



Graphene electronics

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Nanoelectronics FFF160

Outline

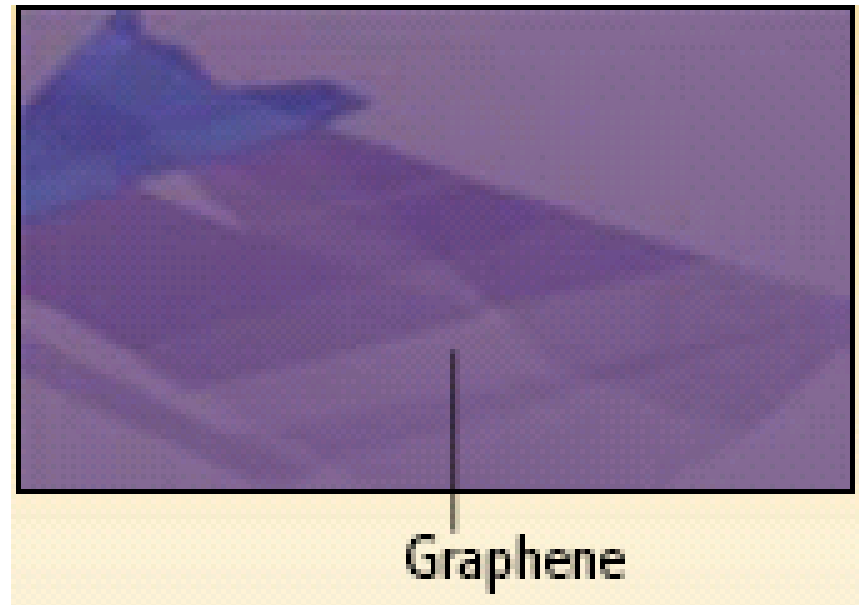
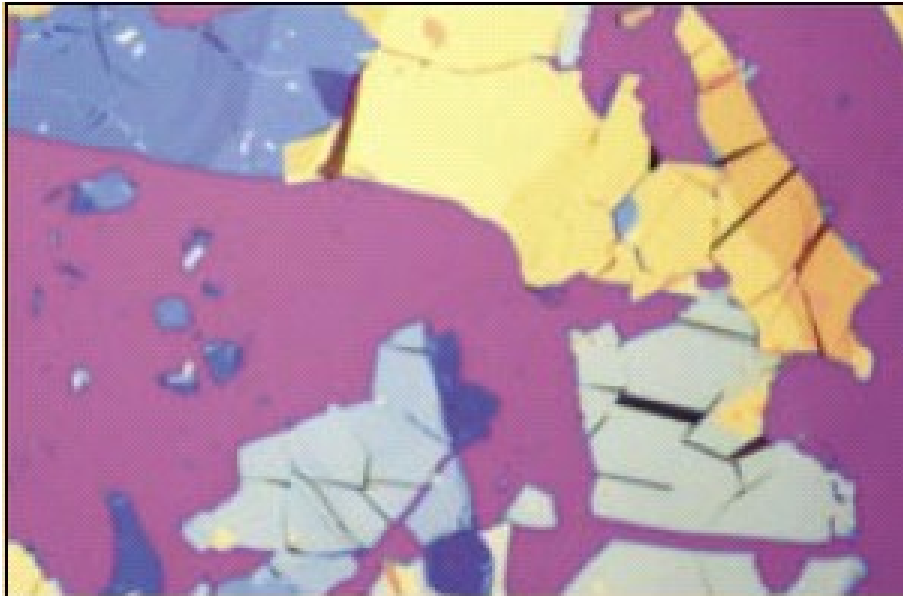
- Graphene production
 - Mechanical exfoliation
 - Epitaxial growth
 - Chemical vapor deposition
- Transport characteristics
- High frequency performance
- Inducing a band gap
 - Nanoribbon
 - Bilayer graphene
 - Chemical modification
- Performance comparison (graphene / CNTs)
- Other electronic CNT/graphene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

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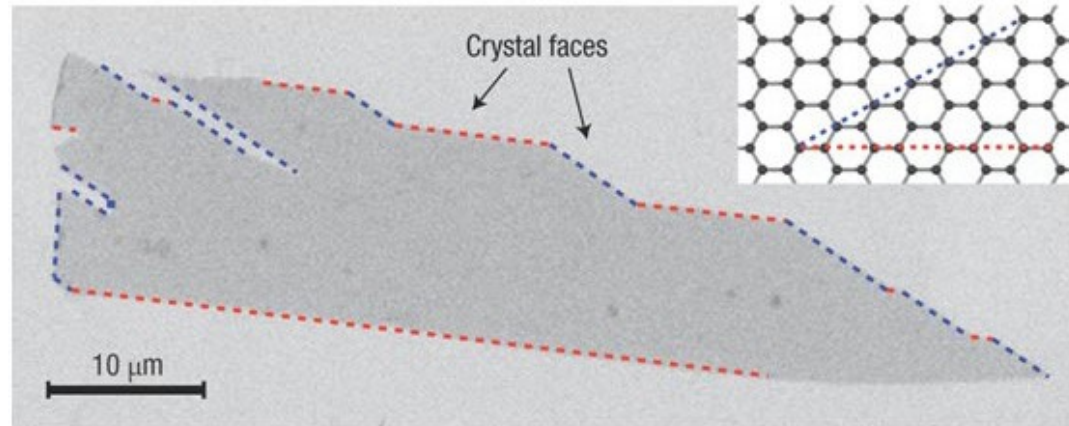
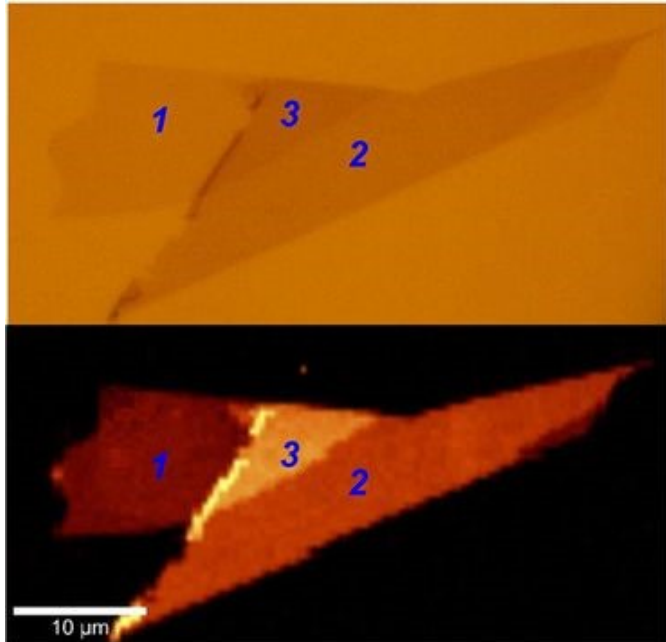
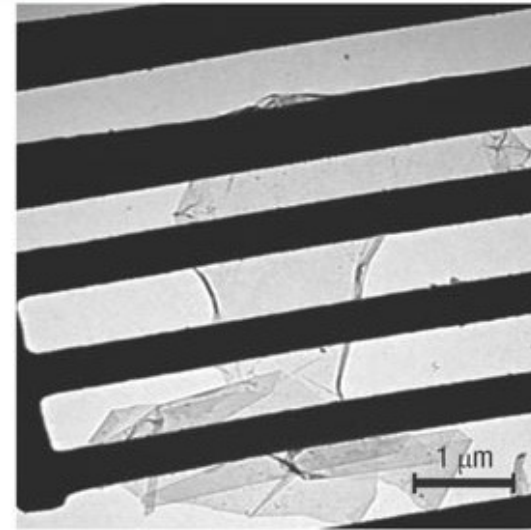
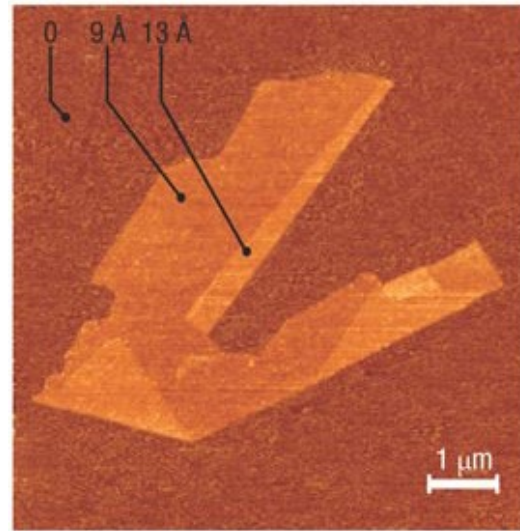
Mechanical exfoliation

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



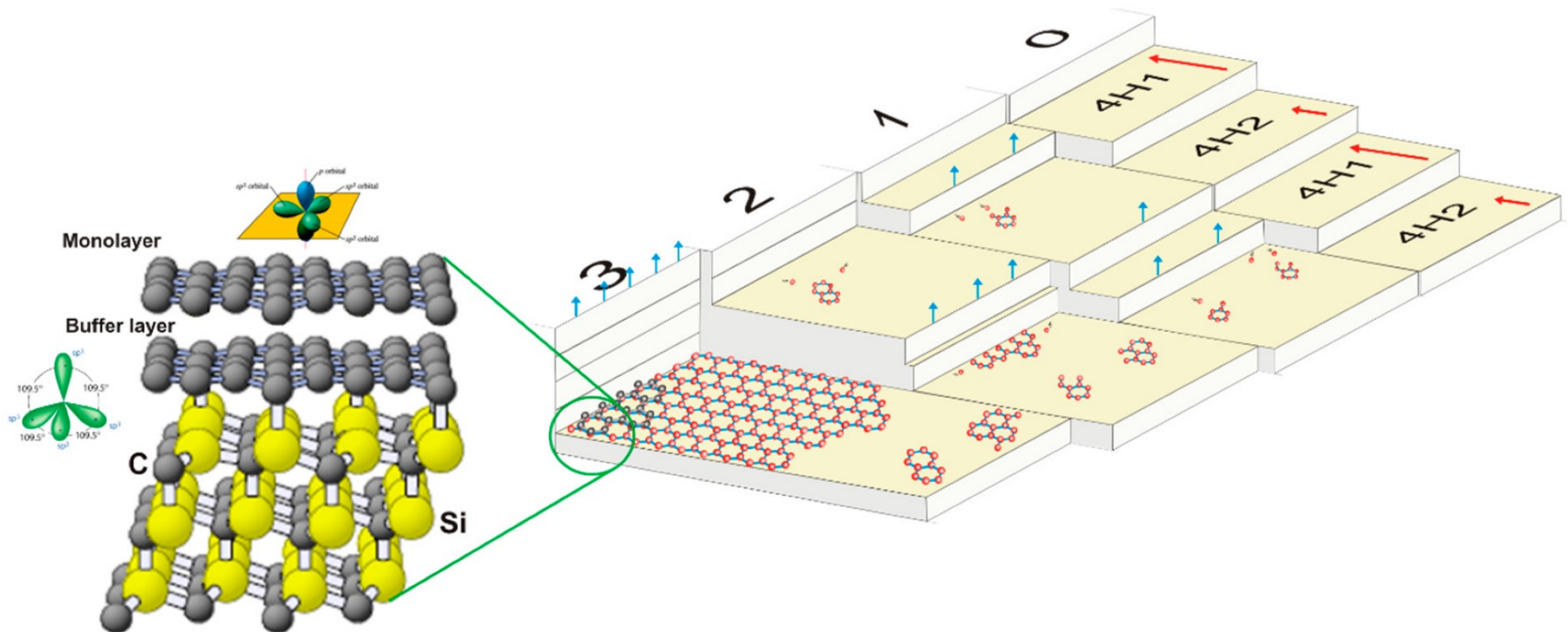
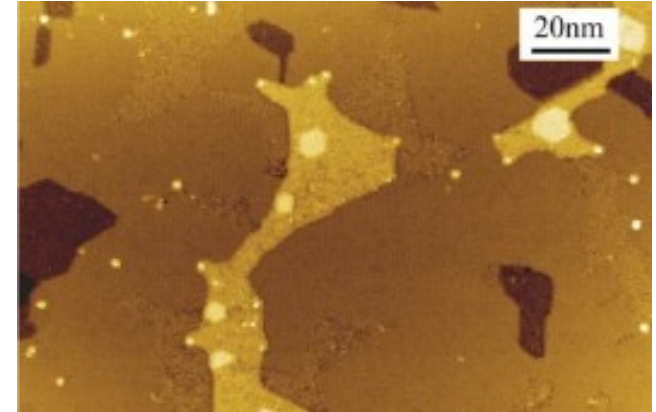
Observing graphene

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

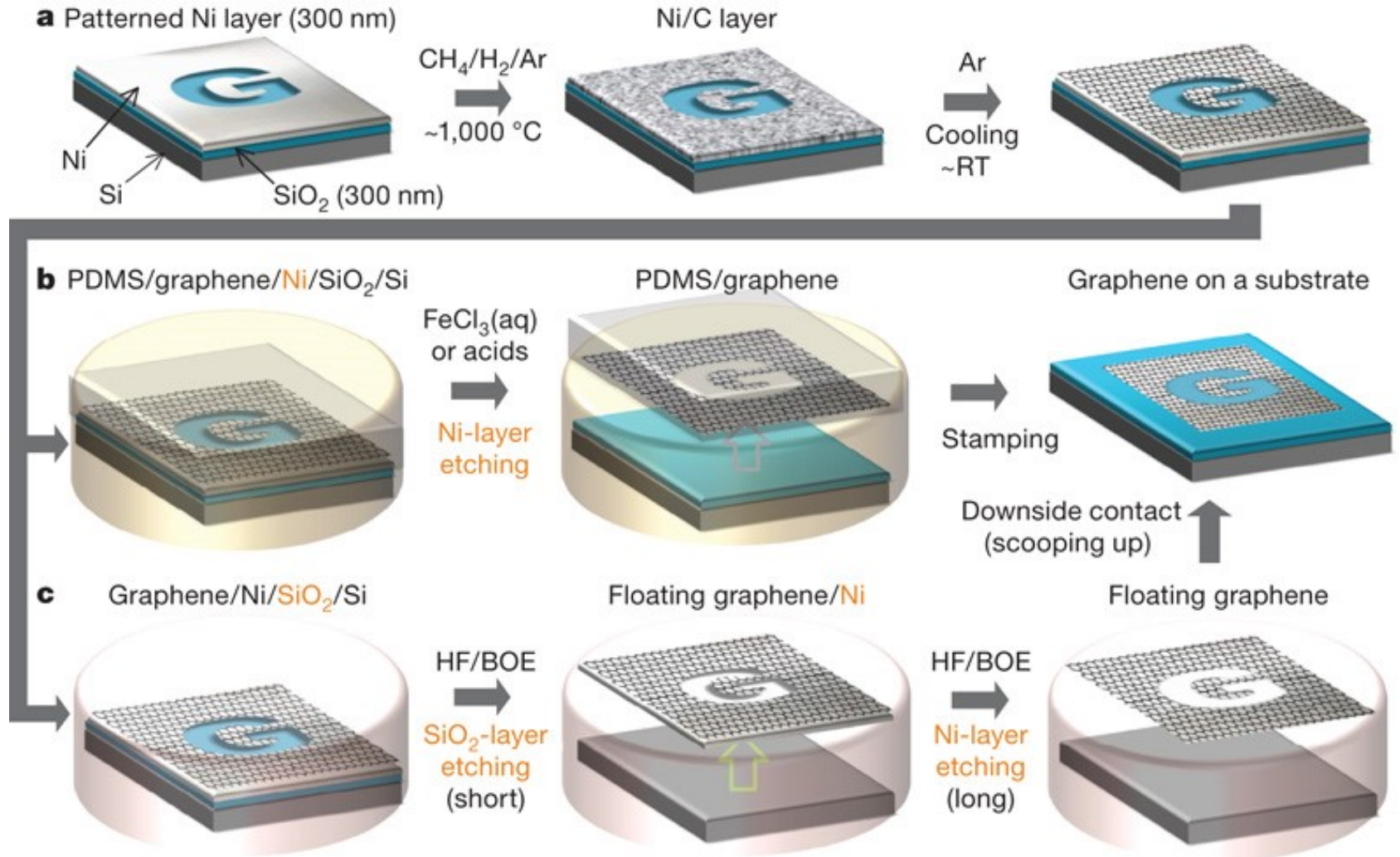


Epitaxial growth on SiC

- Heat to 1550 °C to remove Si which will expose a graphene layer
- Need to remove “coupling” to substrate by e.g. hydrogen treatment

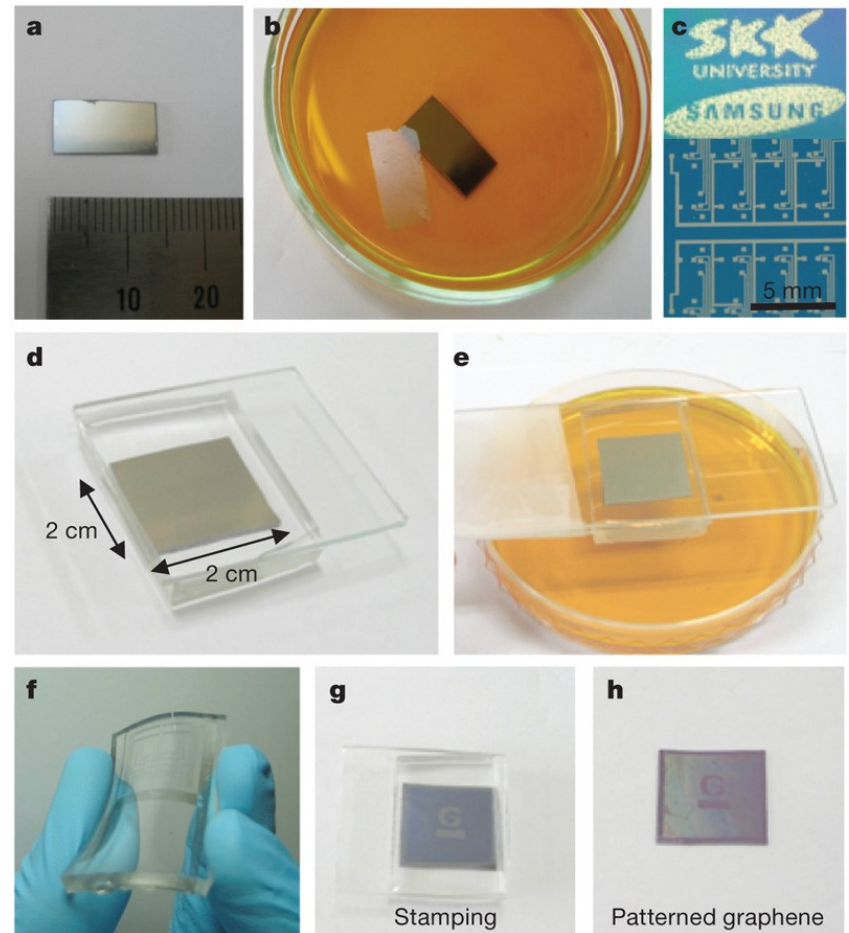
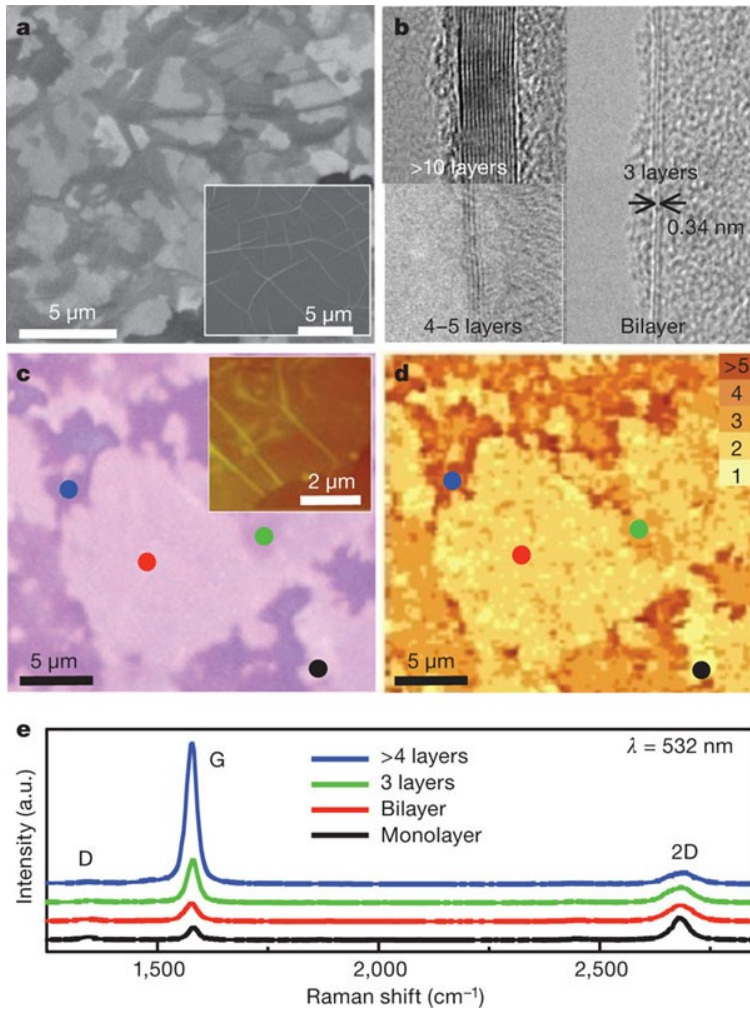


Chemical vapor deposition



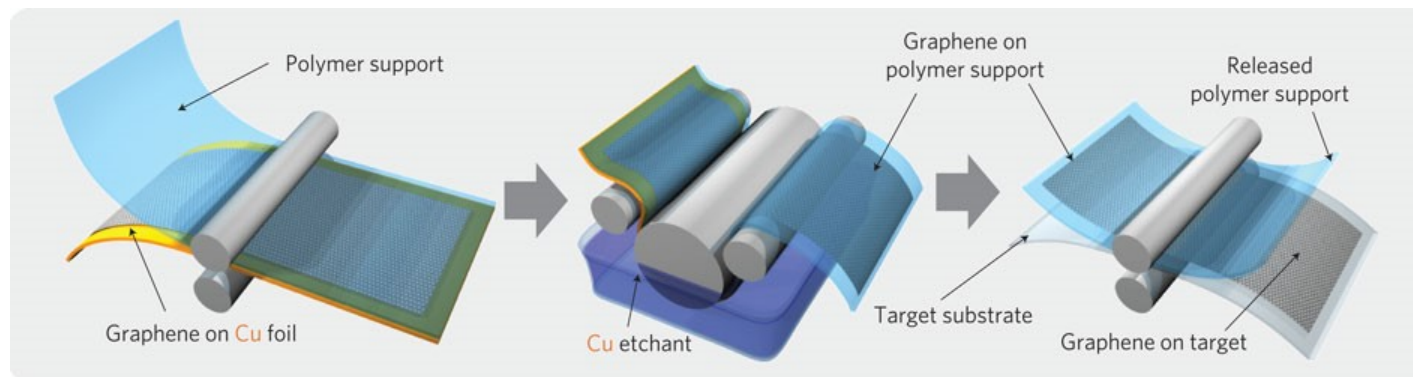
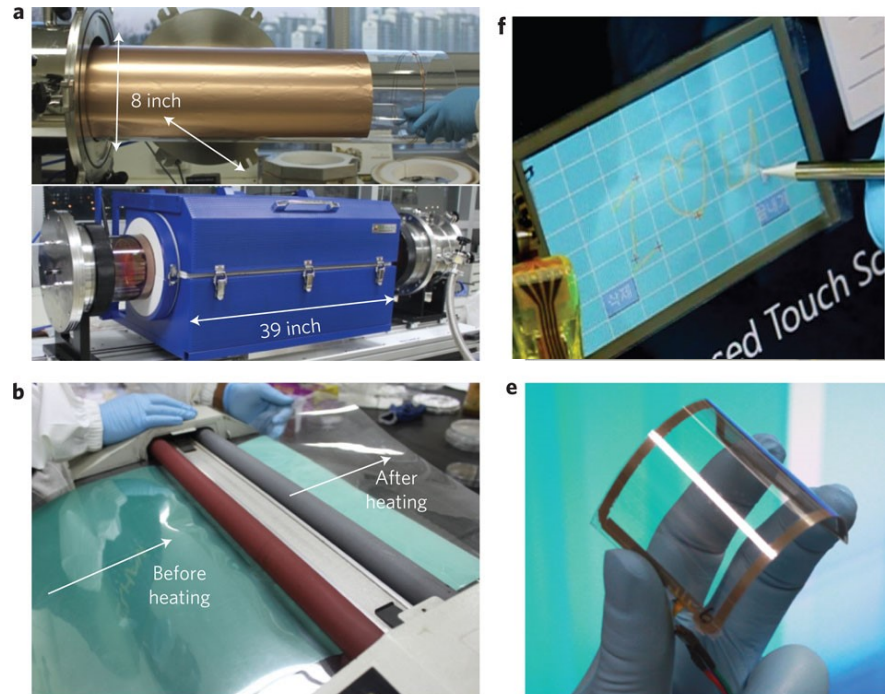
Chemical vapor deposition - result

- Mix of single and multilayered
- $\mu_e = 3,700 \text{ cm}^2/\text{Vs}$ after transfer



Large scale CVD production

- CVD on Cu foil
- 30 inch multilayer flake
- $30 \Omega/\square$ at 90% transparency
- Better than ITO

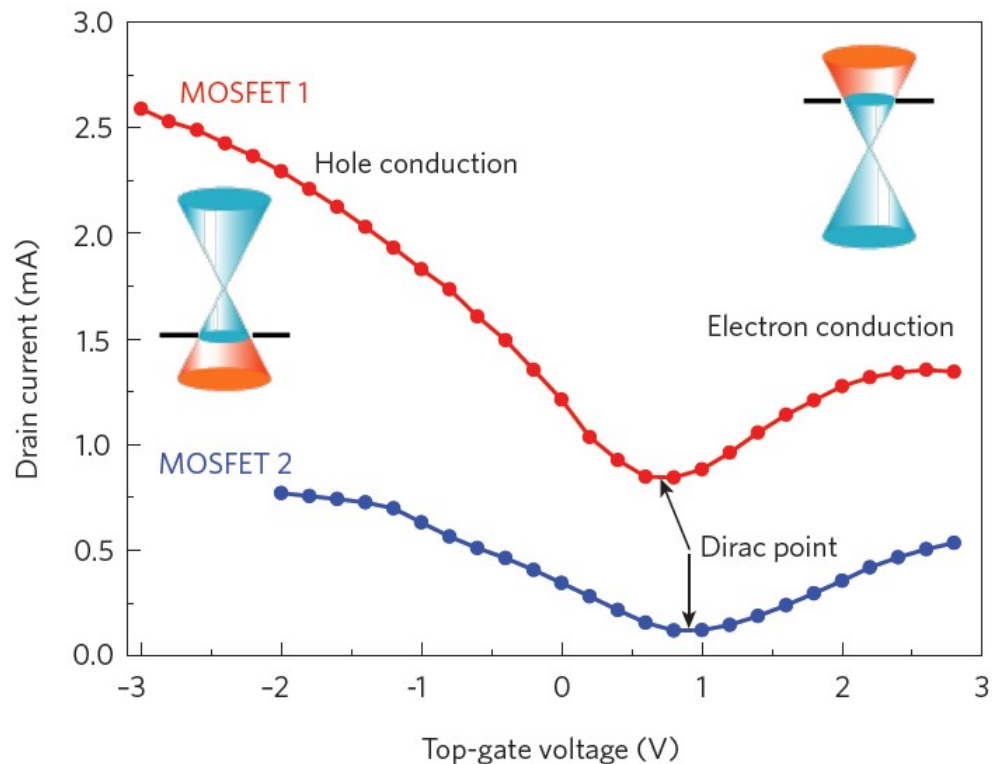


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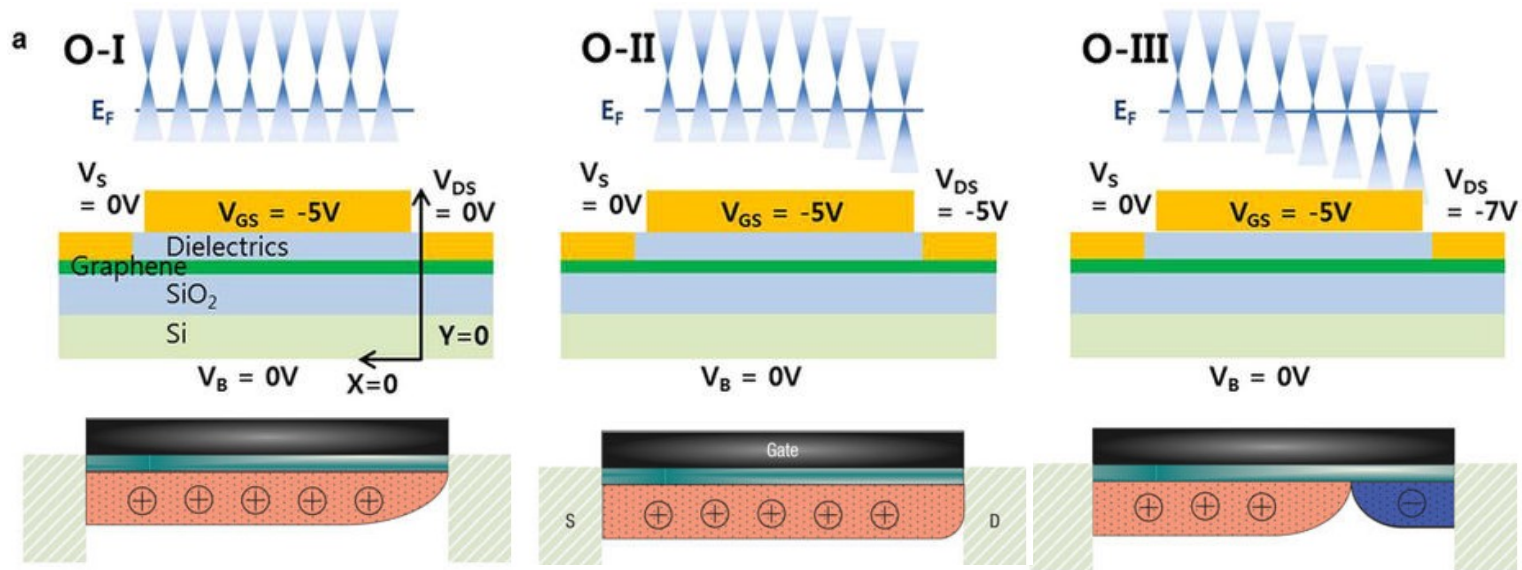
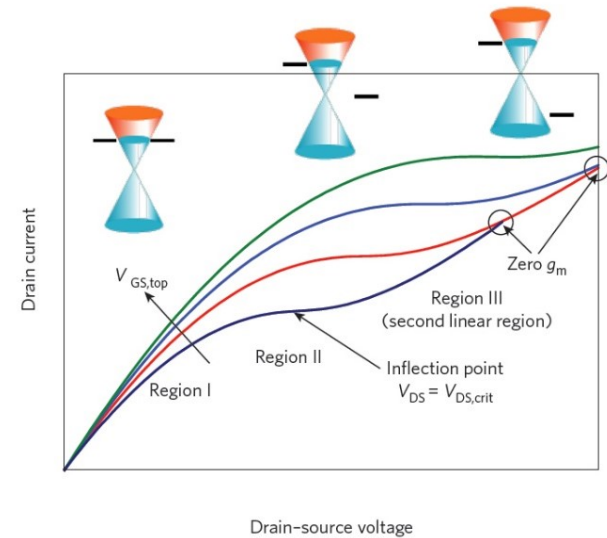
Transfer characteristics

- 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.



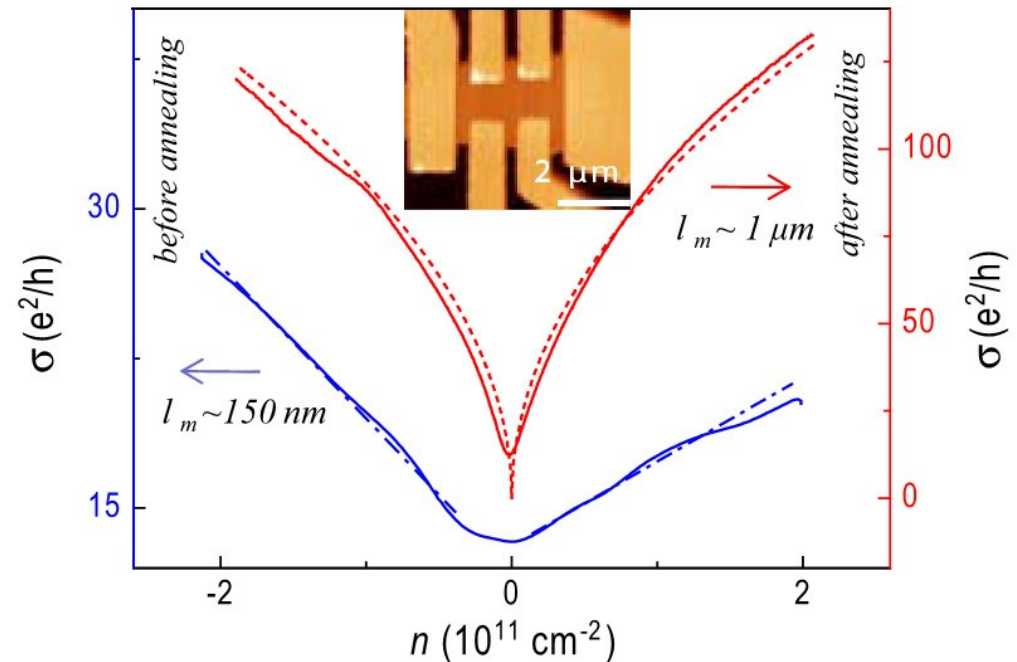
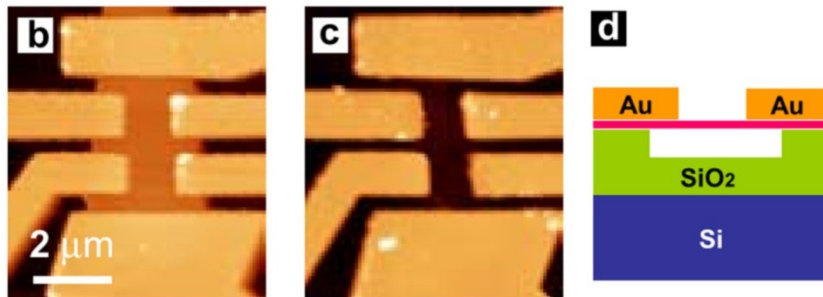
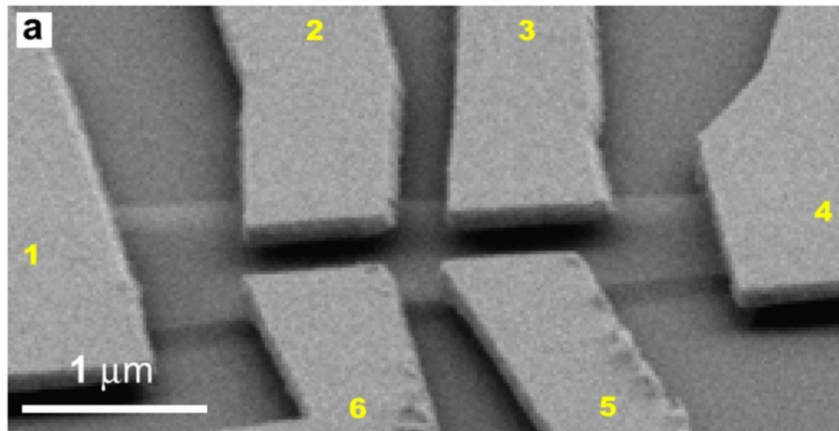
Output characteristics

- 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: $\mu_e = 2\,000 - 30\,000 \text{ cm}^2/\text{Vs}$ (substrate phonons)
- Suspended and annealed flakes: $\mu_e = 230\,000 \text{ cm}^2/\text{Vs}$
- Scattering due to impurities and edges

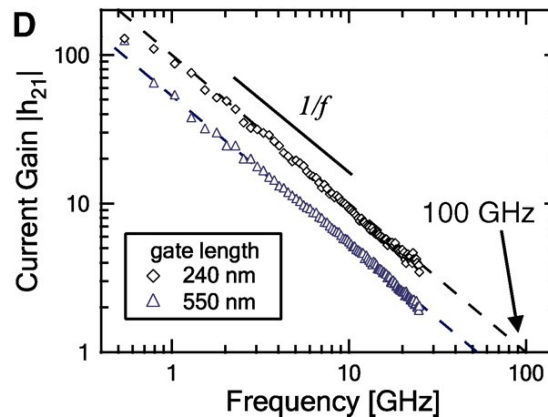
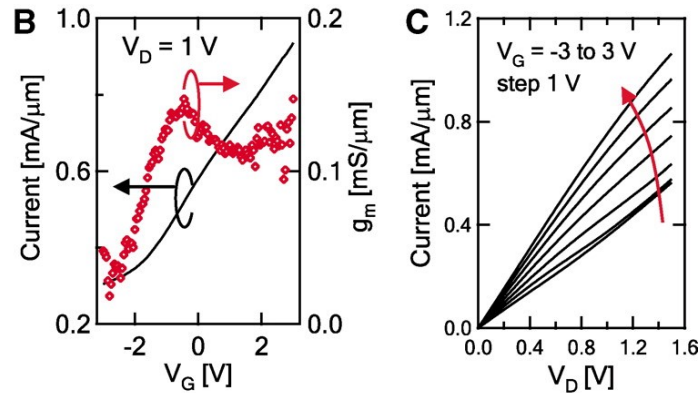
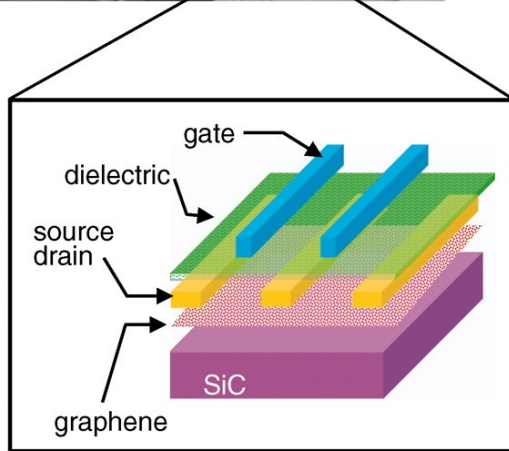
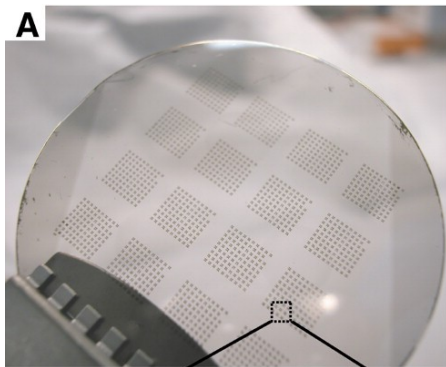
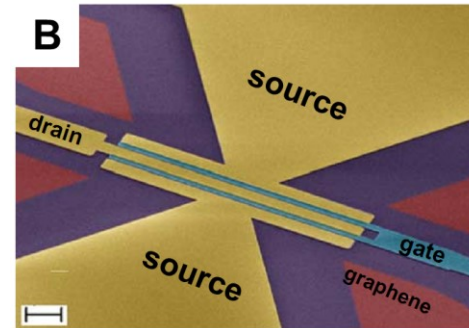


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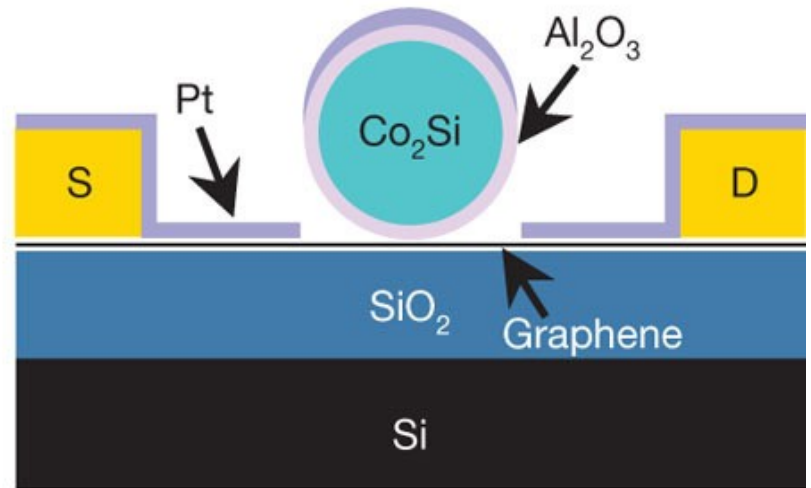
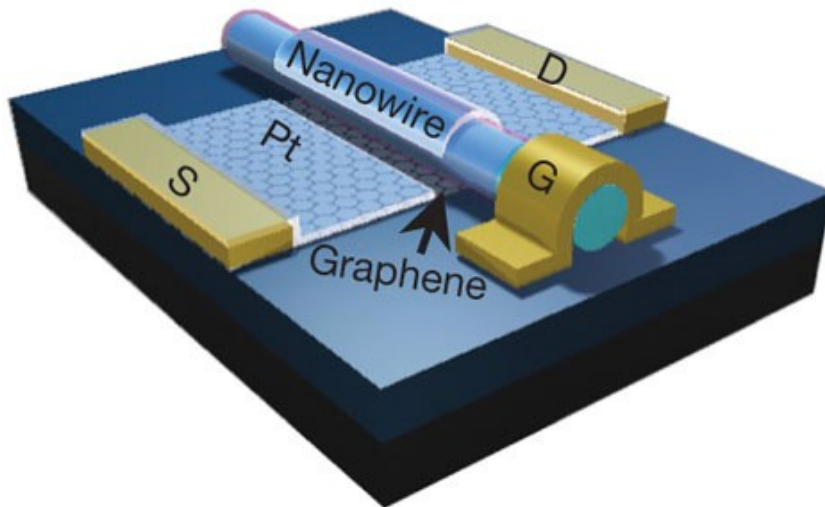
High frequency device

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



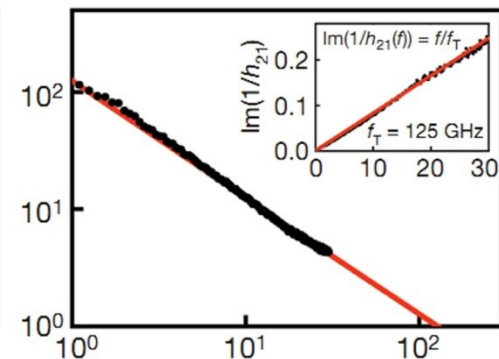
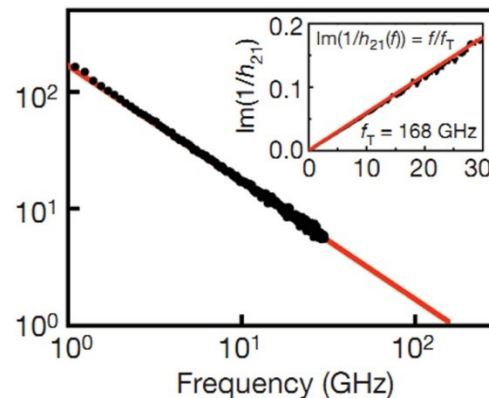
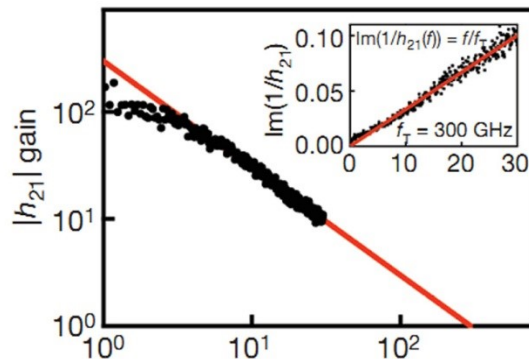
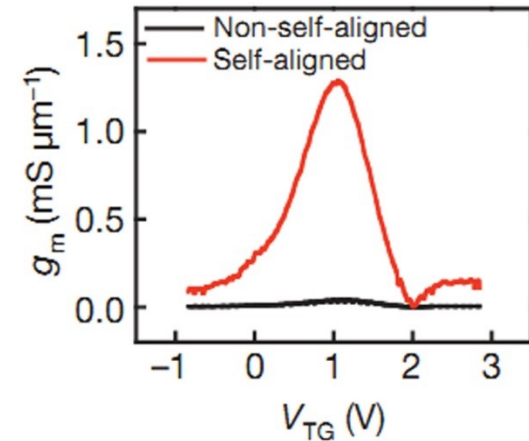
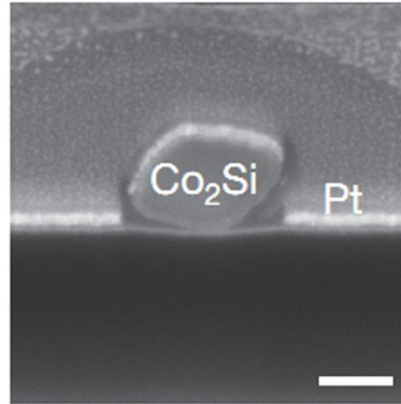
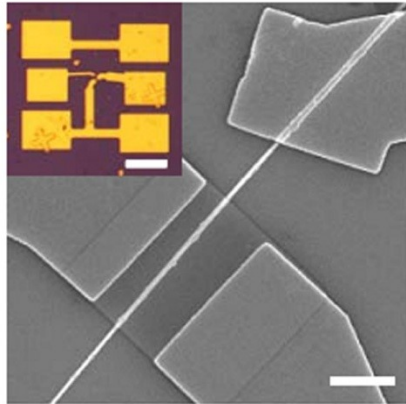
Graphene - nanowire device

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



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

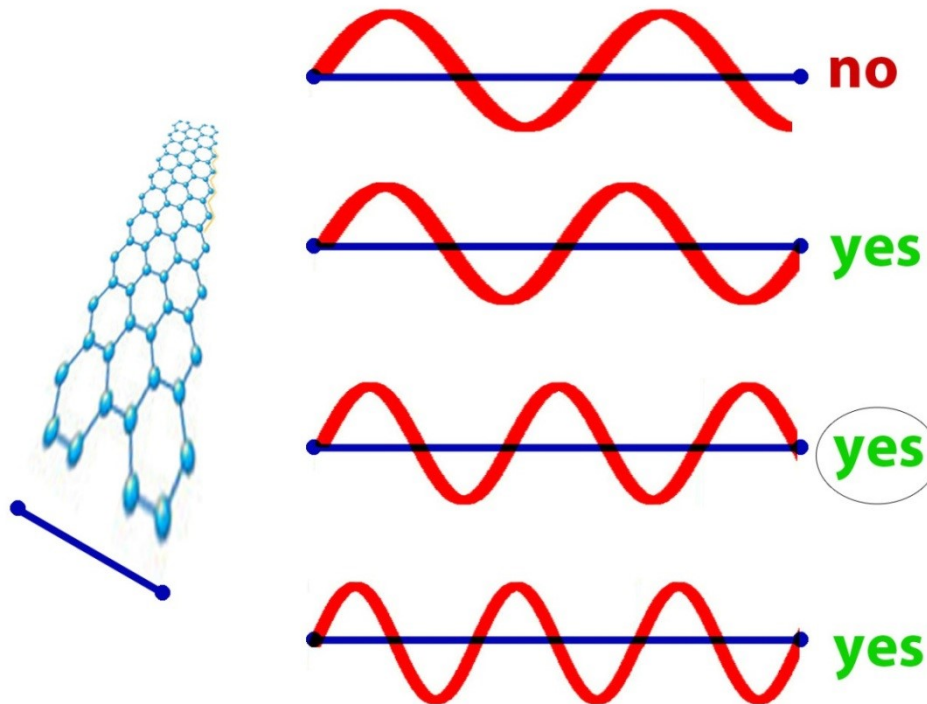


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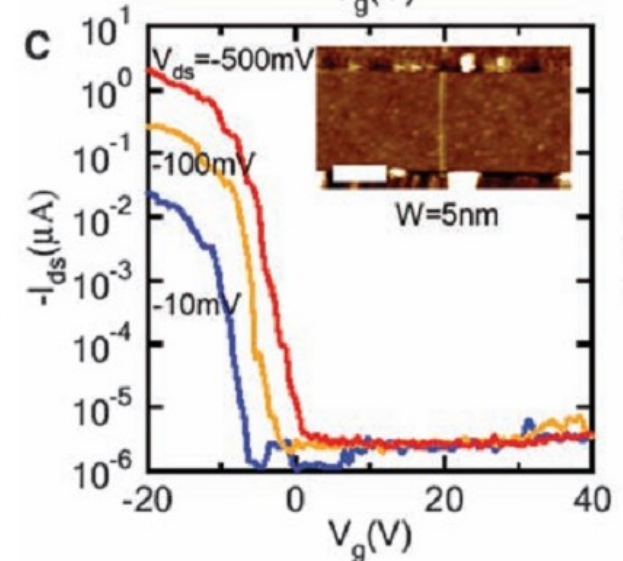
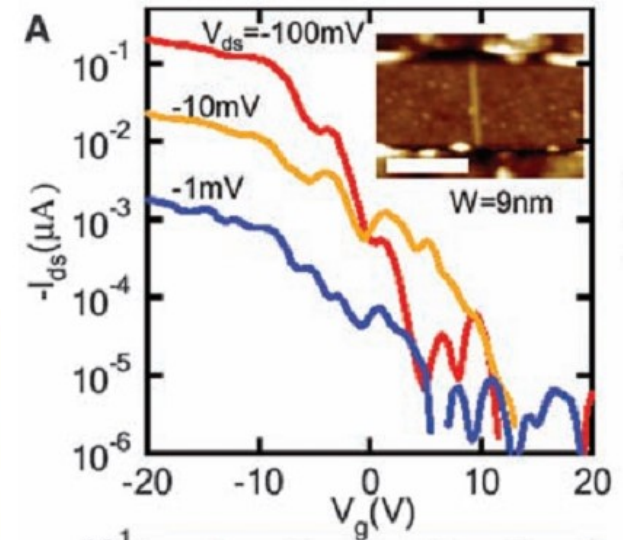
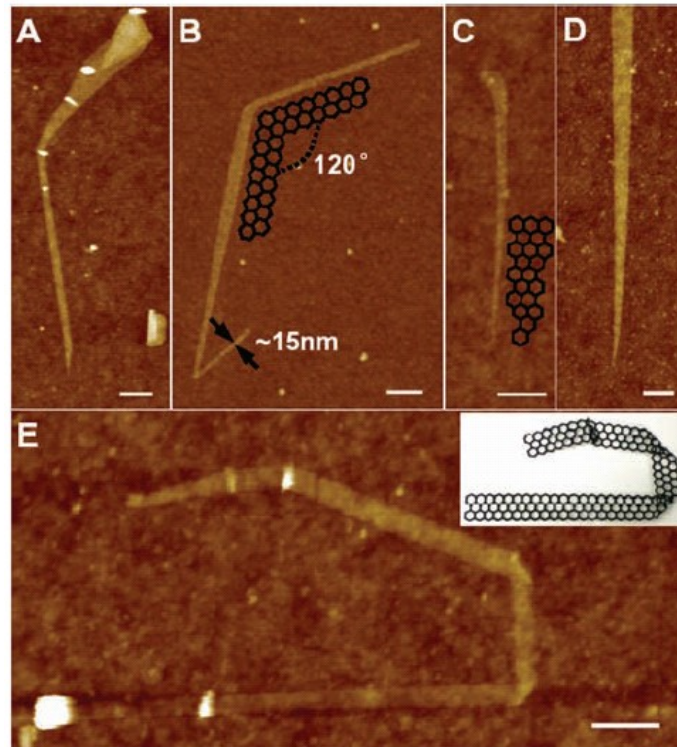
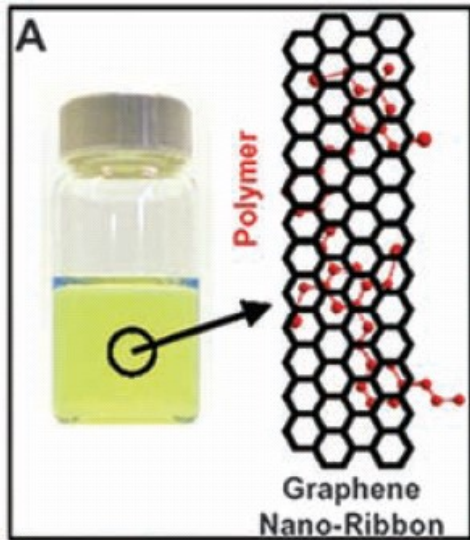
Confinement of electron wavefunctions

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



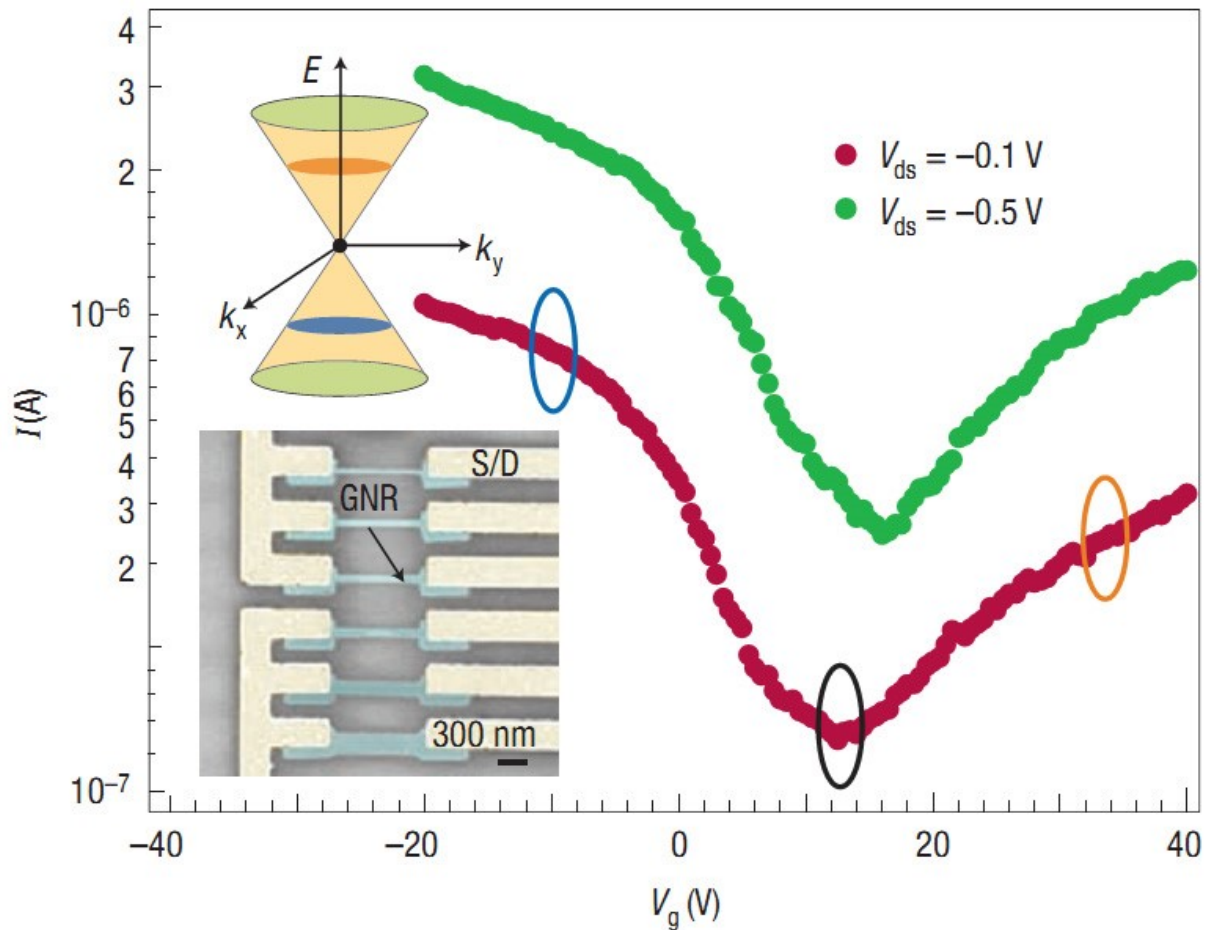
Chemical exfoliation

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



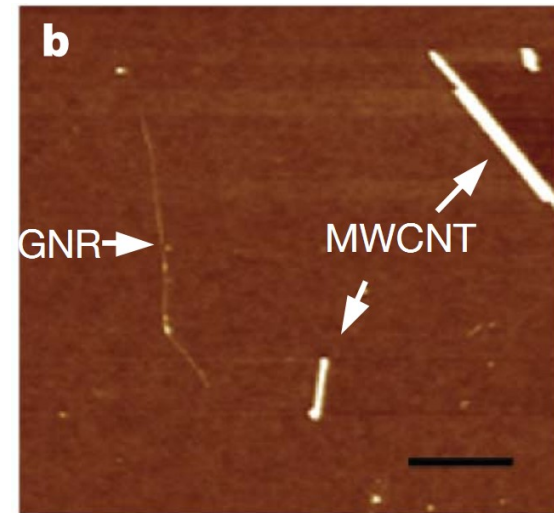
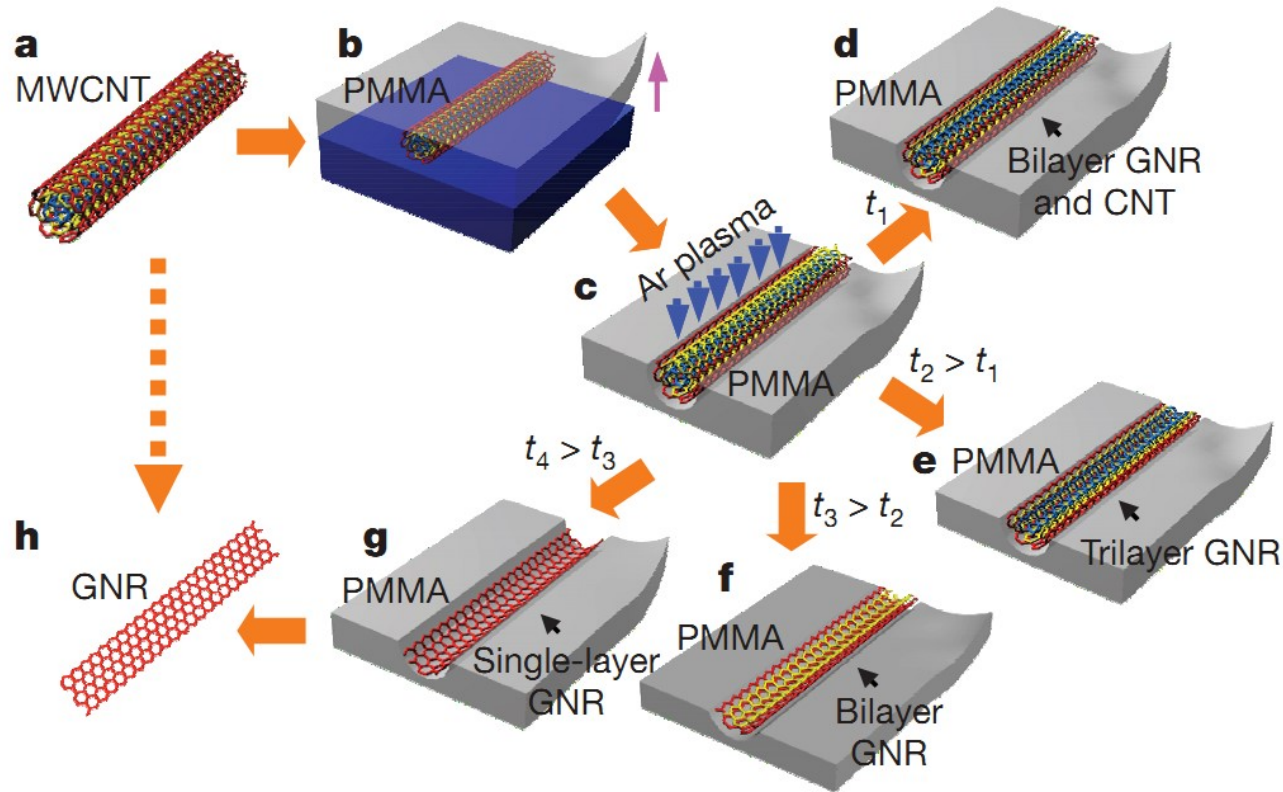
Etching

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



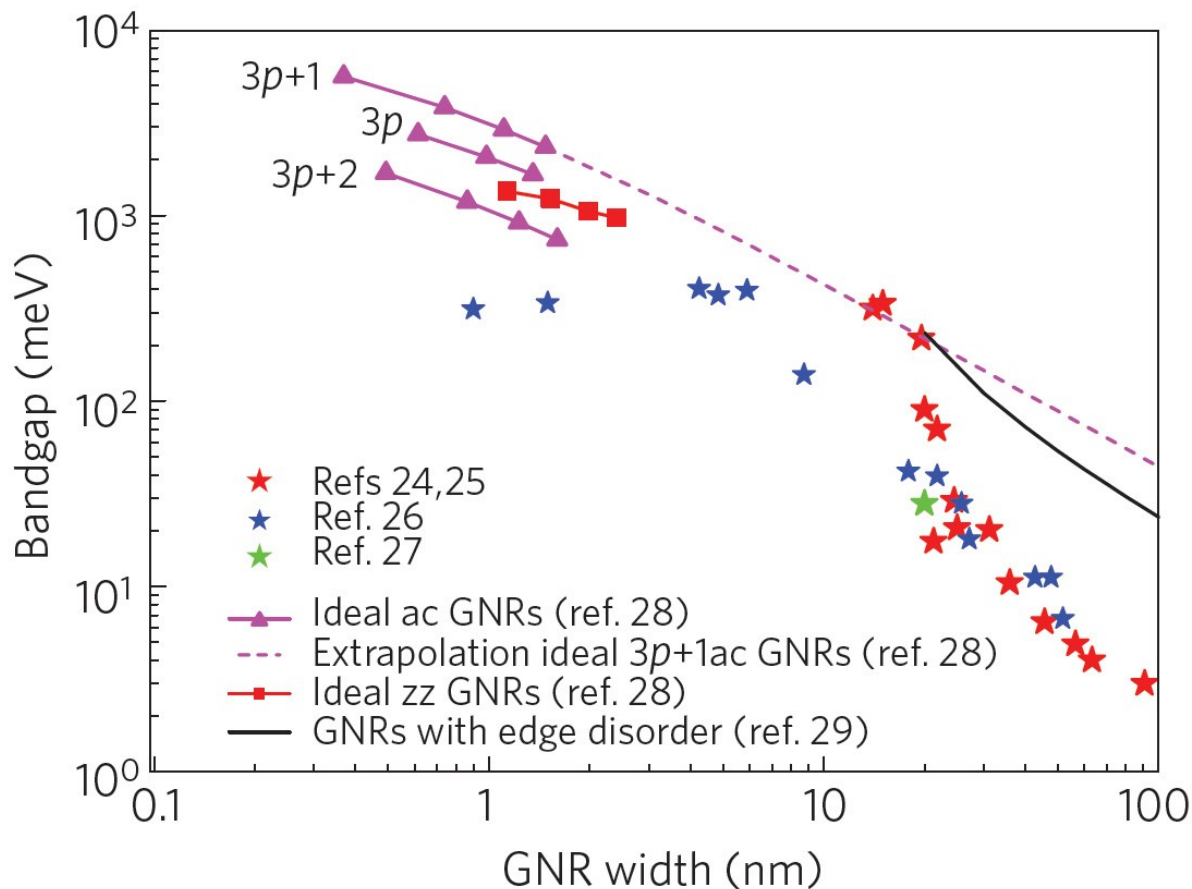
Unzipping a CNT

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



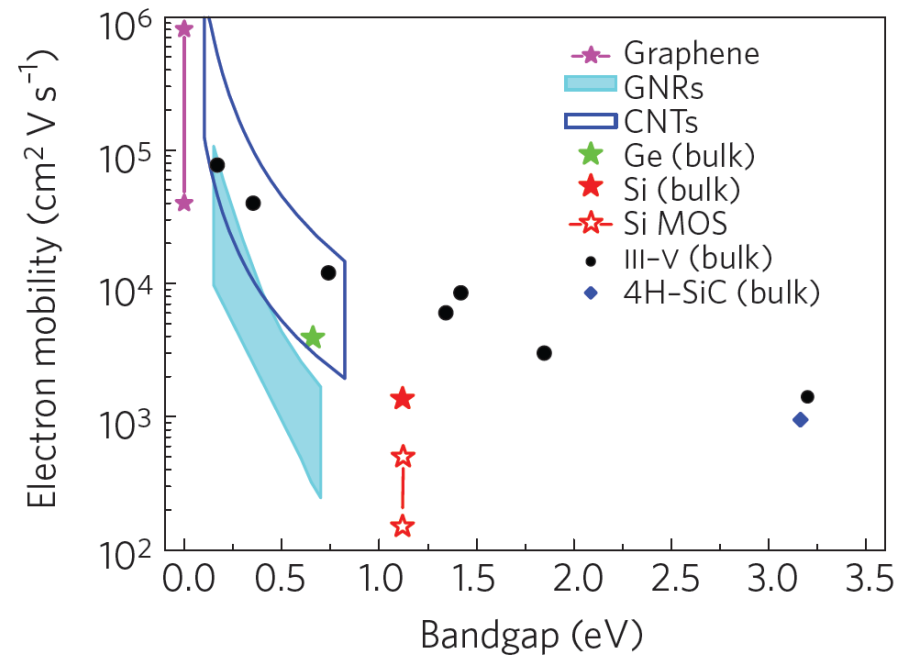
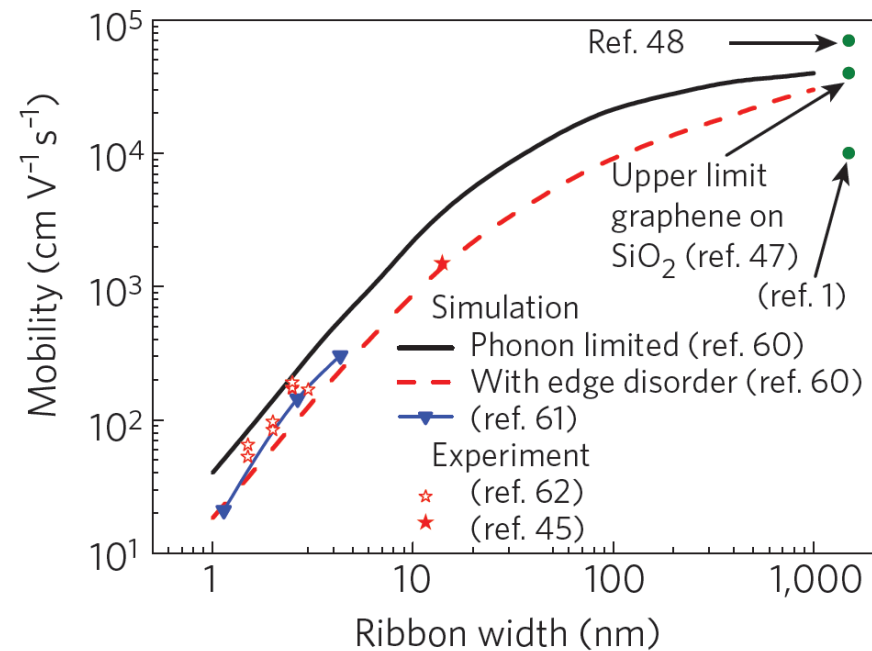
Band gap vs GNR width

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



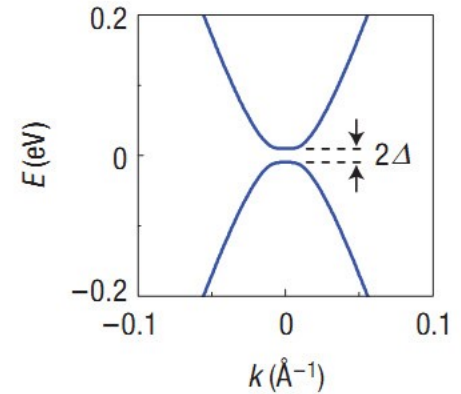
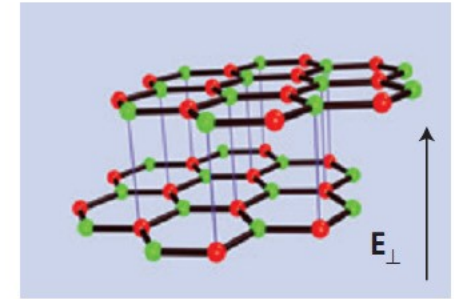
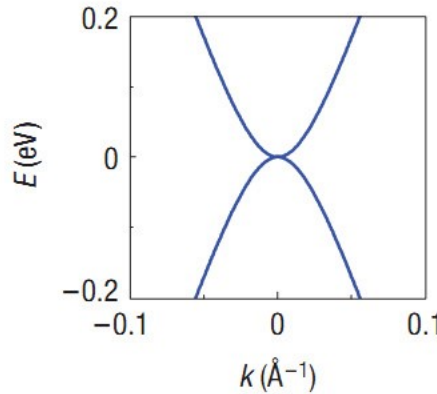
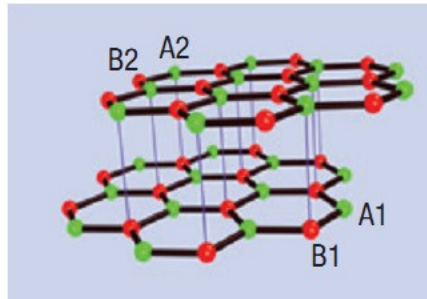
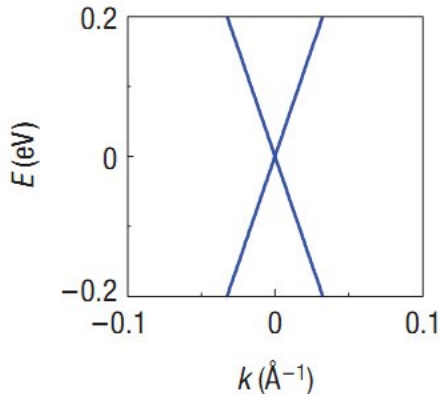
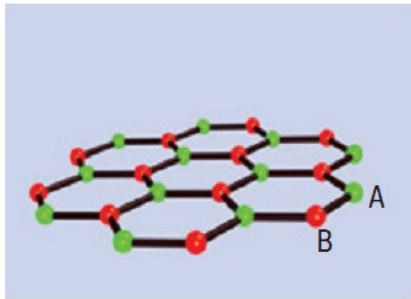
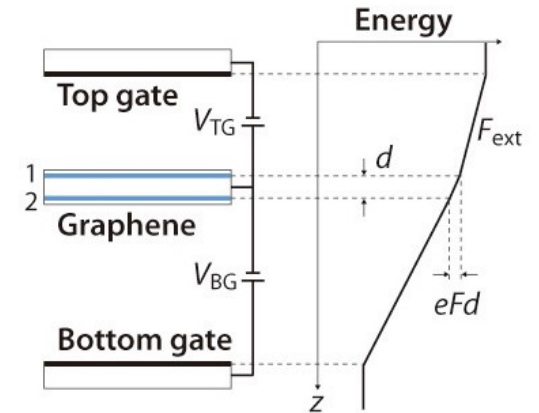
Mobility degradation

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



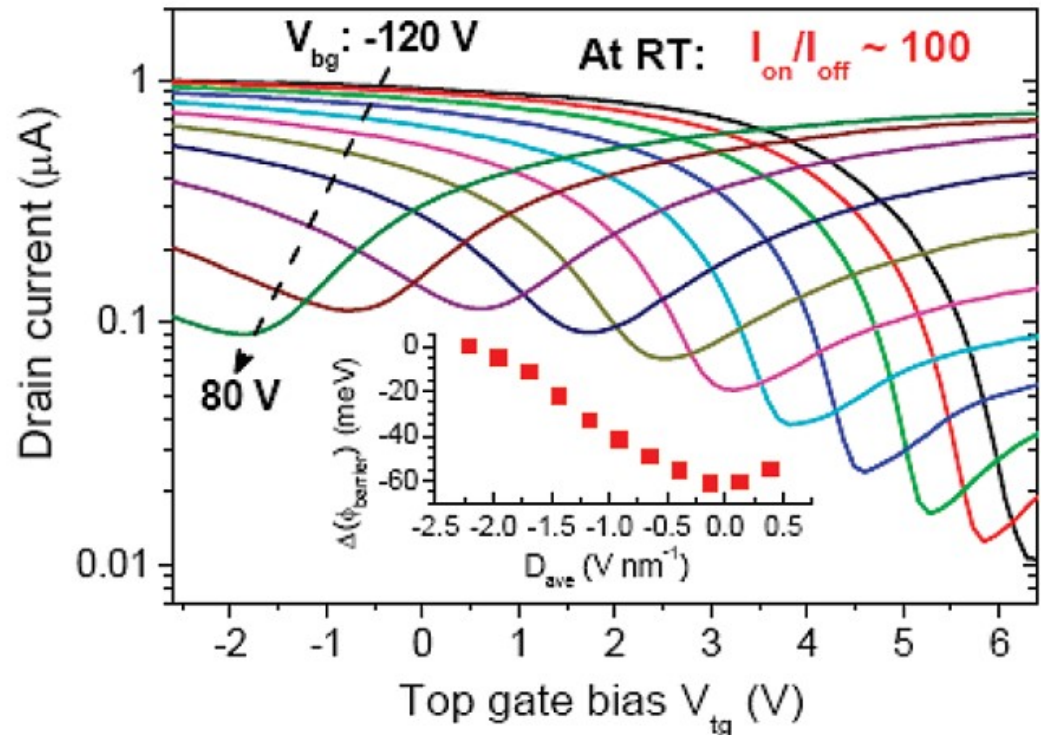
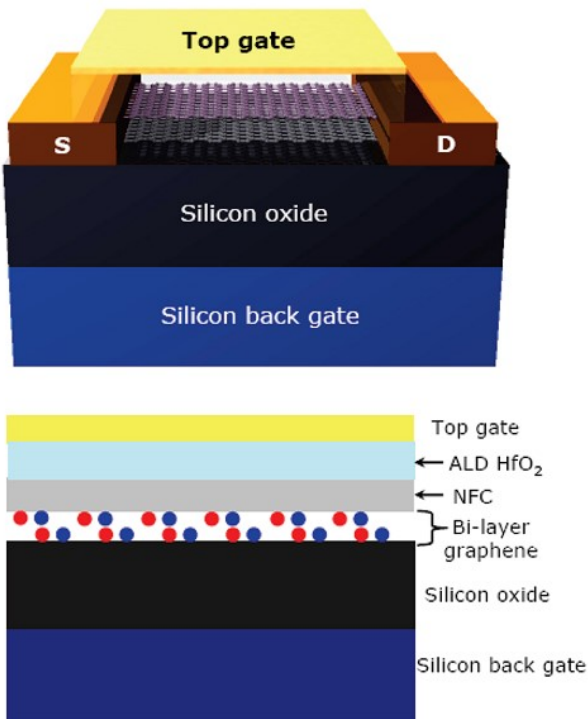
Bilayer graphene

- Perpendicular electric field breaks symmetry in bilayer graphene.
- Band gap proportional to E-field.



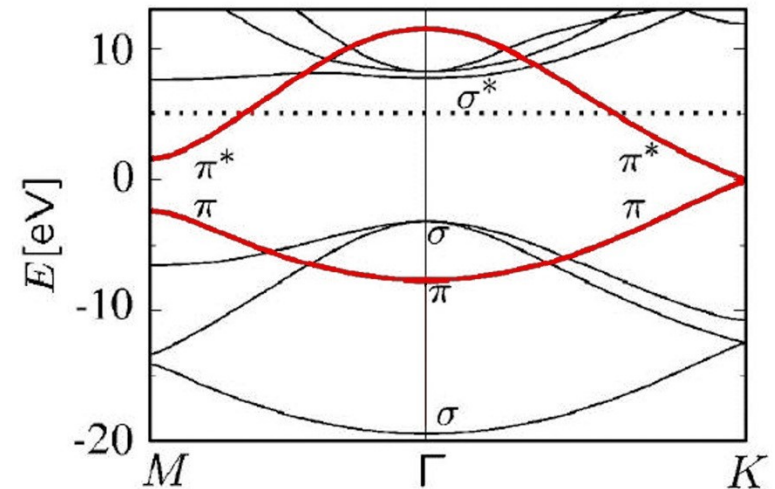
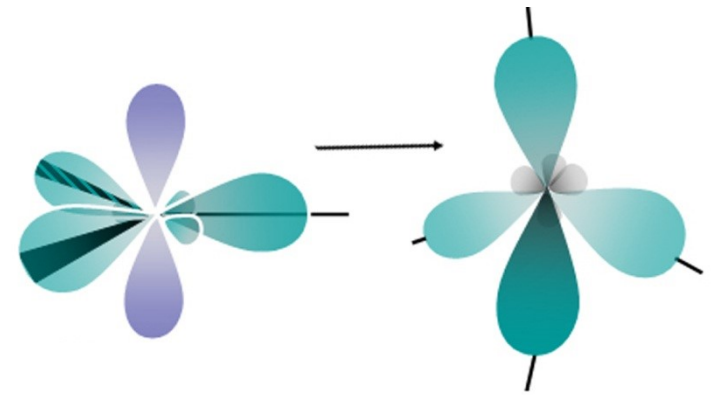
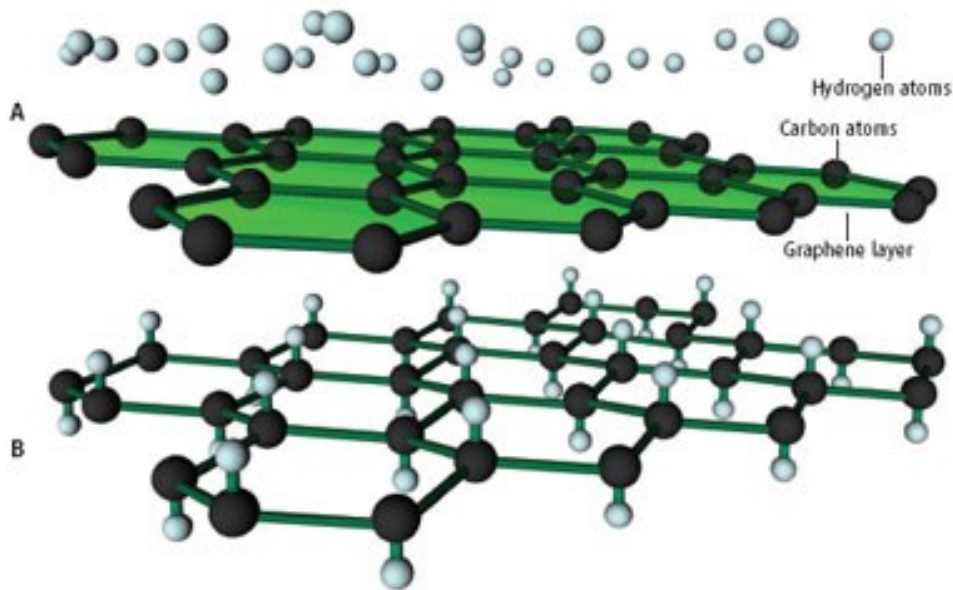
Double gated bilayer device

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



Graphane

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



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Comparing CNT and graphene FETs

Graphene FETs

No band gap gives poor on/off ratio, not for logic only RF

Difficult to control edges which gives mobility degradation

Large area production possible

Only one type of device

Carbon nanotubes FETs

Sufficient band gap for logic

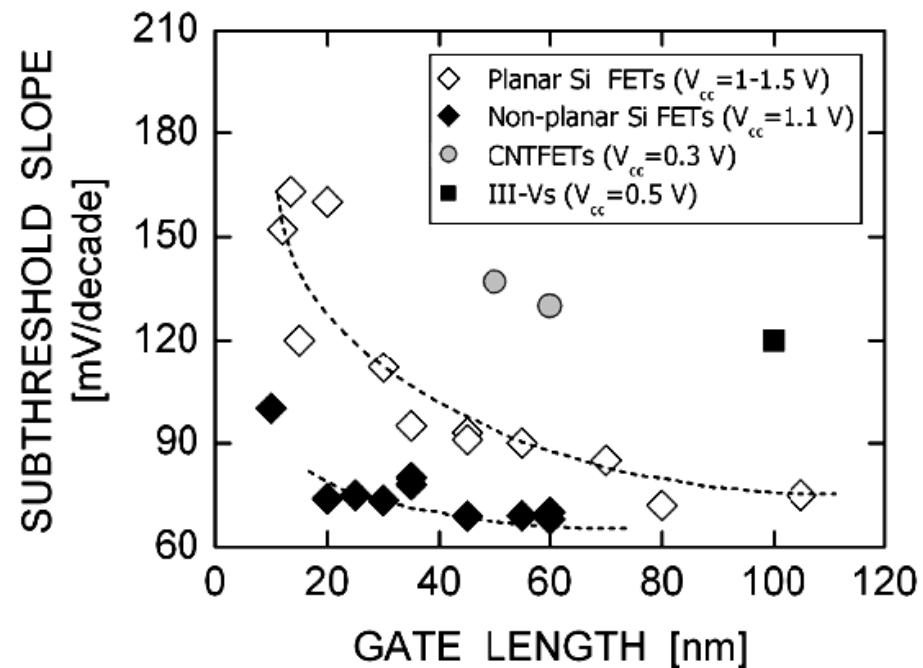
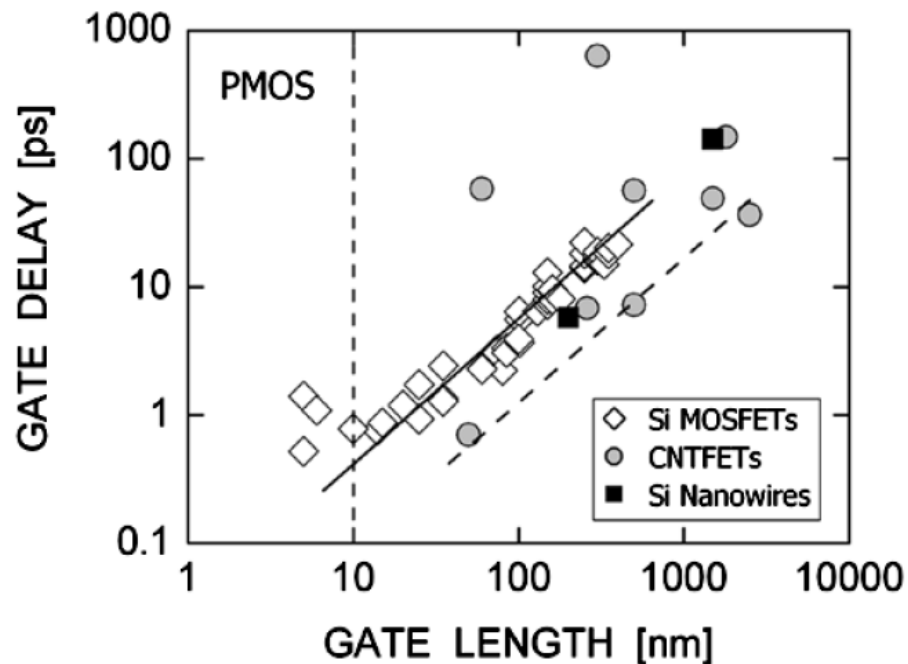
No dangling bonds

Need parallel CNTs to obtain high on-current and g_m

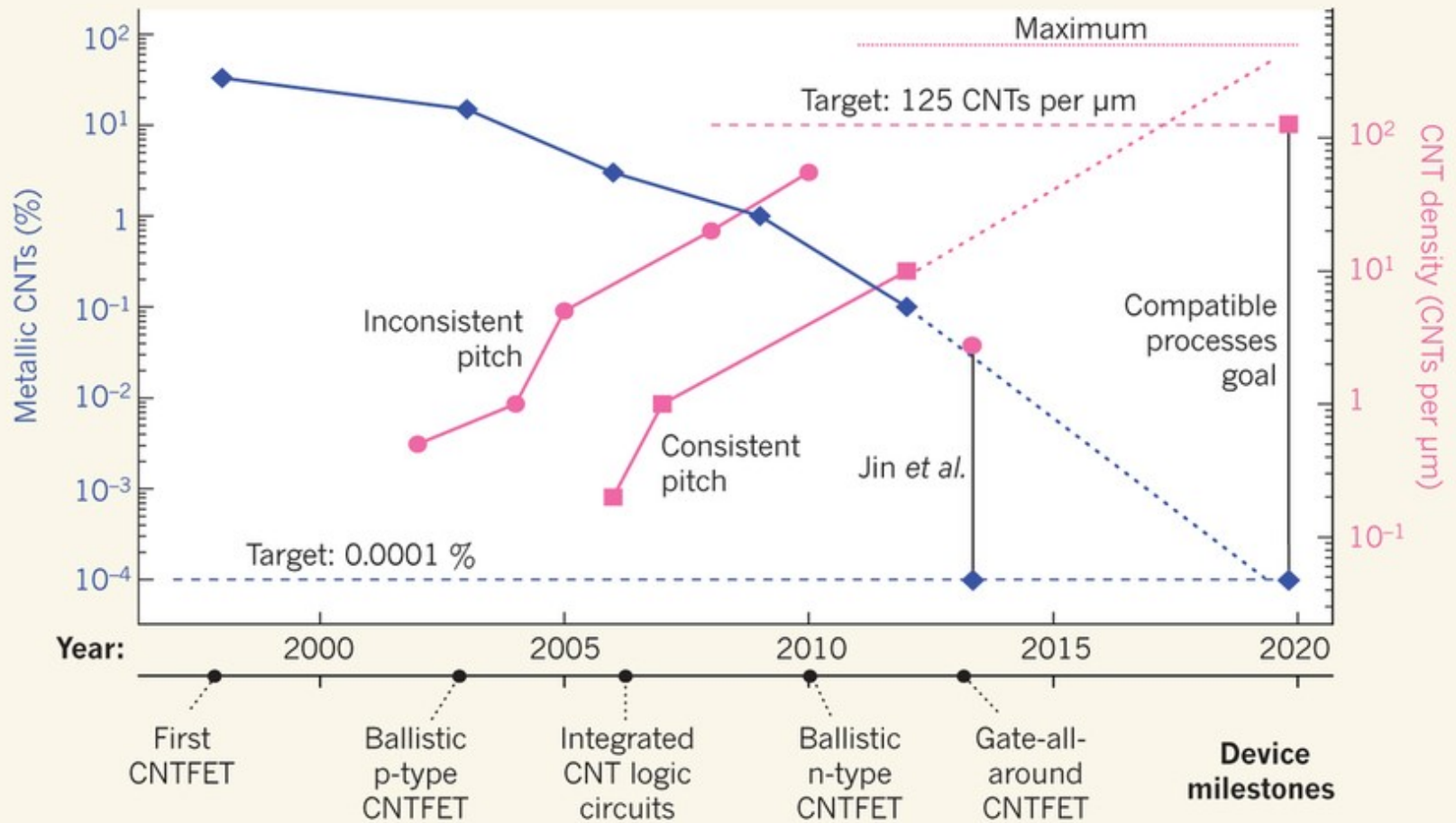
No control of metallic / semiconducting type

Benchmark comparisons

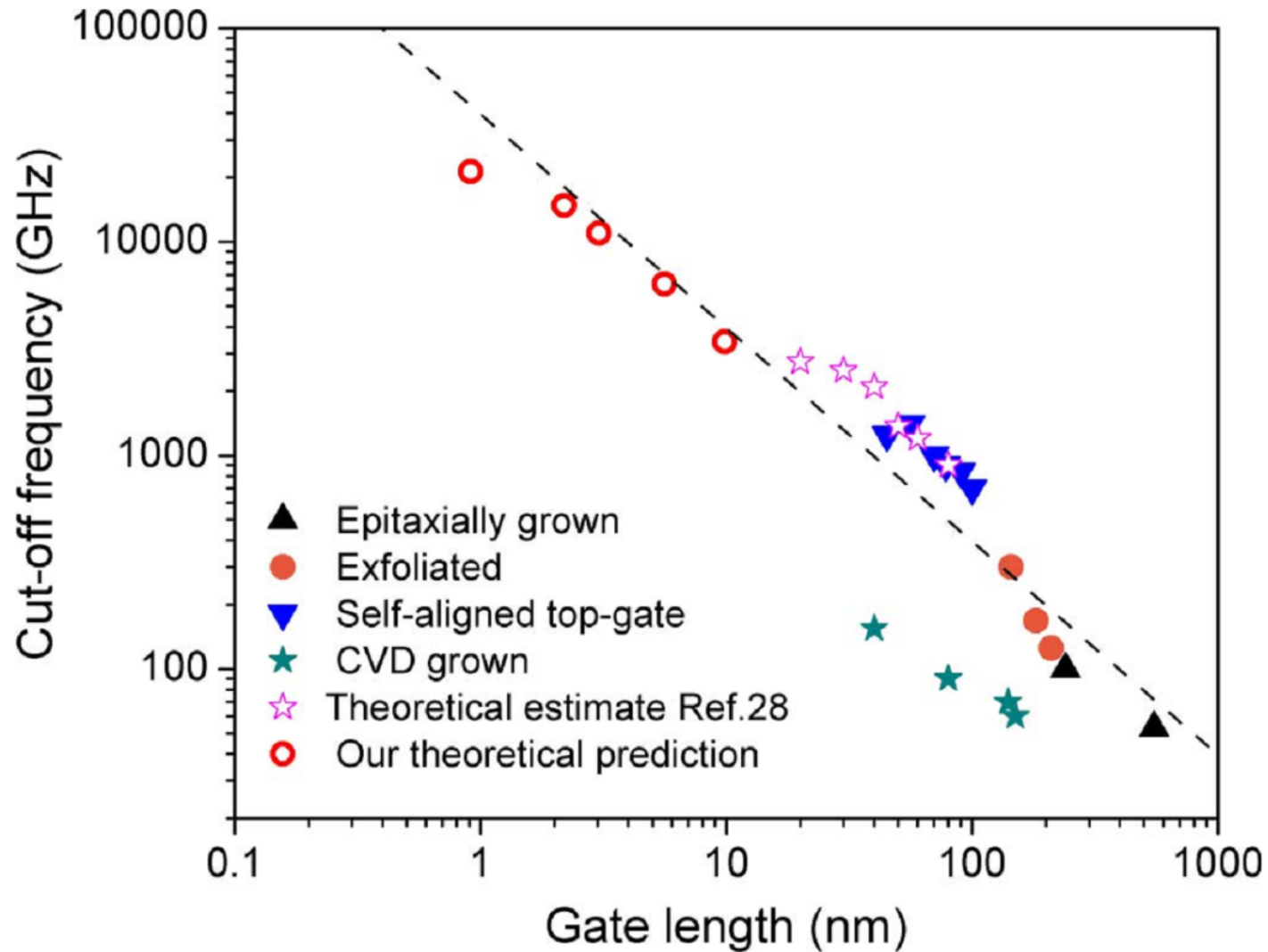
- From DC measurements: gate delay, energy delay product, subthreshold slope
- Large spread in results for CNTs
- Gate delay (CV/I) may be quite incorrect



CNT density and purity

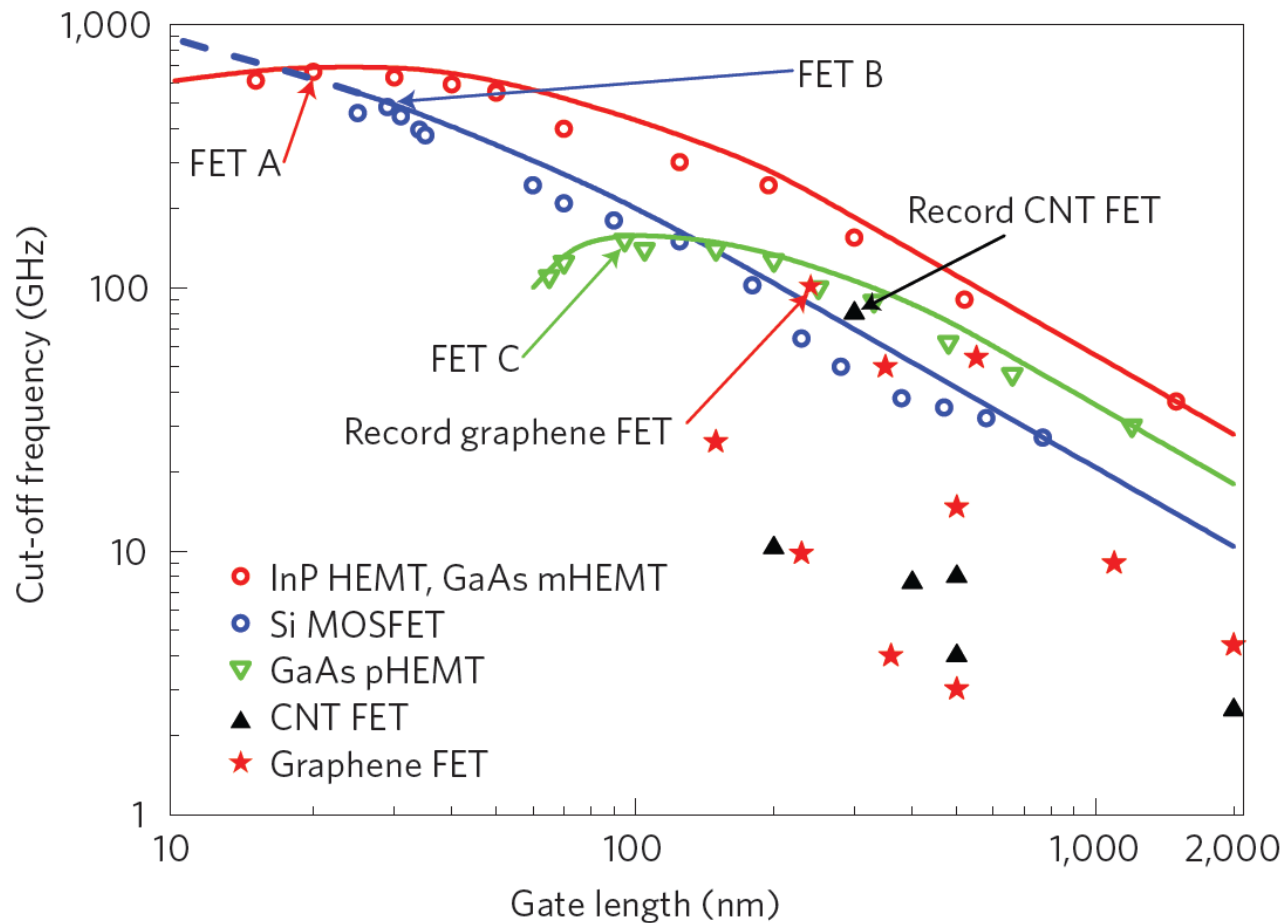


Graphene gate length scaling



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?

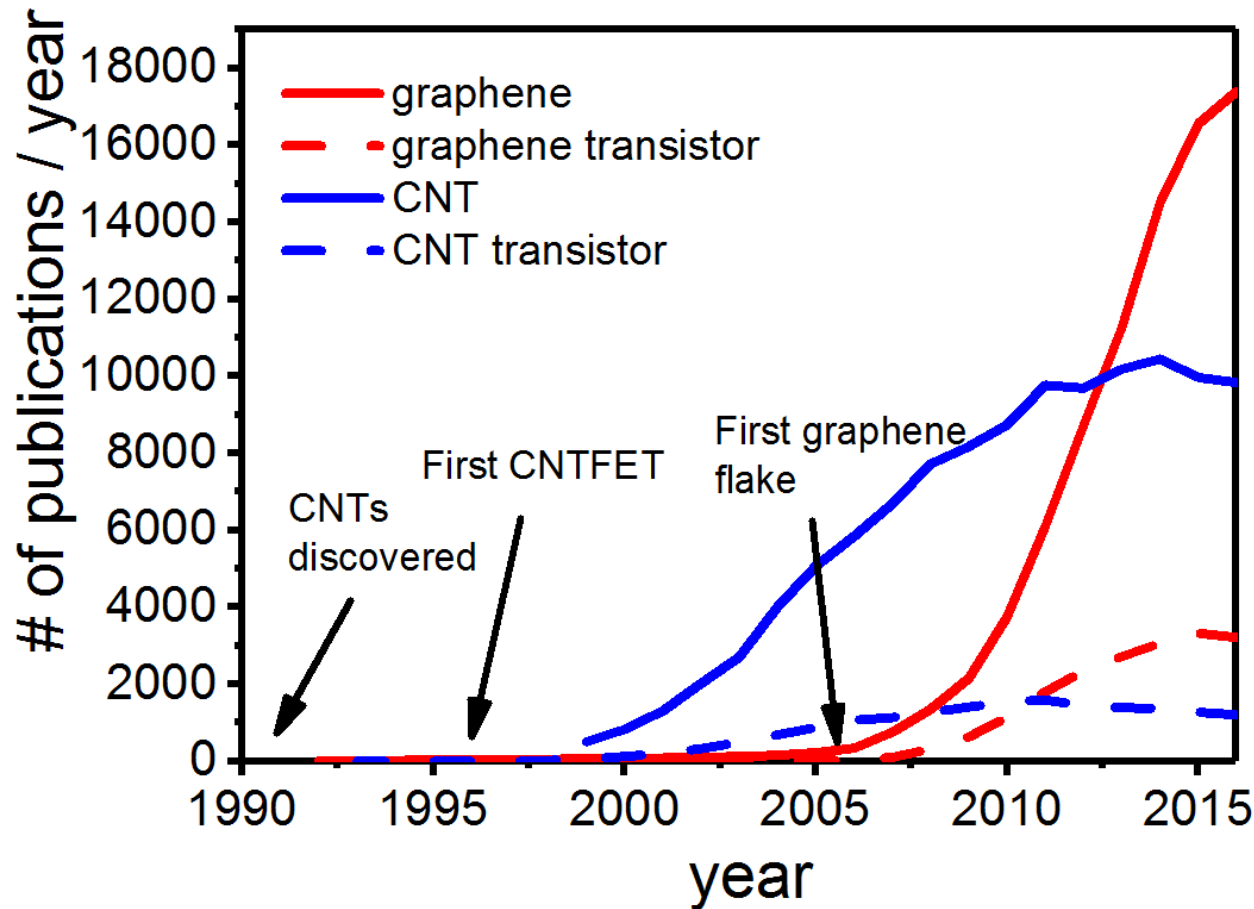
- + High mobility
- + High carrier velocity
- + High current density
- + Good electrostatics
- + Compatible with high-k dielectrics
- + Same electron/hole band structure
- + "cheap" starting materials

Why not?

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

Very active research

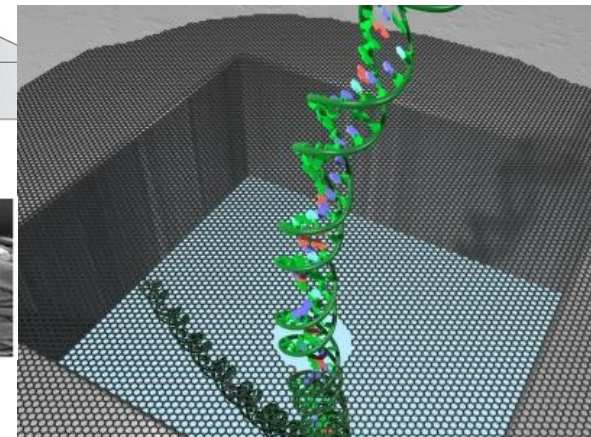
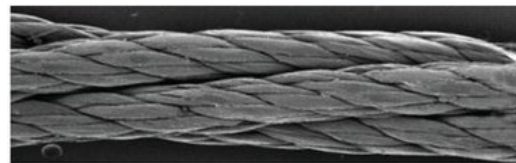
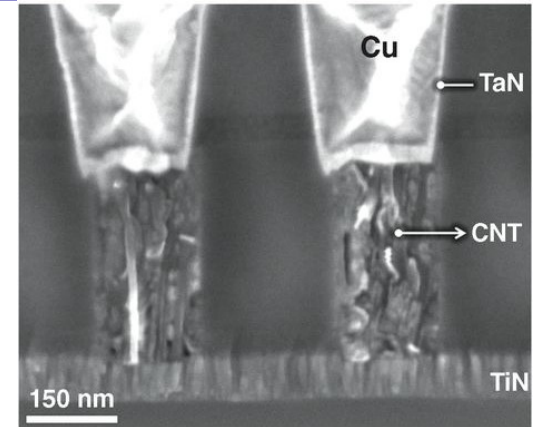
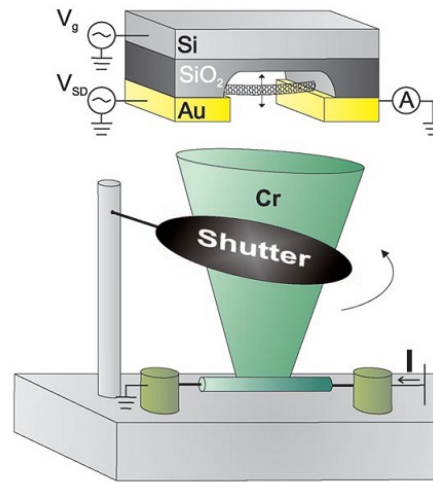
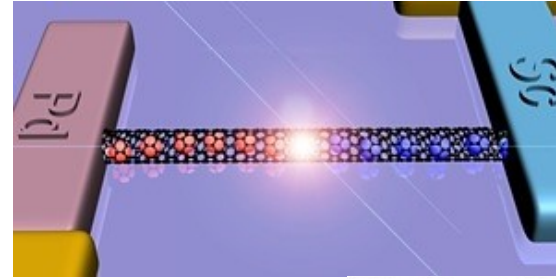
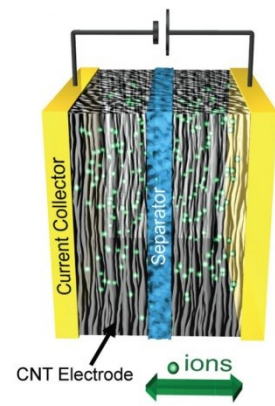
- Rapidly increasing # of publications
- Graphene > CNTs in 2011



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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

