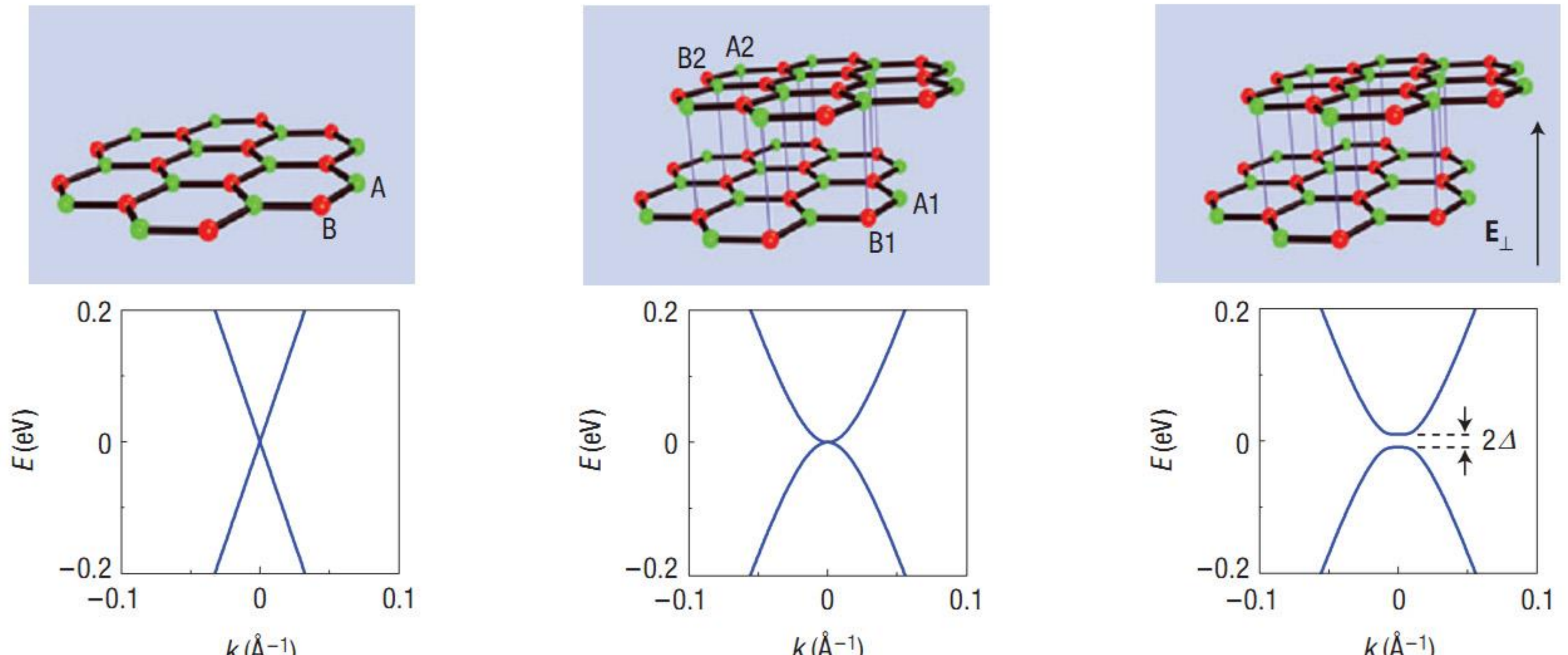


Bilayer graphene

- A perpendicular electric field breaks symmetry in bilayer graphene. Different energy for atoms in the two layers

- Band gap proportional to field opens

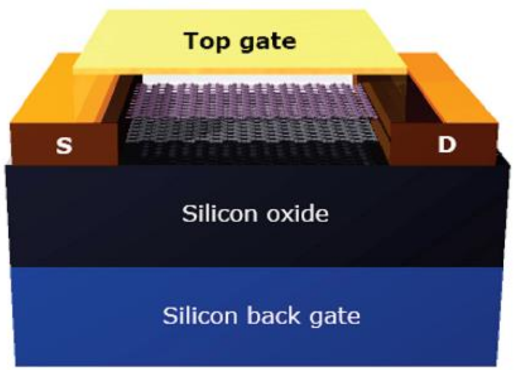


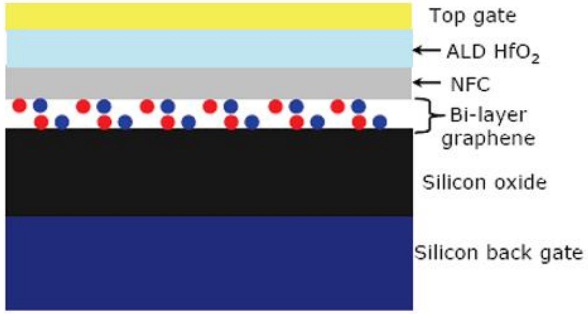


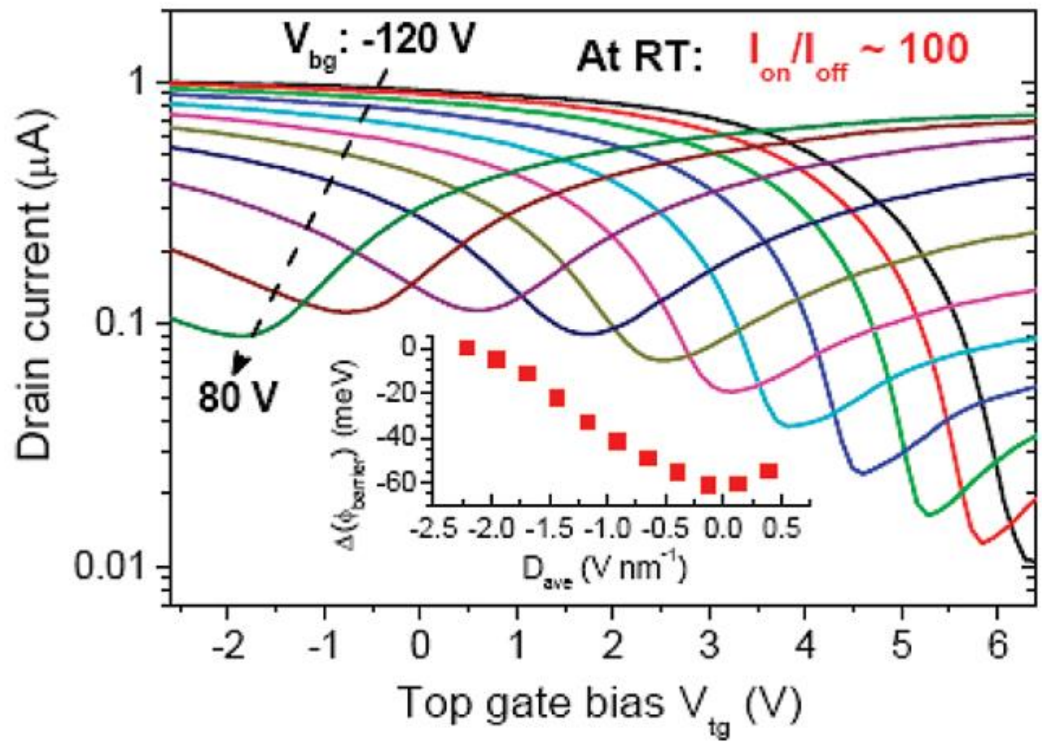
Oostinga et al. *Nature Mat.* **7**, 151 - 157 (2007)

Double gated bilayer device

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



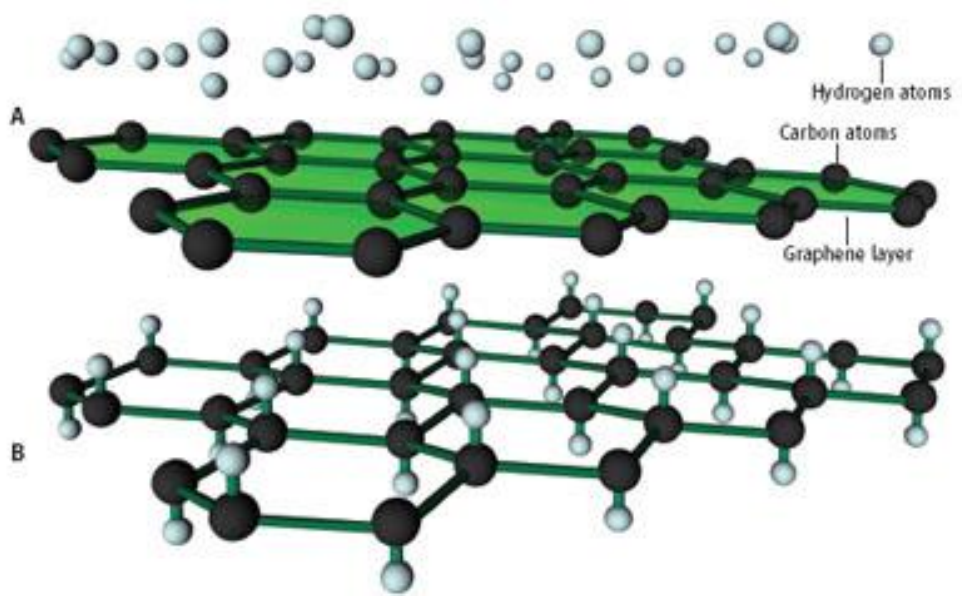


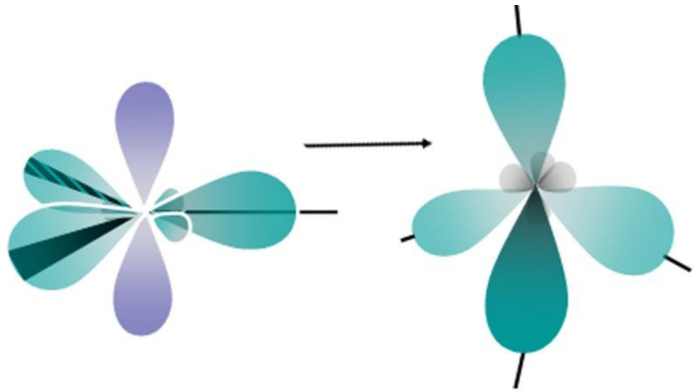


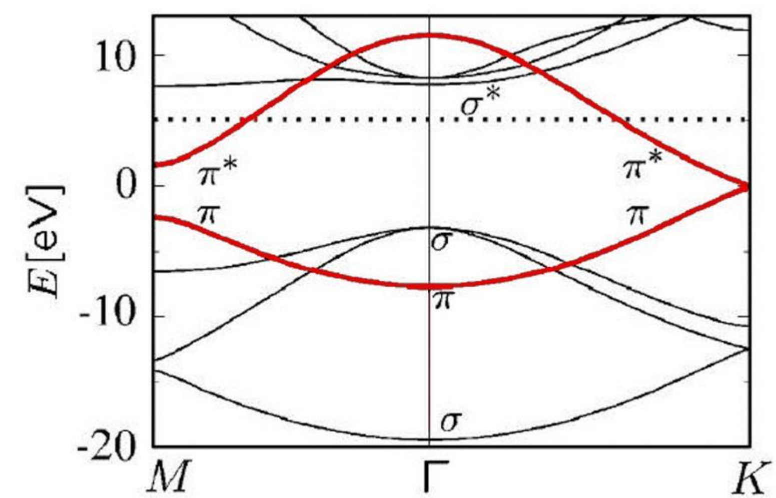
Xia et al. *Nano Lett.* **10**, 715–718 (2010)

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

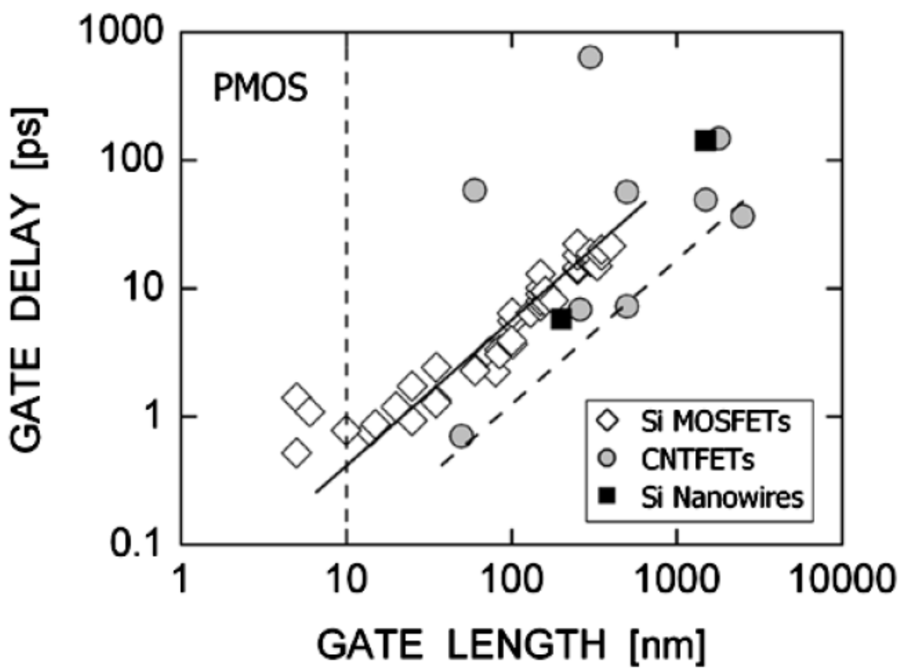
Graphene FETs	Carbon nanotubes FETs
No band gap gives poor on/off ratio, not for logic only RF	Sufficient band gap for logic
Difficult to control edges which gives mobility degradation	No dangling bonds
Large area production possible	Need parallel CNTs to obtain high on-current and g_m
Only one type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

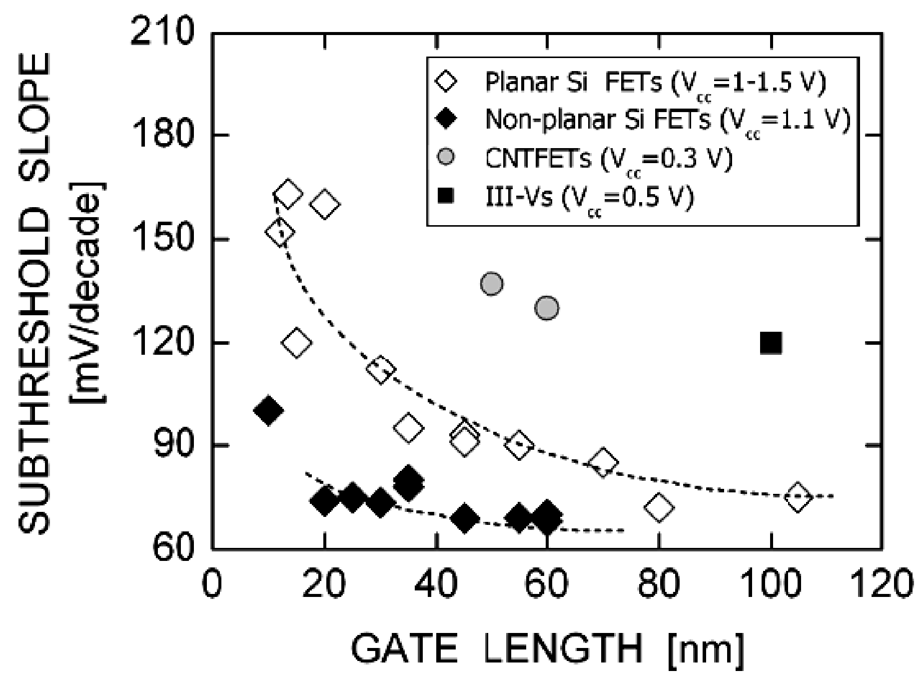
The future according to ITRS

- The International Technology Roadmap for Semiconductors plans future development
- Mainly digital logic
- Keeps track of new devices and materials

Benchmark comparisons

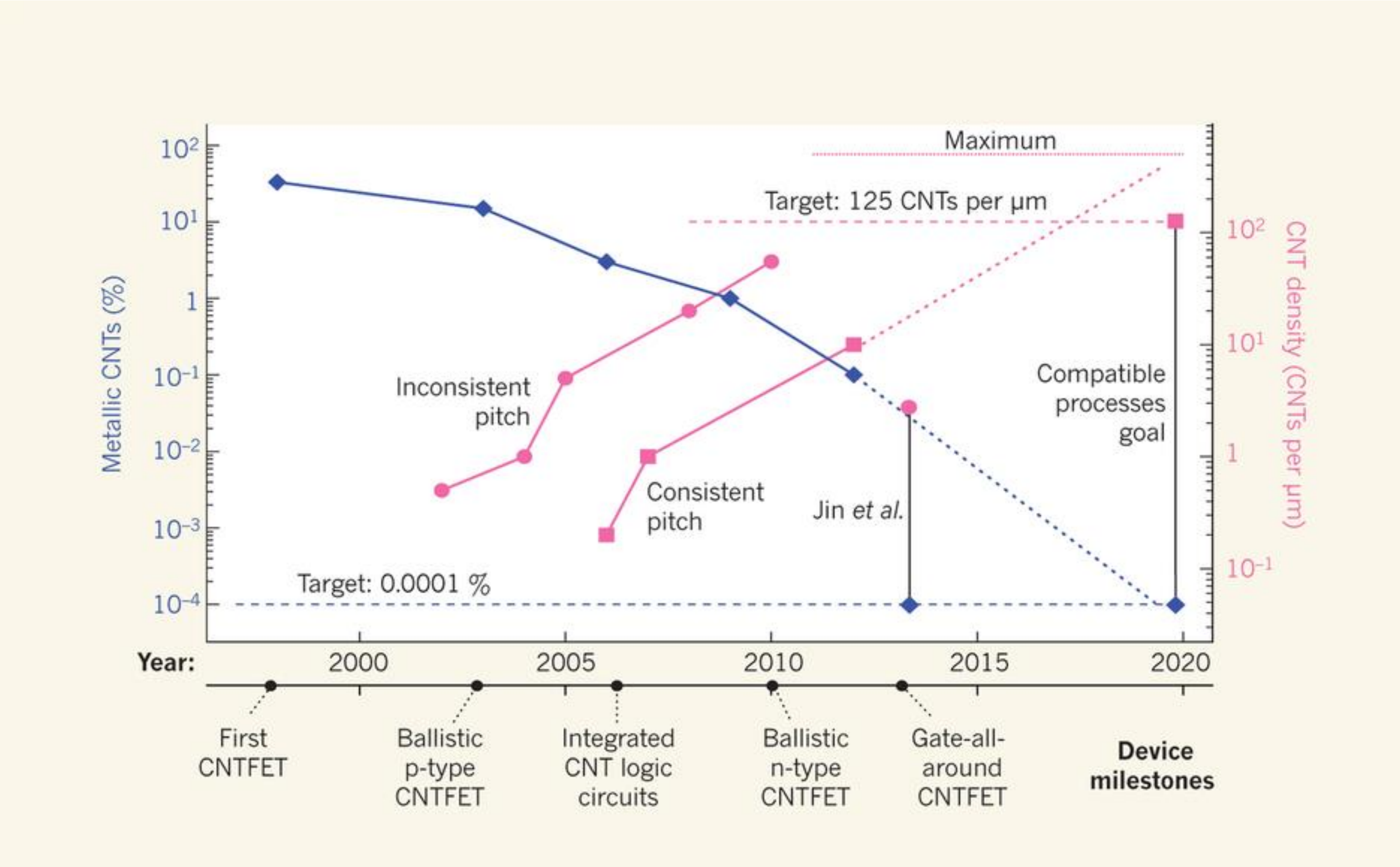
- From DC measurements: gate delay, energy delay product, subthreshold slope
- Large spread in results for CNTs
- Gate delay (CV/I) may be quite incorrect





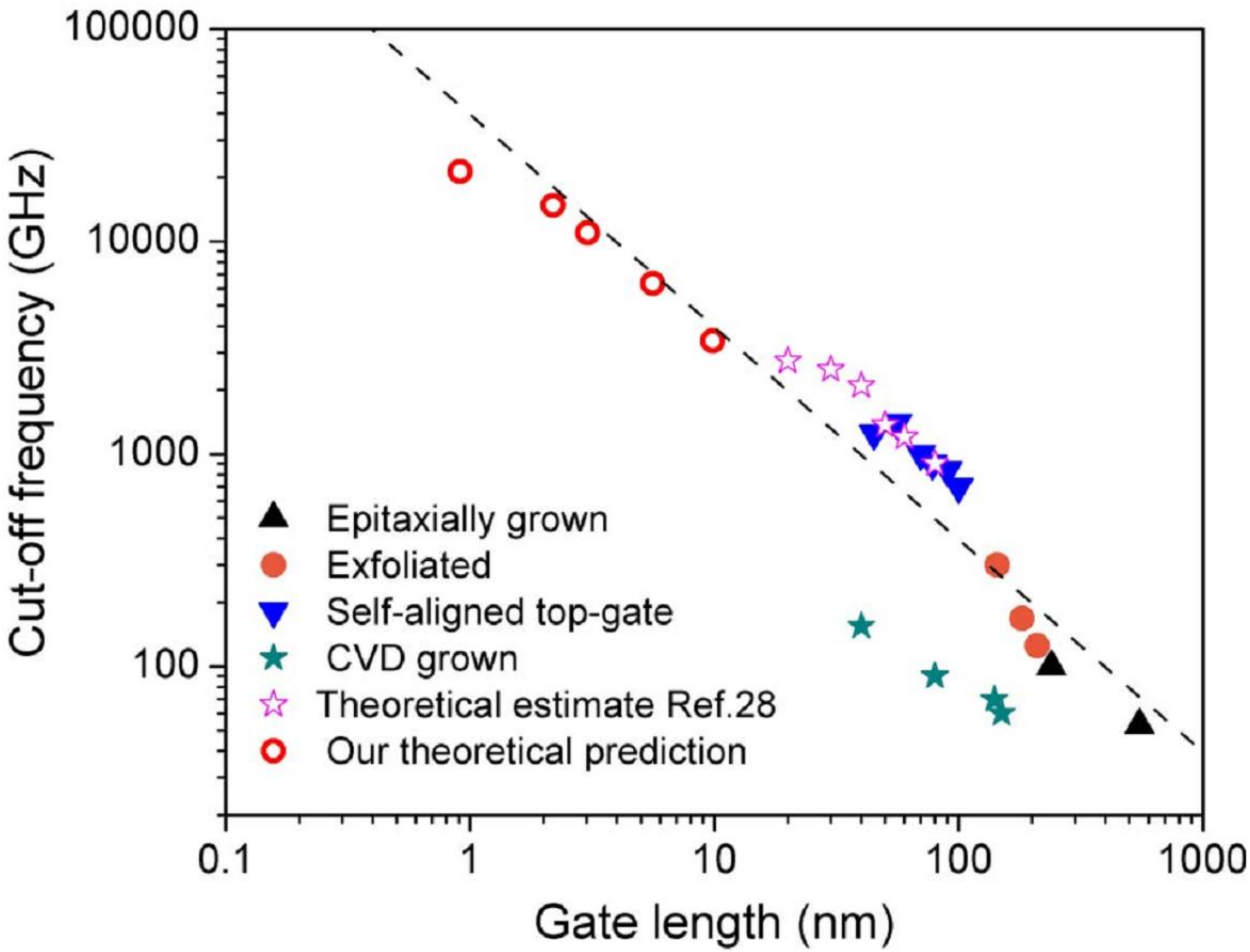
Chau et al. *IEEE Trans. Nanotechnol*. **4** (2005)

CNT density and purity



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

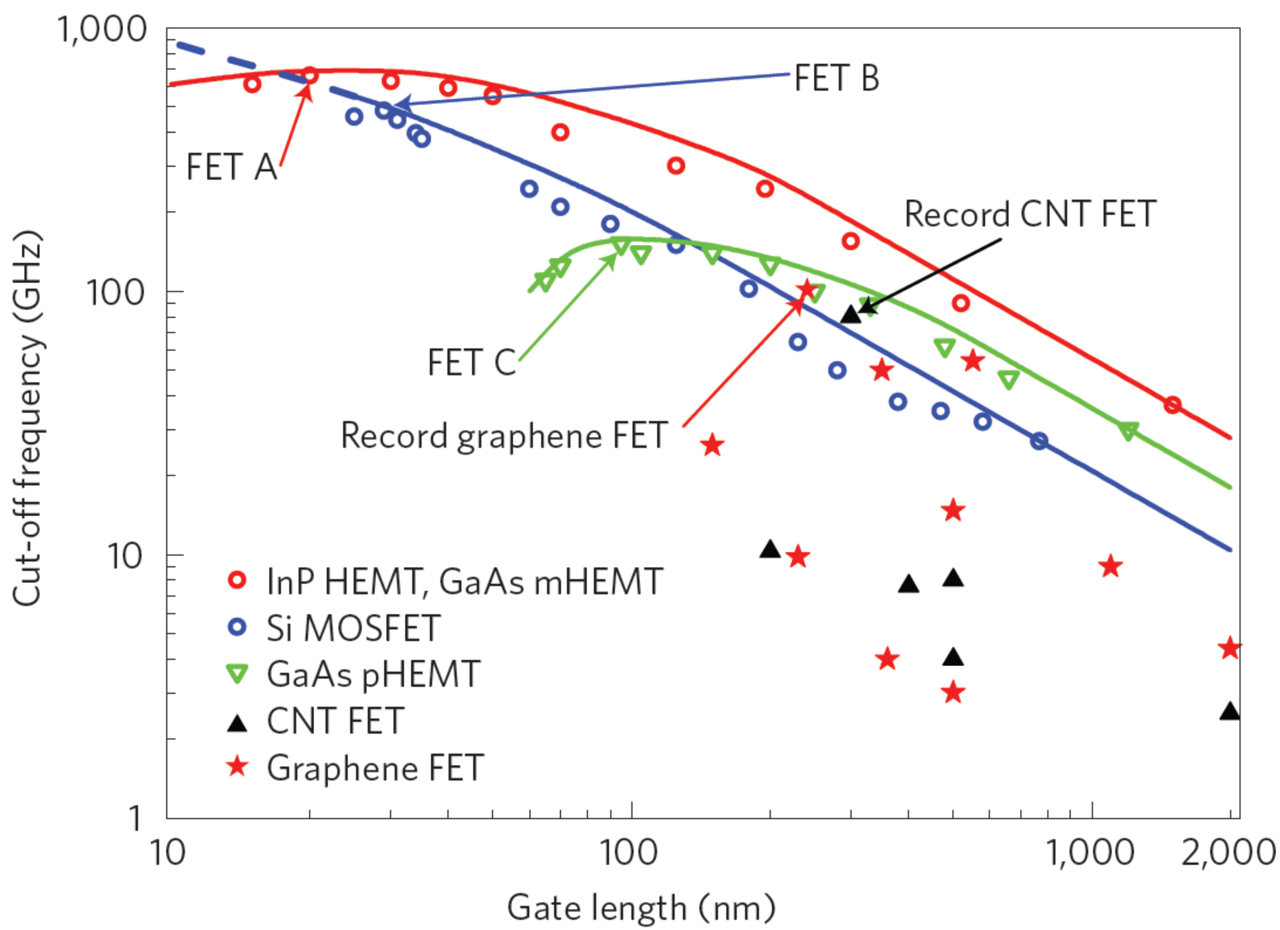
Graphene gate length scaling



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



Why carbon electronics?

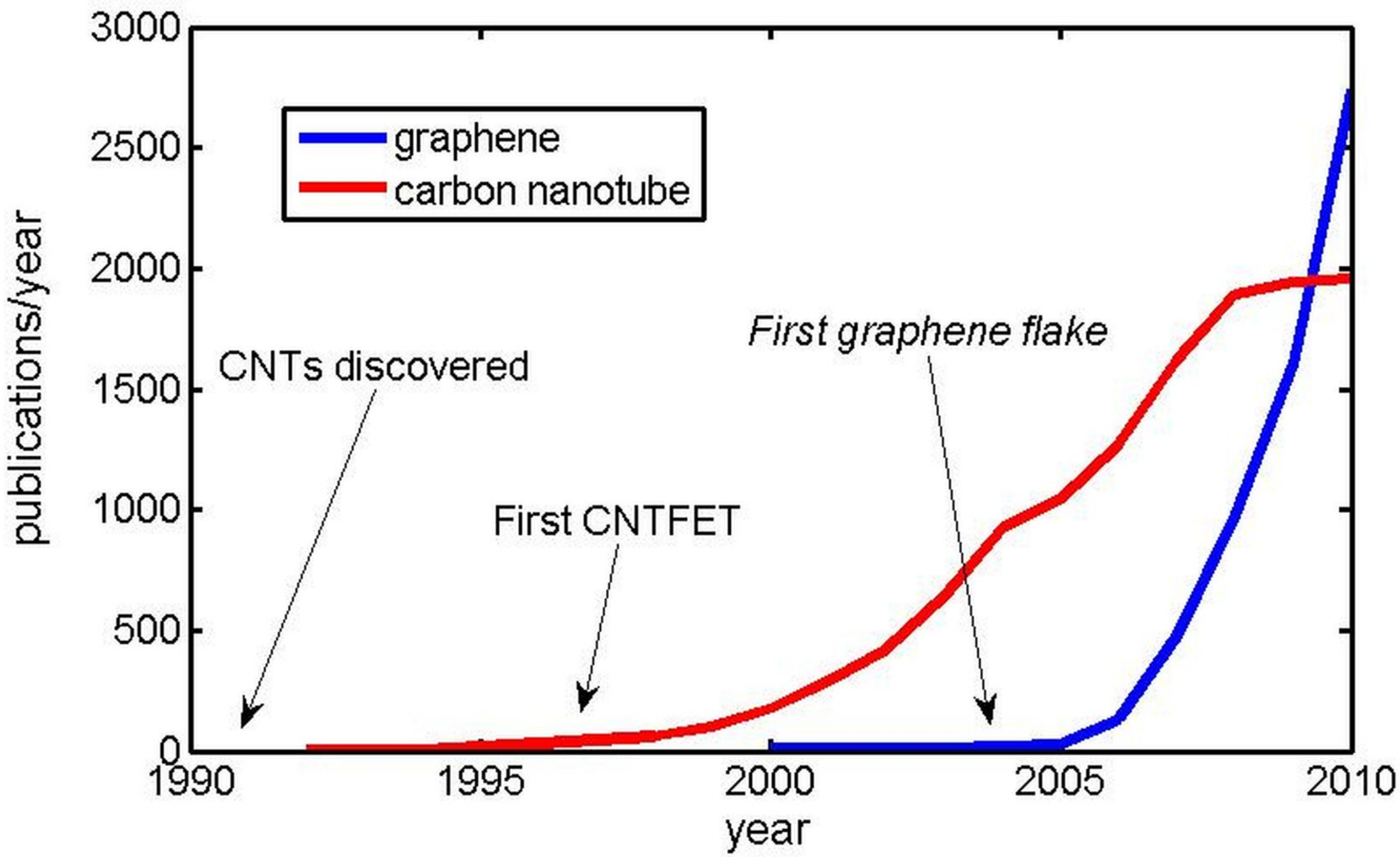
+ High mobility
+ High carrier velocity
+ High current density
+ Good electrostatics
+ Compatible with high-k dielectrics
+ Same electron/hole band structure

Why not?

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

Very active research

- Rapidly increasing # of publications
- Graphene > CNTs in 2009



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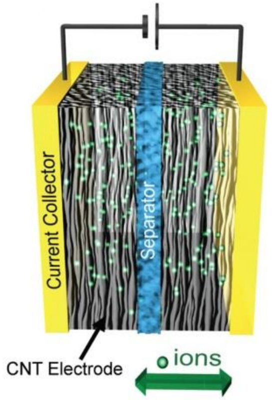
Not only transistors



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