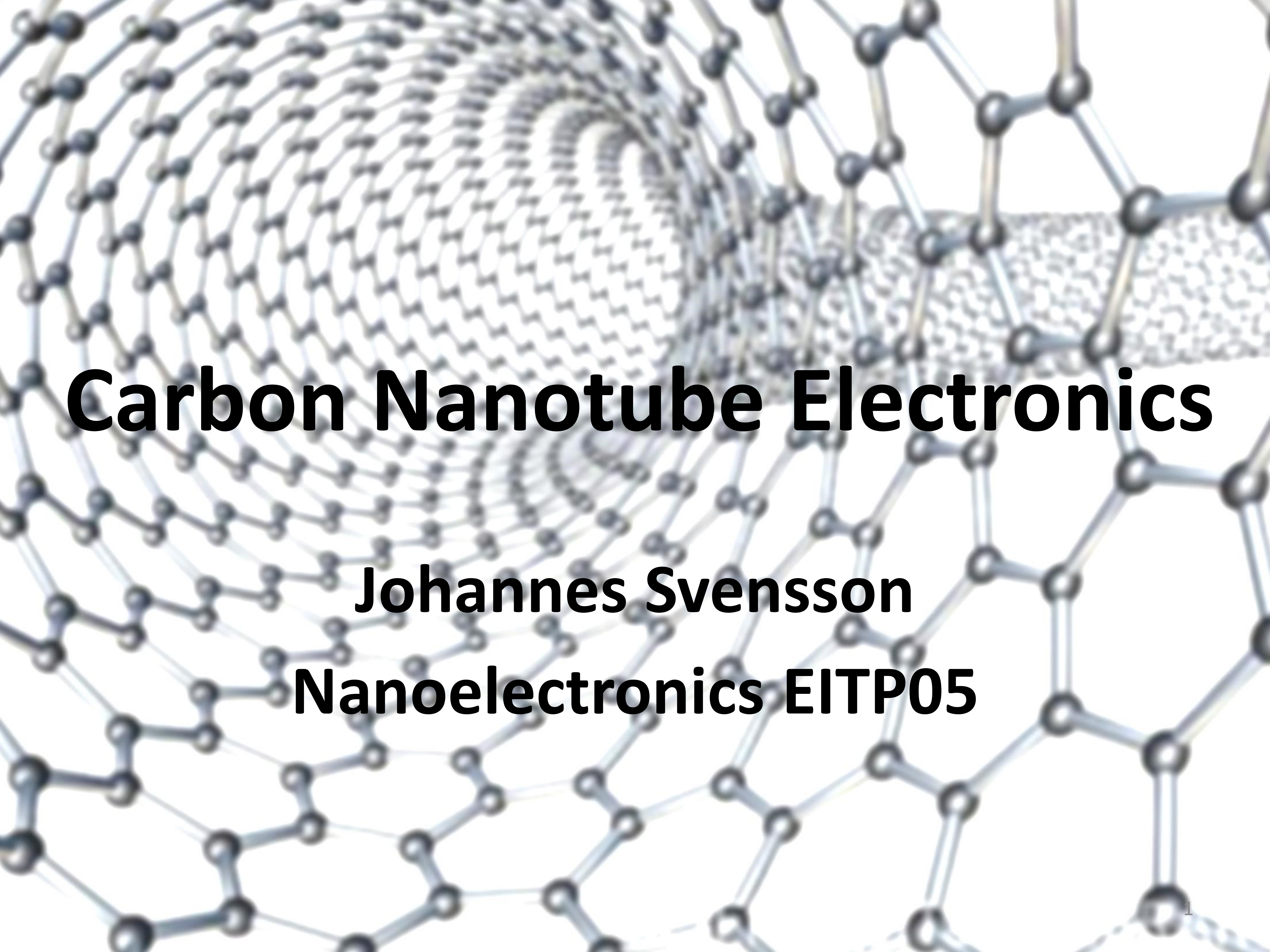

# Carbon Nanotube Electronics

## Johannes Svensson

## Nanoelectronics EITP05

# Outline

- Basics of graphene and CNTs
  - Structural
  - Electronic
  - Production of CNTs
- Advantages of CNTs for FETs
  - Electrostatics -> length scaling
  - High-k compatibility
  - Band-to-band tunneling
- Challenges of CNT integration
  - Contacts
  - Doping
  - Positioning
  - Chirality control
- Towards integration
  - Flexible electronics
  - High frequency performance

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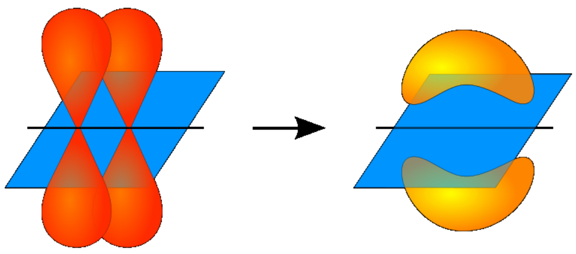
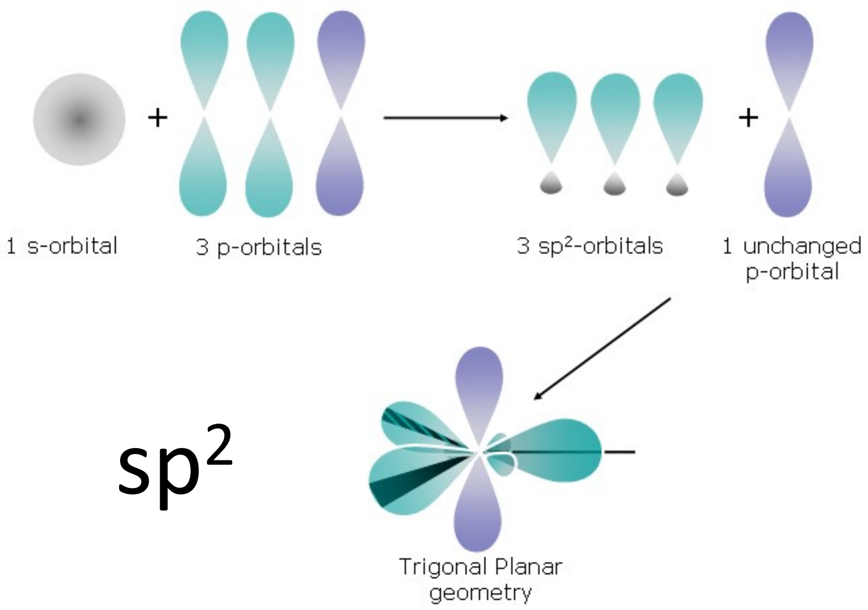
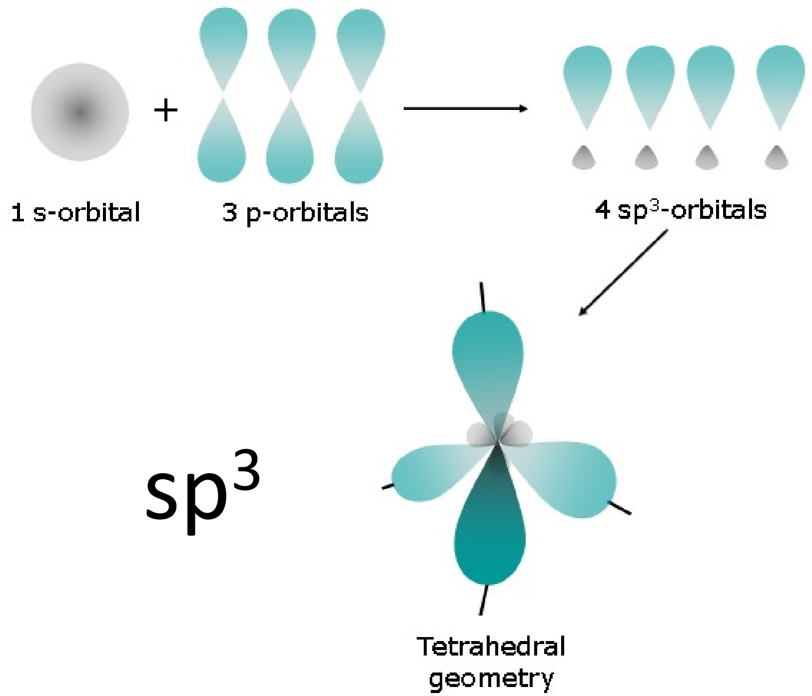
# Hybridisation of carbon orbitals

- 4 valence electrons
- 1 s-electron can ”mix” with 1-3 p-electrons
- $sp^2$ have three σ-bonds in a plane + π-bond
- $sp^3$ have four σ-bonds






sp²



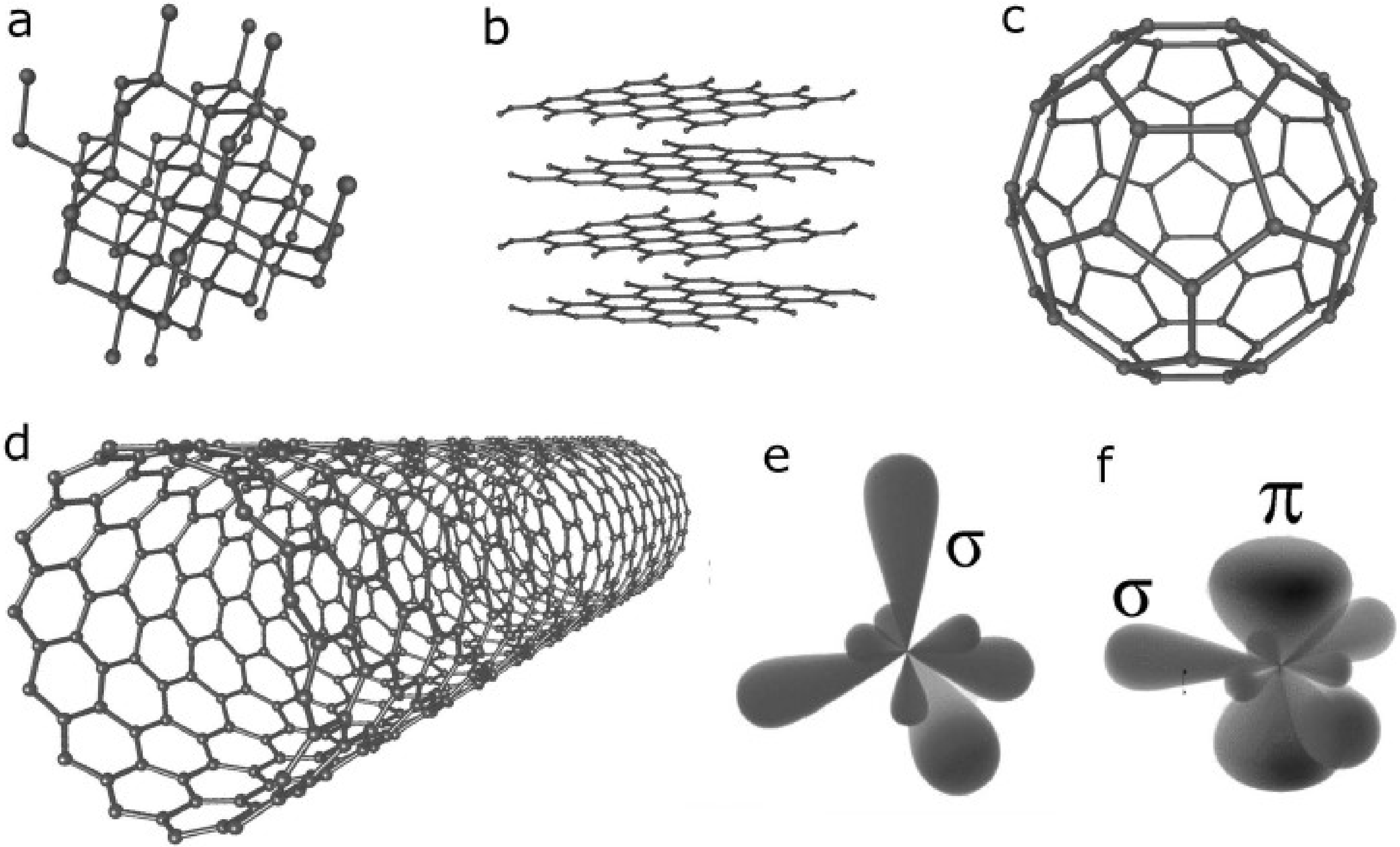

sp³

# Carbon allotropes

**diamond**

**graphite**

**$C_{60}$ (fullerene)**

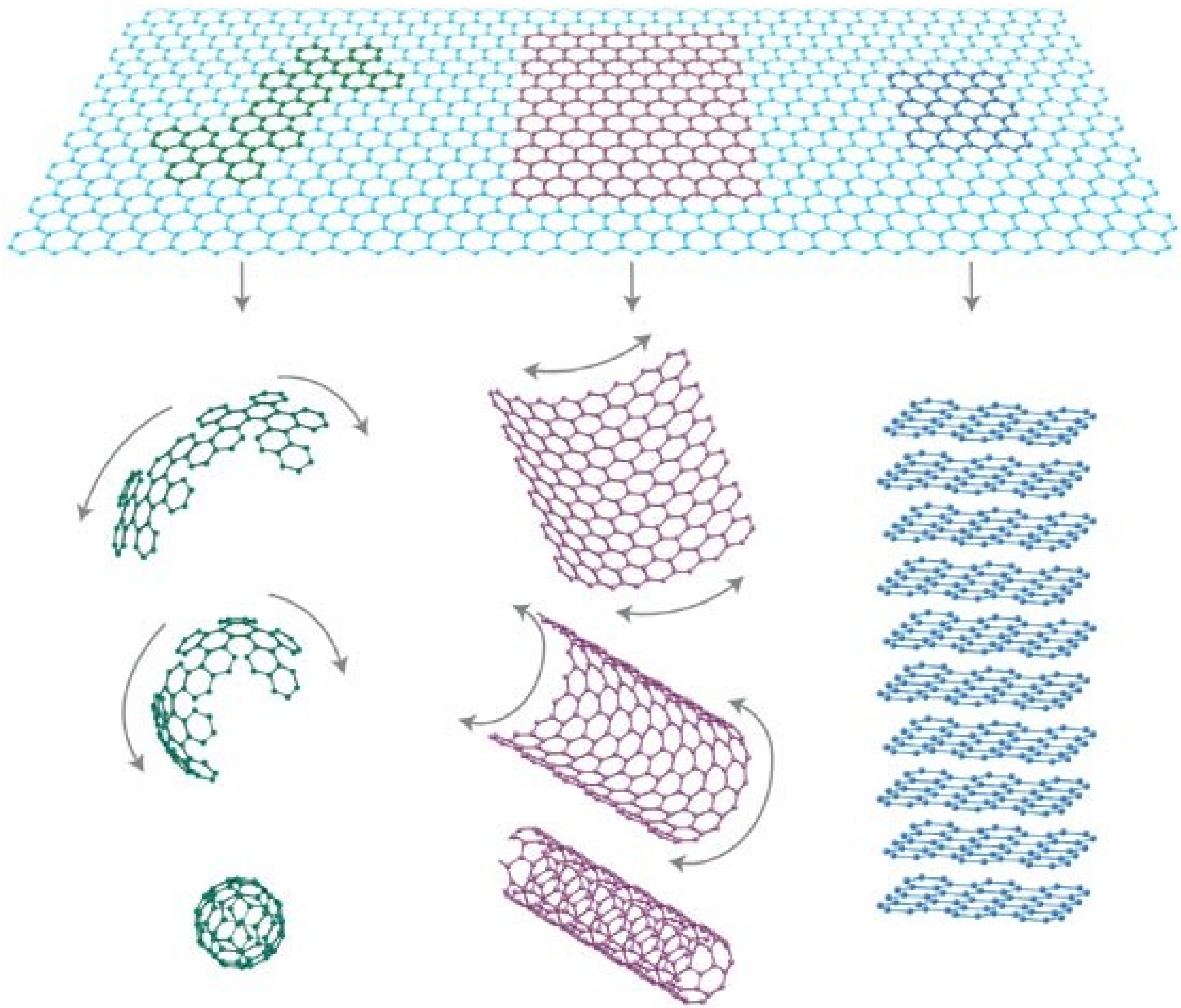



**Carbon nanotube**

**$sp^3$**

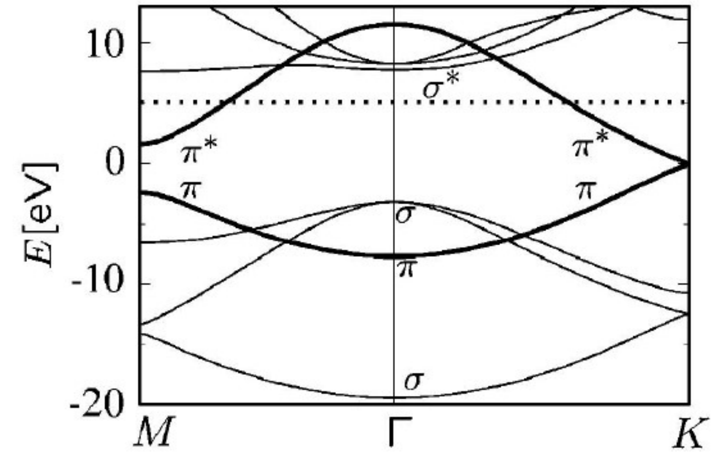
**$sp^2$**

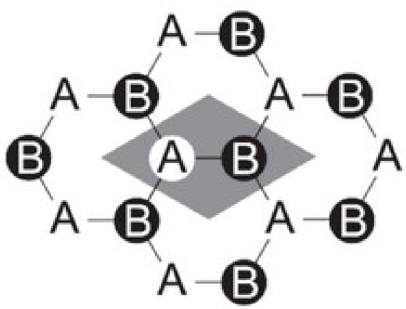
# Graphene is mother of all $sp^2$-carbon

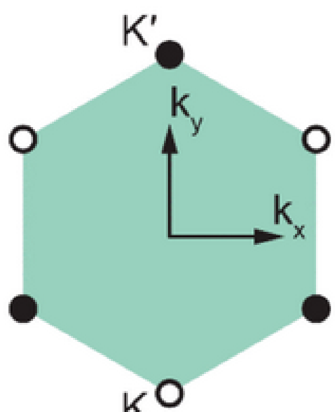


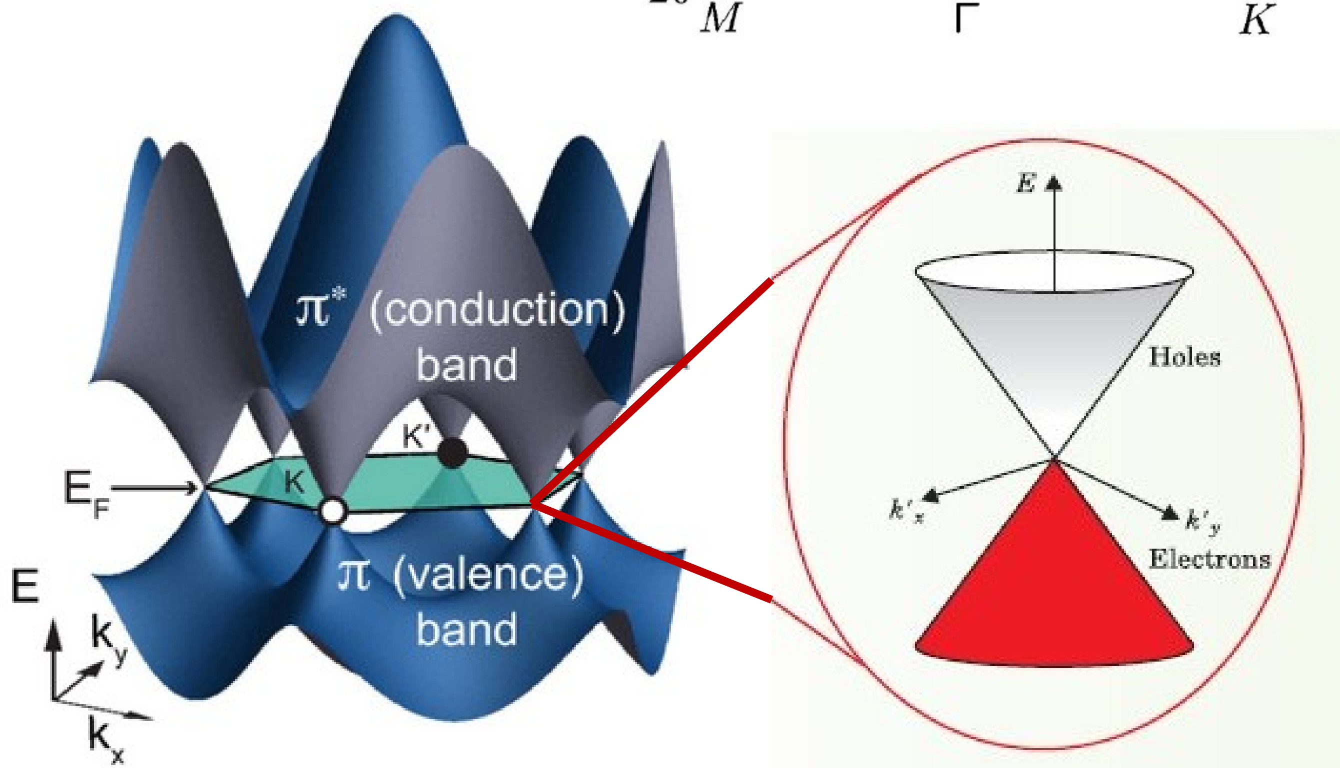
# Graphene band structure

- Semimetal: no band gap and zero DOS at $E_f$
- Only π-bands are relevant for transport
- Conduction and valence bands meet at the K/K'-points
- Linear dispersion near $E_f$



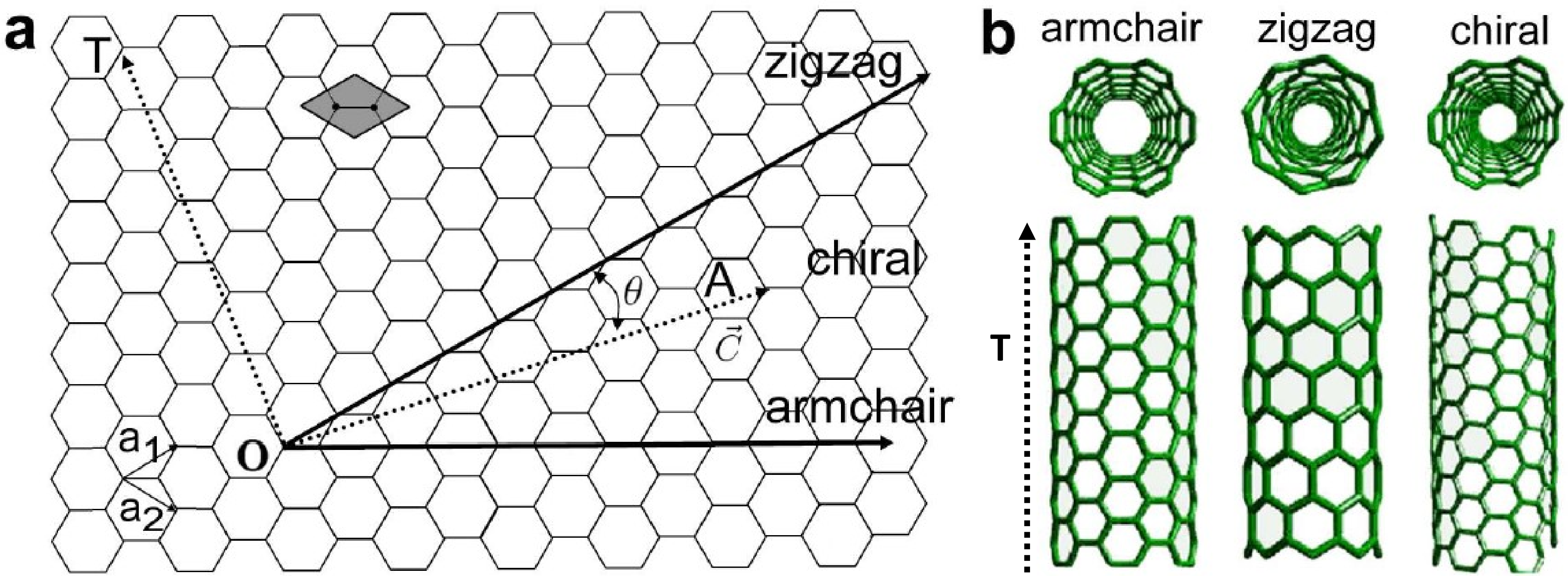



# Rolling graphene into CNT

- Cut graphene into narrow strip and roll into tube
- Different structure depending on direction of cut
- Armchair, zigzag, chiral CNTs
- Chirality defined by index (n,m)

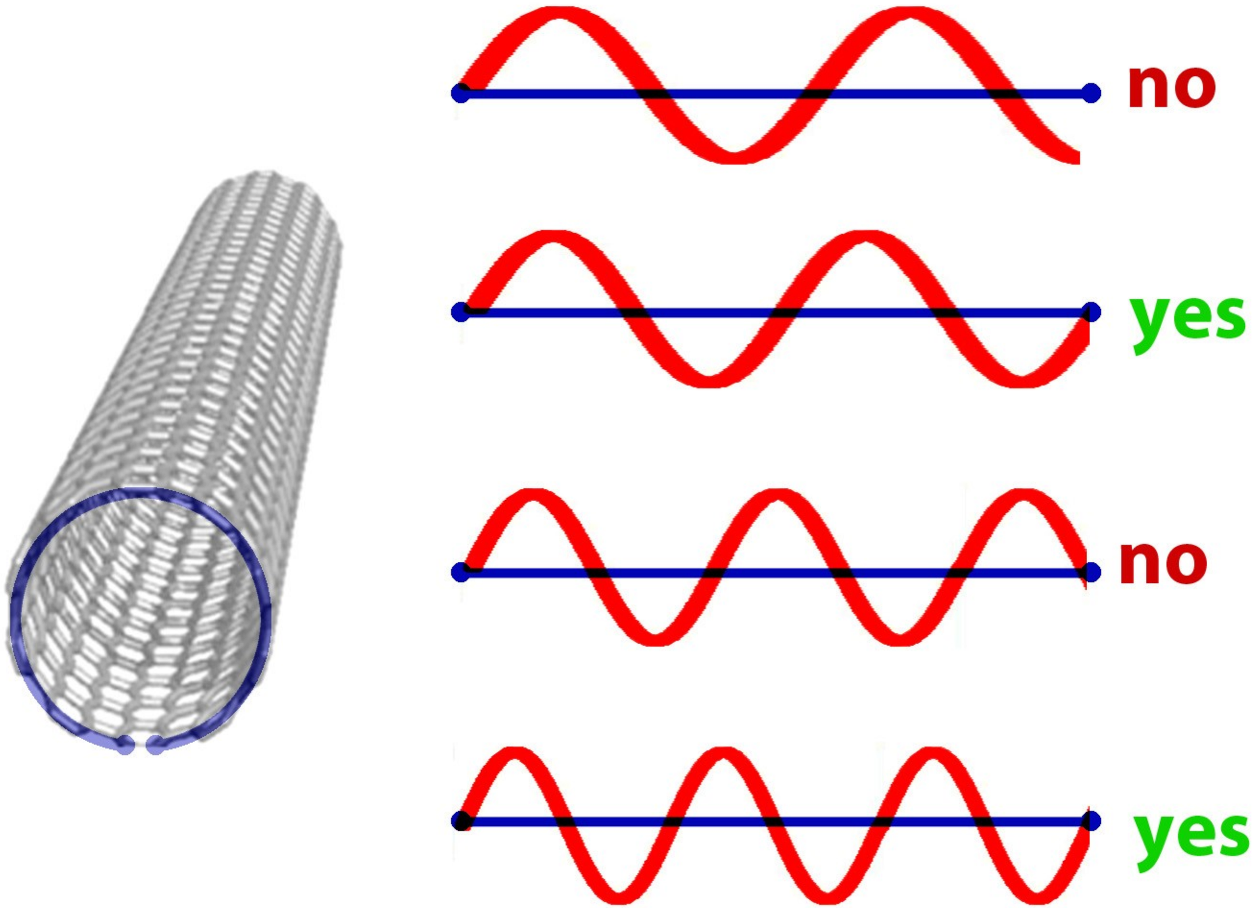
$$\vec{C} = n\vec{a}_1 + m\vec{a}_2$$

$n = m$ $\quad n = 0$



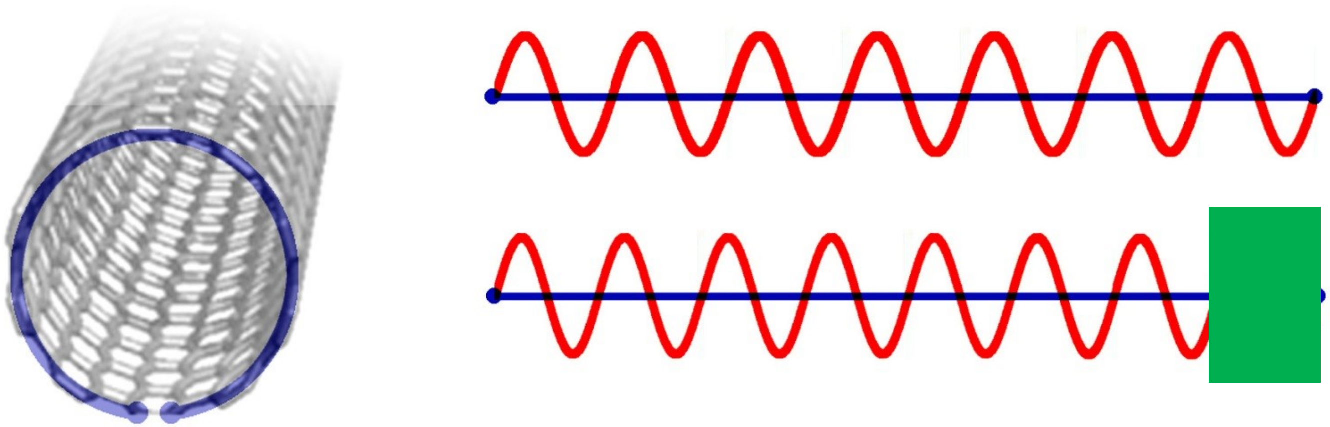
# Confinement of electron wavefunctions

- Have to have continous wavefunction around circumference
- Periodic boundary conditions
- Only some wavevectors $k_{\perp} = 2n\pi/C$ with n=1,2,3... allowed



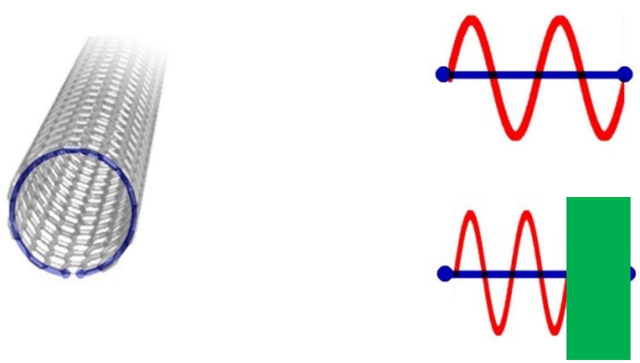
# Diameter dependence of confinement

large diameter = small energy difference



Next
allowed $k_\perp$

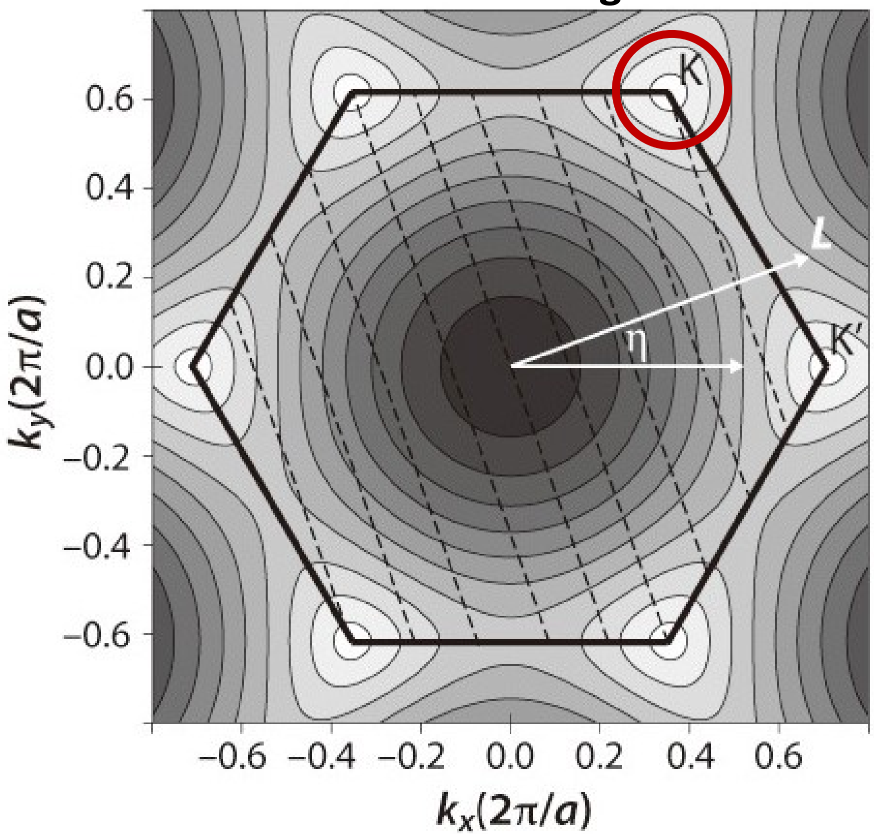
small diameter = large energy difference



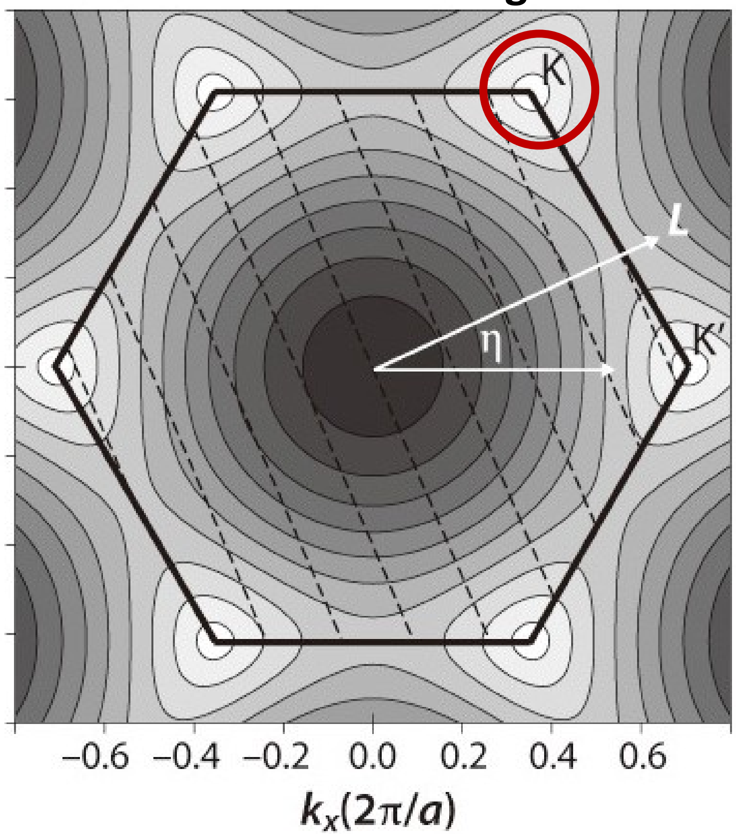
# Confinement of electron wavefunctions

- Slices in graphene dispersion relation of allowed wavevectors around circumference
- Position of slices depends on chirality
- Small diameter CNT have larger distance between slices

**Slice through K**



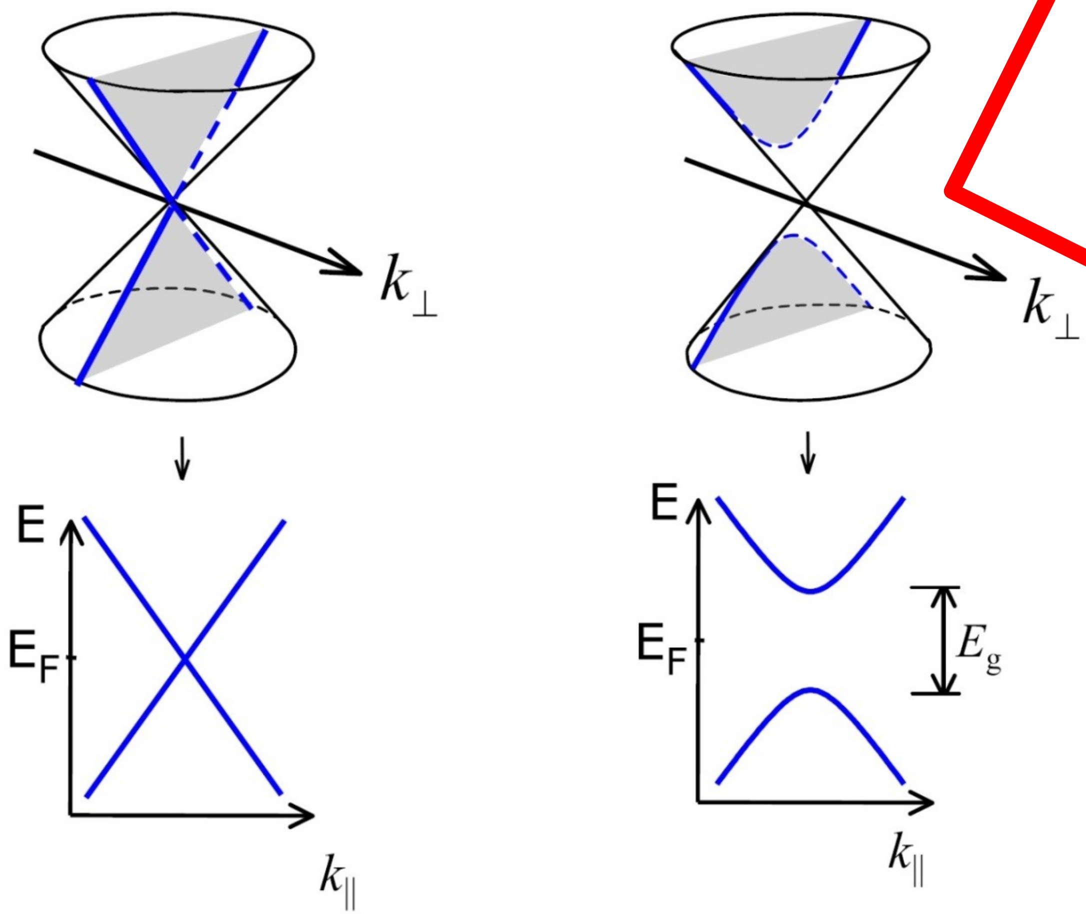

**Slice not through K**



# Allowed wavevectors

- n-m = 3i with i=1,2,3... -> slice goes through K-point -> metallic CNT
- n-m ≠ 3i -> slice does not go through K-point -> semiconducting CNT with parabolic bands

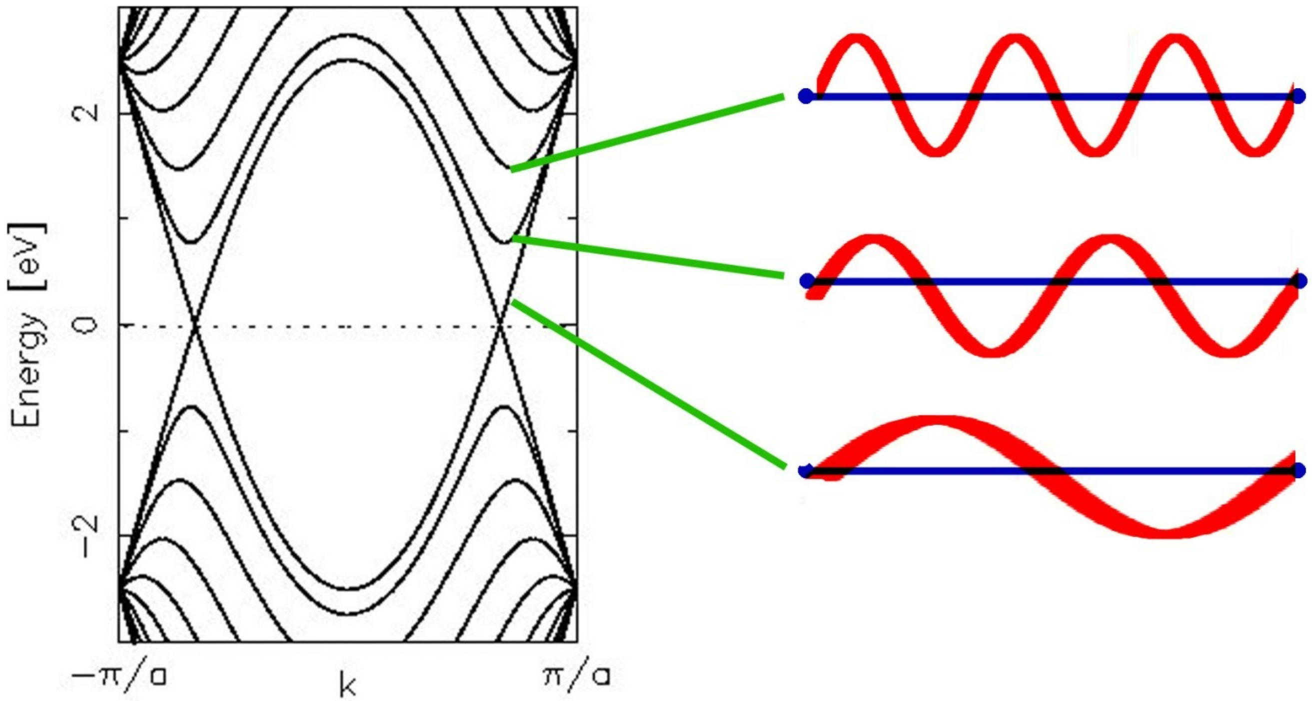
**Semiconducting or metallic only depending on structure**

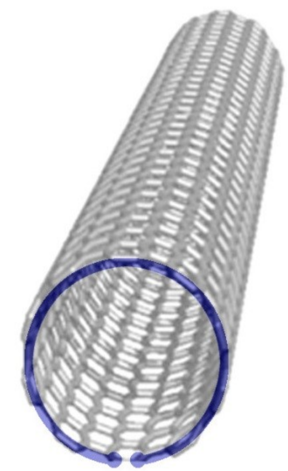



$$E(k) = \pm\left((\hbar v_F k)^2 + (E_g/2)^2\right)^{1/2}$$

# Subbands

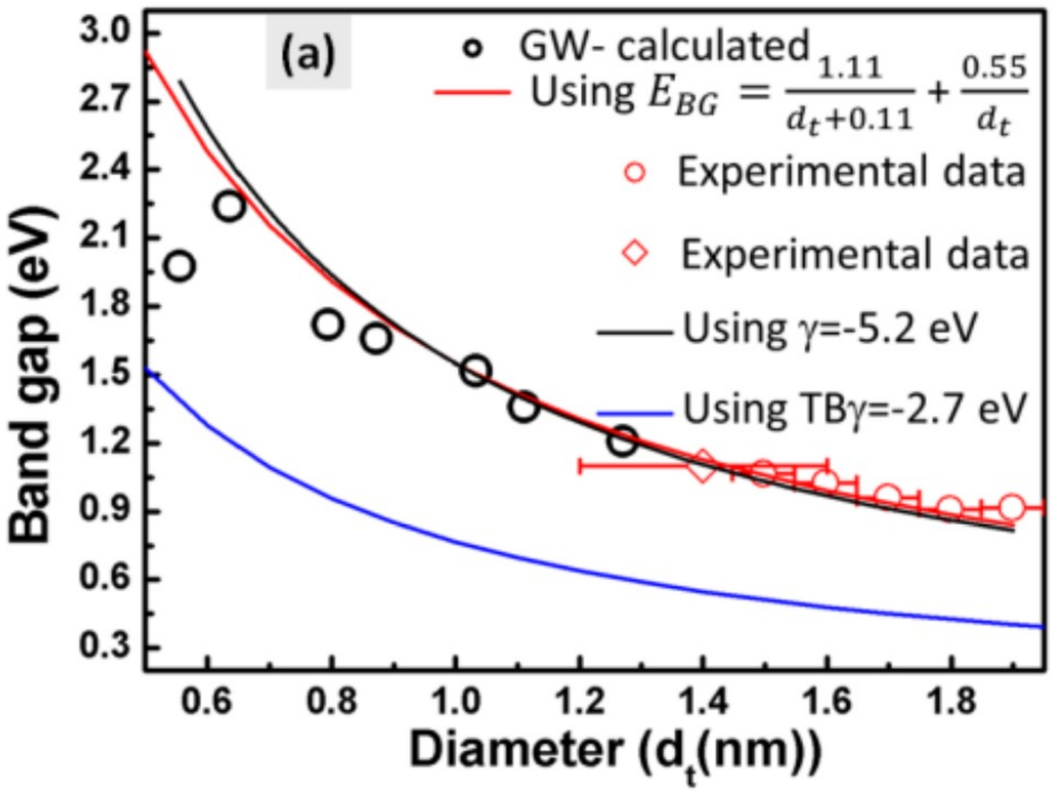
- π-bands split into 1D subbands of increasing energy
- Mainly important at high gate voltages or for optical transistions
- Wavefunctions just schematic, need TB calculation



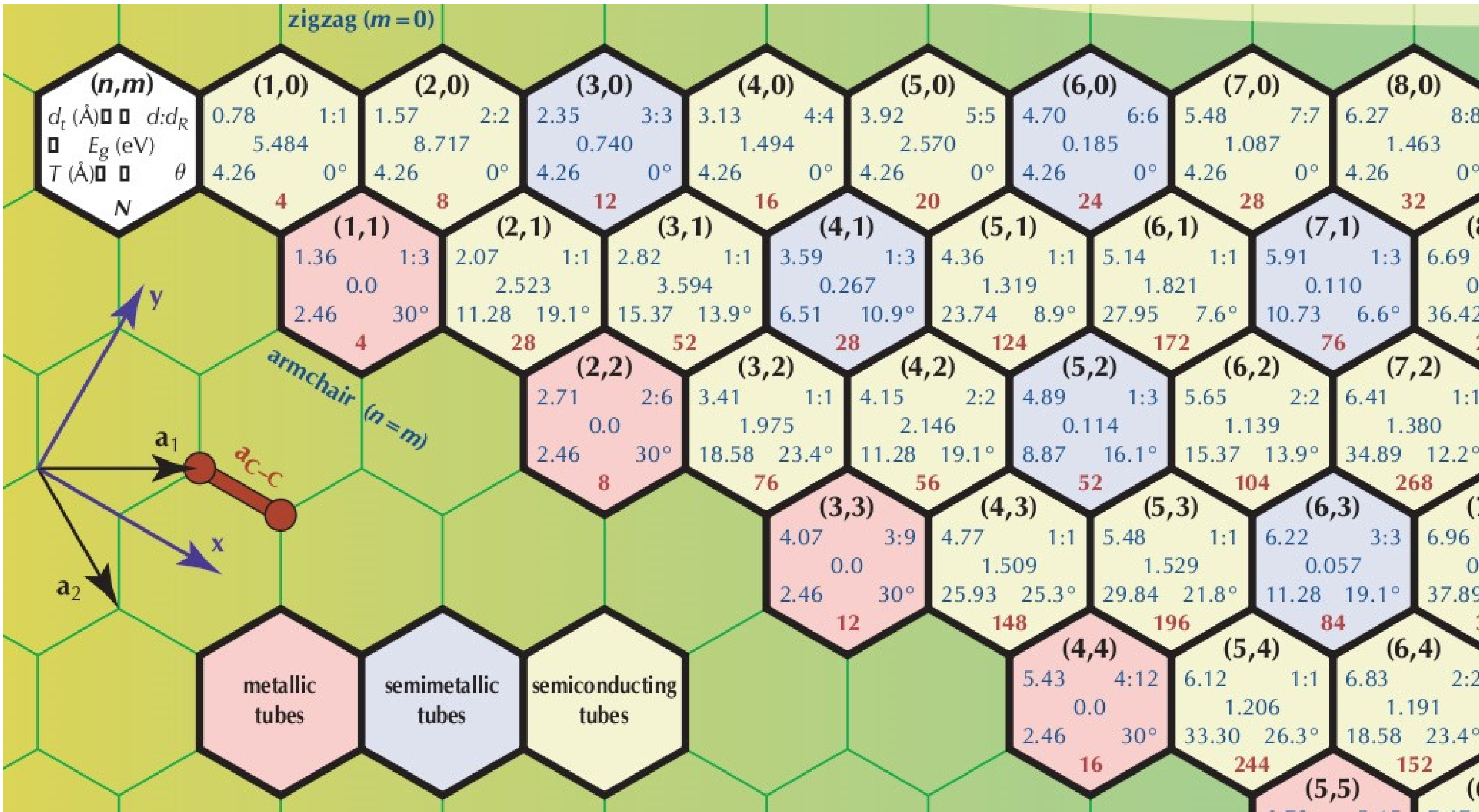
# Band gap vs diameter

- Linear dispersion of graphene gives $E_g$ inversely proportional to diameter for CNTs
- Curvature induced gap of 10's of meV in most of the "metallic" CNTs
- Only armchair CNTs truly metallic



# All CNTs are different

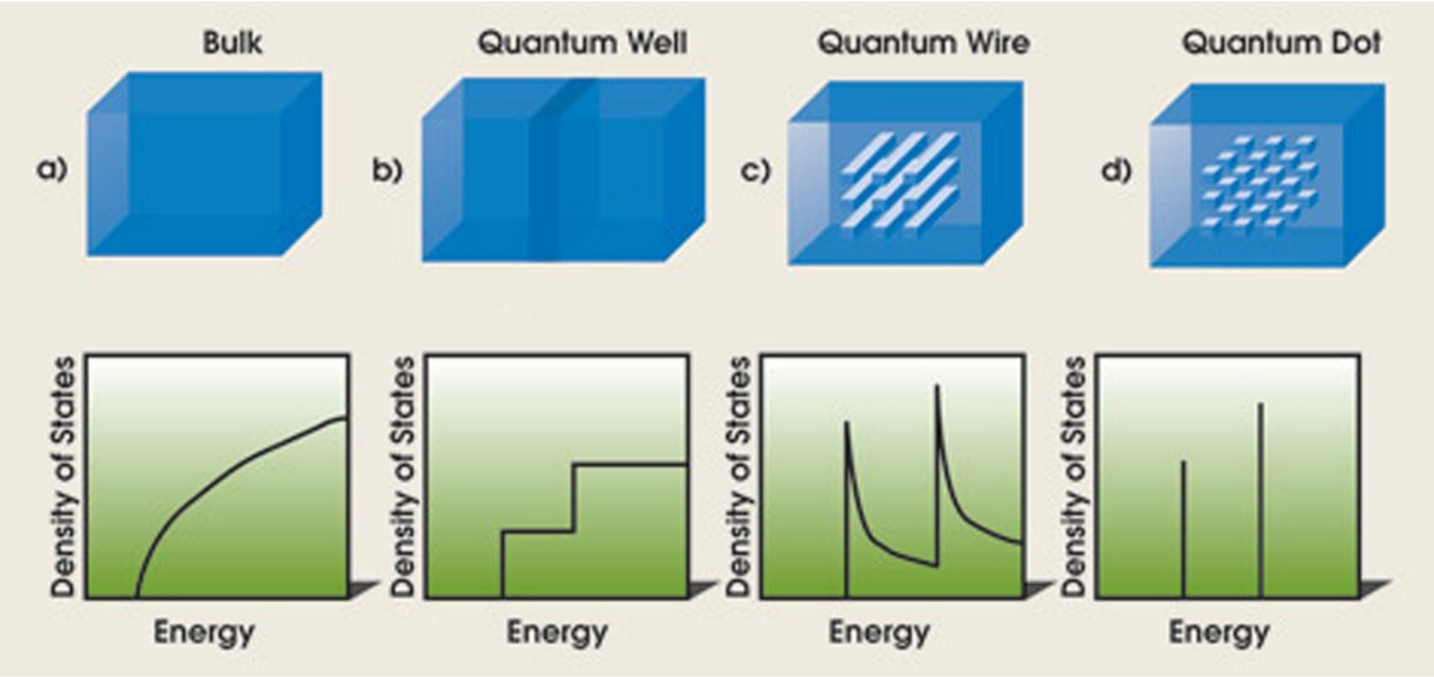
- 1/3 metallic or small gap
- 2/3 semiconducting with different gap

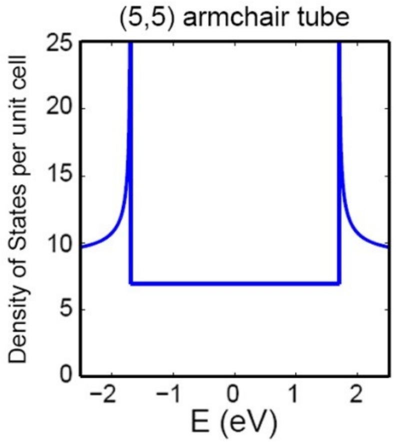


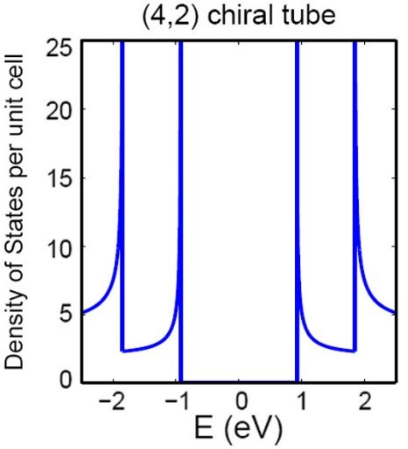
# Density of states

- Van Hove singularites with high DOS at band edges
- Can be seen in scanning tunneling microsope or capacitance measurements
- Strong influence on optical properties

$$g_i(E) = \frac{4}{\pi \hbar v_{\mathrm{F}}} \left[1 - (E_{\mathrm{g}}^i / 2E)^2\right]^{-1/2}$$

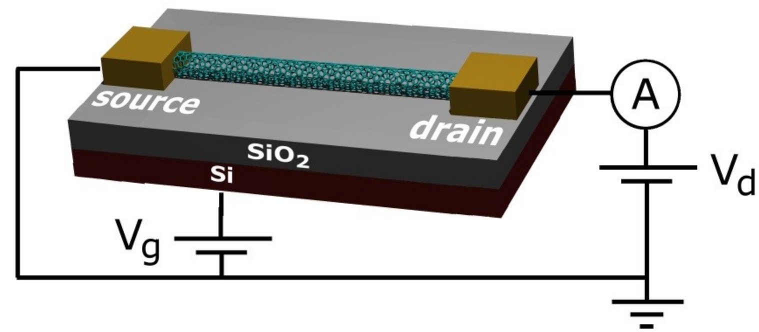


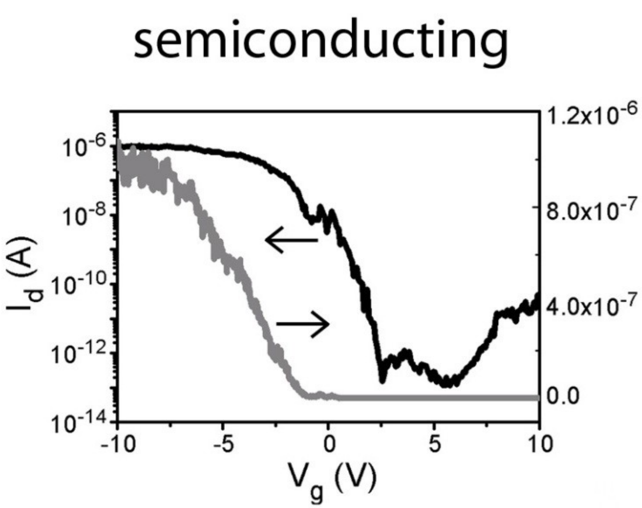



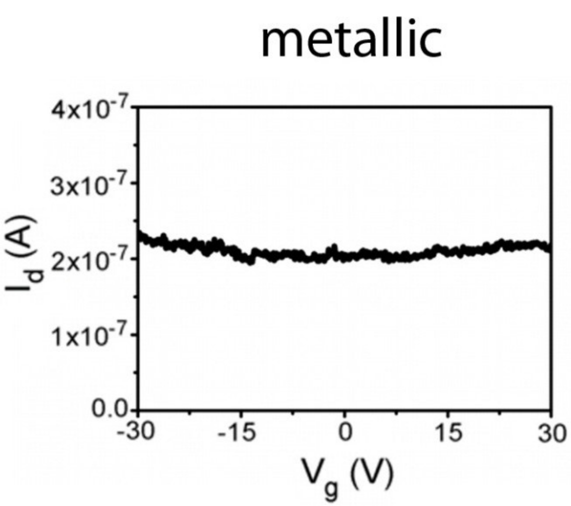
# Electrical characteristics

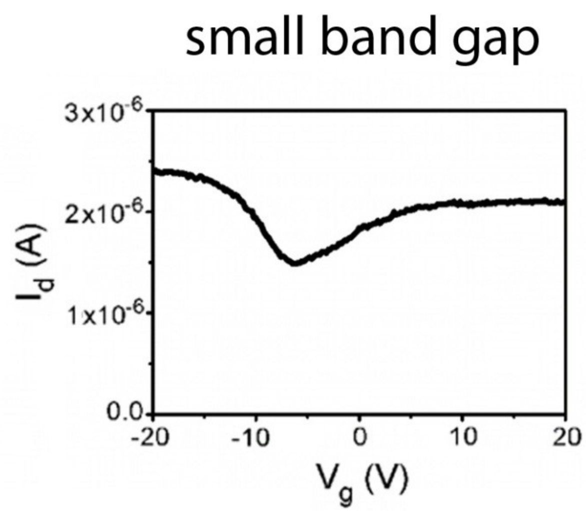
- Three types
  1. Semiconducting: strong gating effect
  2. Metallic: no gating effect
  3. Small gap semiconducting: some gating effect




- Can withstand $10^9$ A/cm$^2$

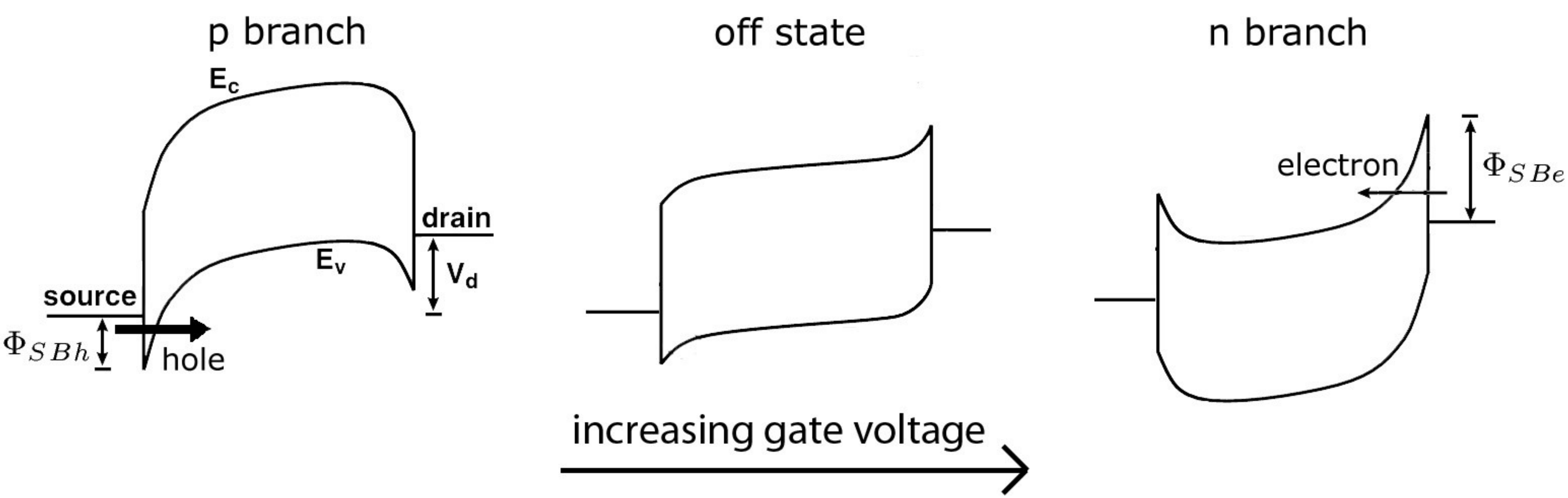


# Contacts influence conduction type

- First CNTFETs had Schottky barriers at metal contacts
- Tunneling through SB determines transport
- Negative gate voltages -> hole transport
- Positive gate voltages -> electron transport
- Similar SB heights -> ambipolar characteristics

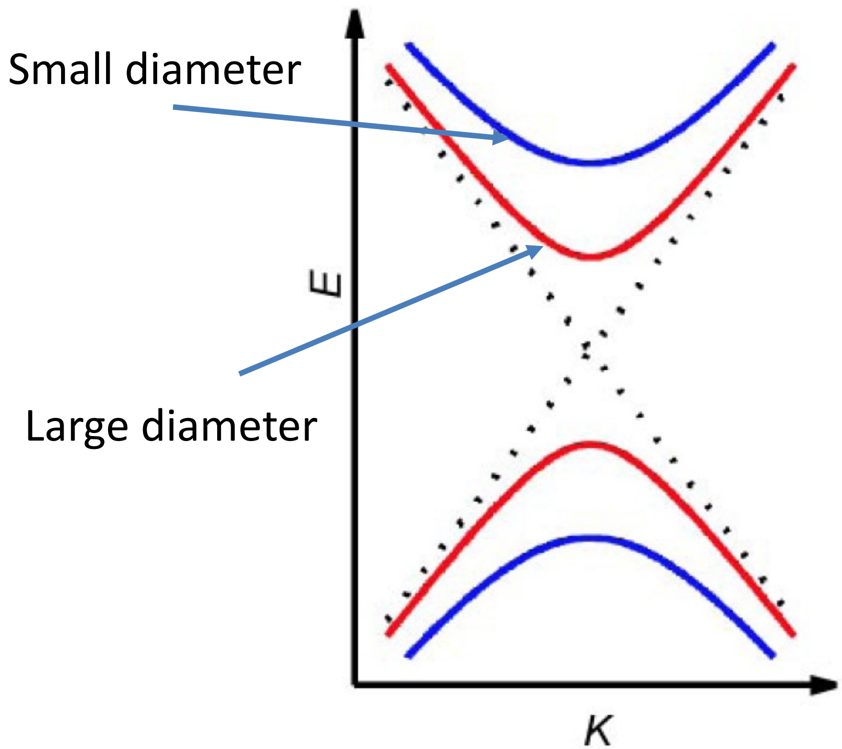


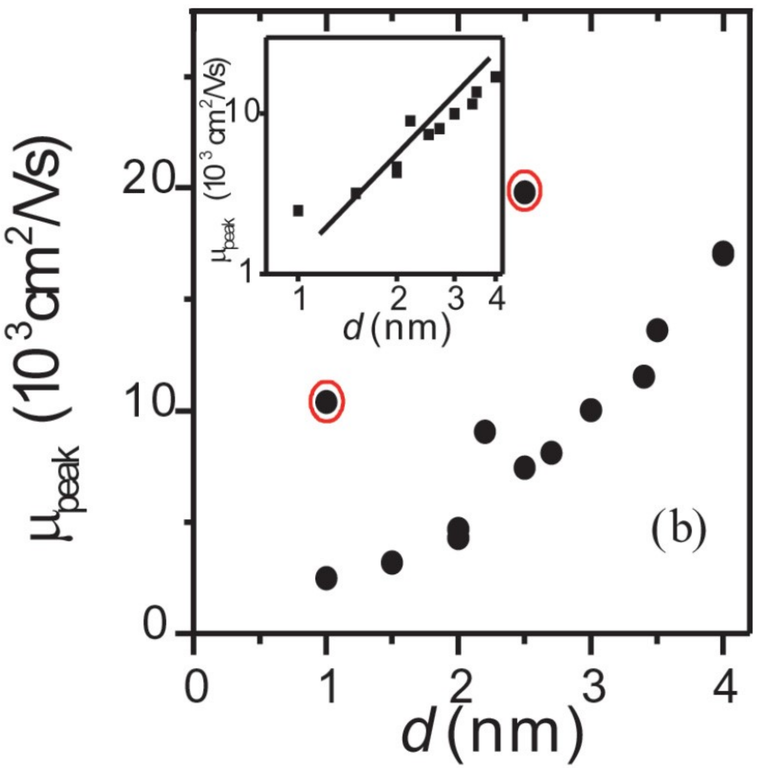
# Mobility vs diameter

- Lower curvature of bands for smaller diameter -> mobility proportional to $d^2$
- $\mu$ > 100 000 $cm^2/Vs$ at 50 K

$$m^* = \hbar^2 \cdot \left[\frac{d^2\varepsilon}{dk^2}\right]^{-1} .$$

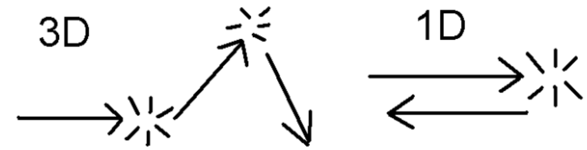
$$\mu_{FE} = \frac{L^2}{C_g}\frac{\partial G}{\partial V_g}$$



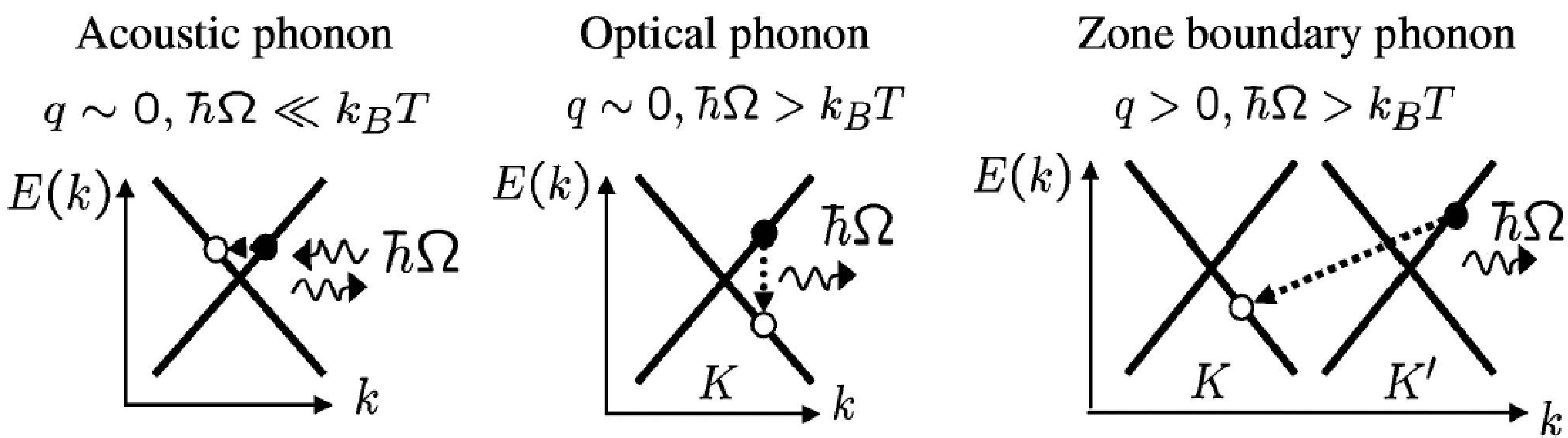



# Scattering

- Elastic scattering has to reverse direction of electron



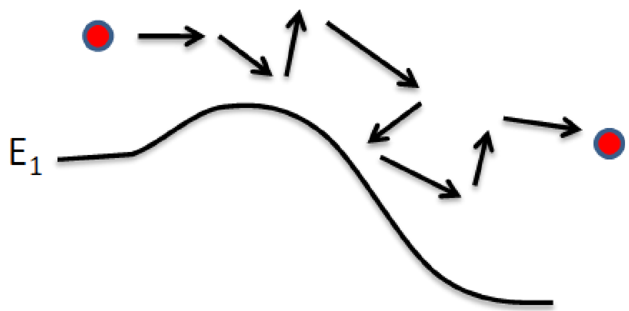

- Acoustic phonon scattering dominates at low bias and gives mfp > 300 nm -> ballistic transport possible
- Optical phonons scattering dominates only at high bias and gives mfp = 15 nm
- Potential variations or phonons in substrate under CNT can also scatter electrons



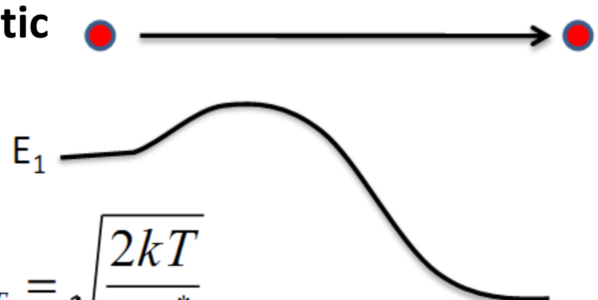
# Ballistic transport

- Channel length << mfp -> no scattering in channel
- Mobility not relevant but injection velocity is
- $R_{min} = h/4e^2 = 6.5$ kOhm in ballistic 1D system with 4 modes

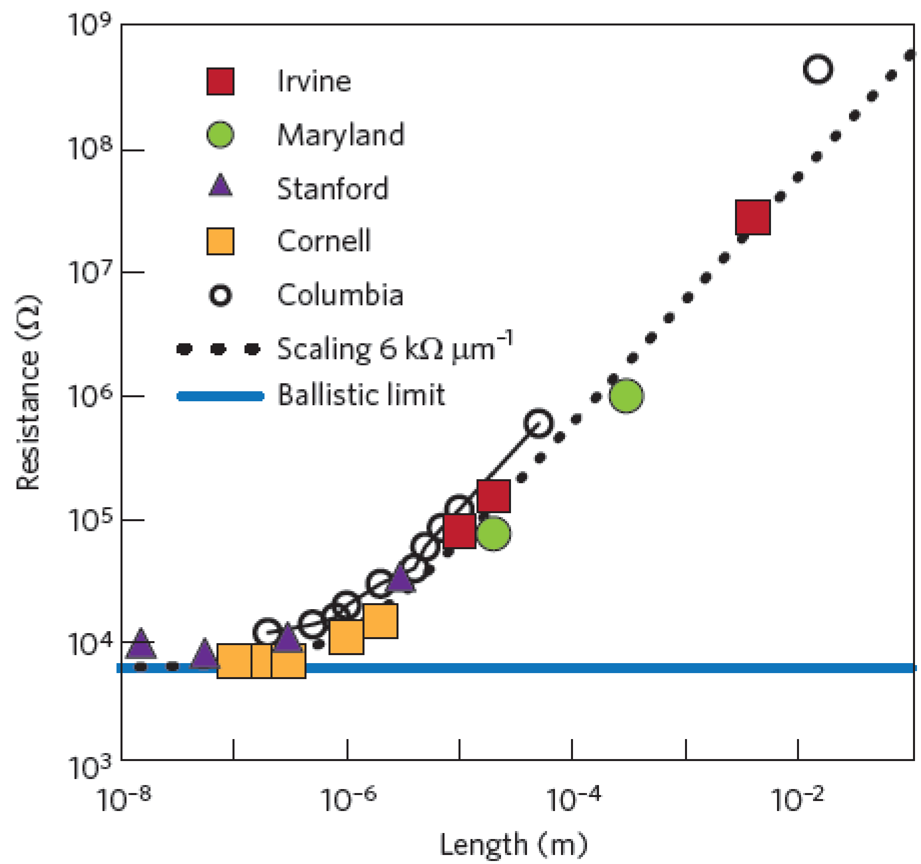
**Drift-diffusion**




**Ballistic**

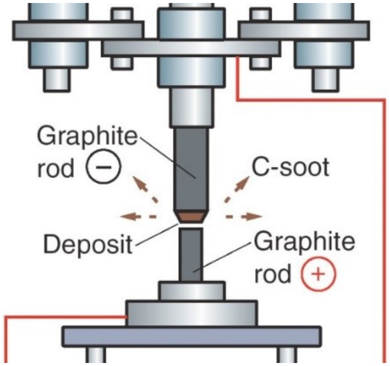



$$v_T = \sqrt{\frac{2kT}{\pi m^*}}$$

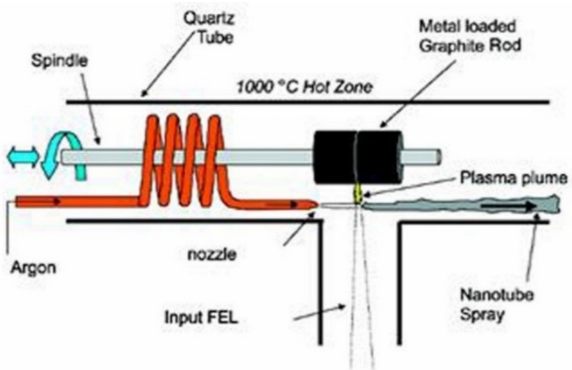


# Production of CNTs

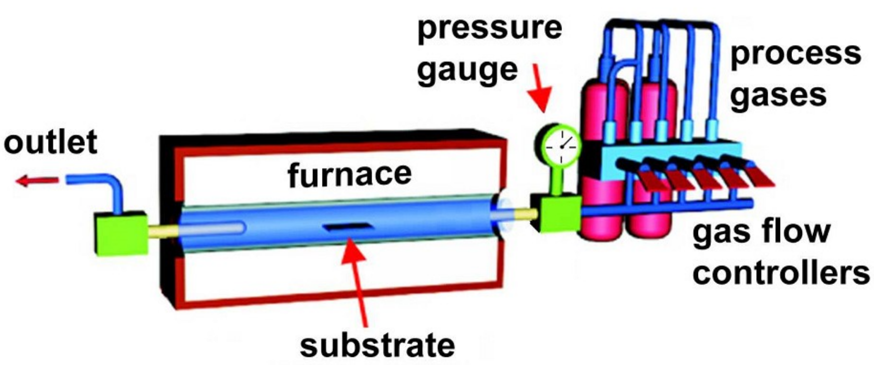
- Arc discharge: high voltage creates spark between graphite rods

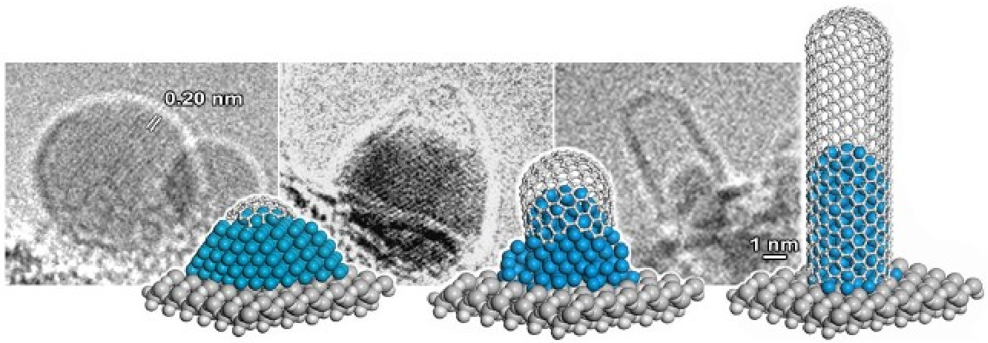



- Laser ablation: laser vaporises graphite target



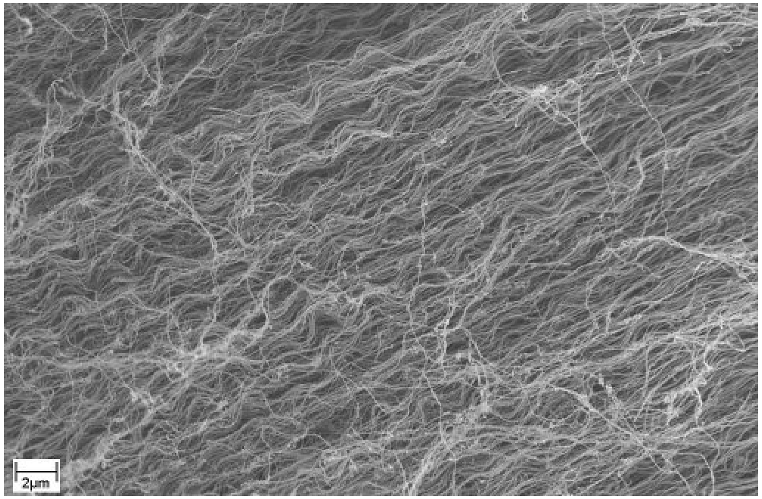

- Chemical vapor deposition: metal catalyst particles decompose hydrocarbon gas

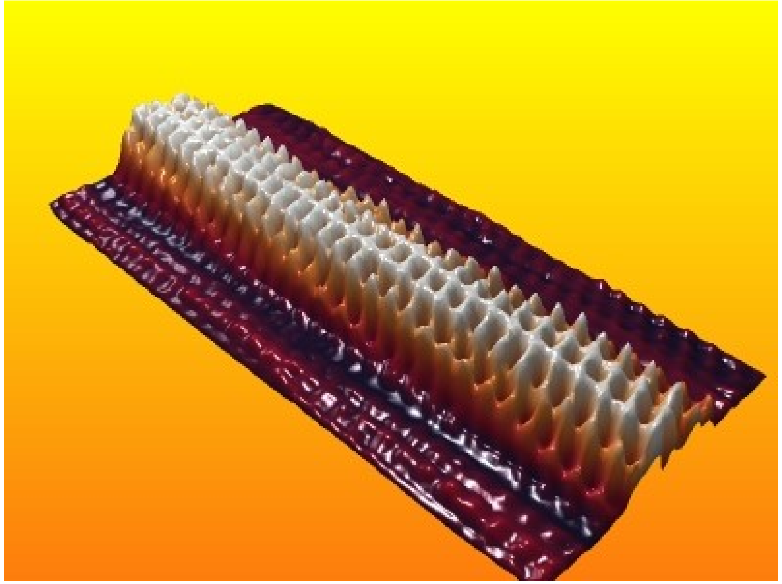


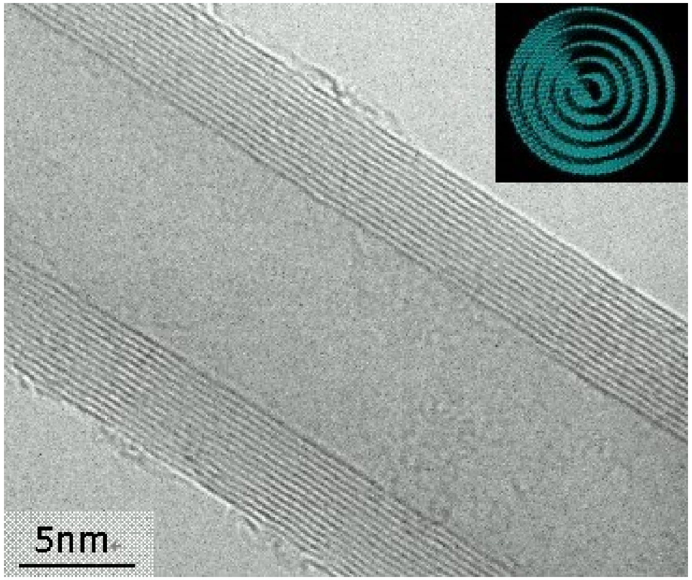



# Grown CNTs

- d=1-4 nm, L > 30 cm
- Can be imaged using SEM, TEM, AFM, STM
- Deposit from suspension or grow on device substrate
- Mix of metallic, semiconducting and small band gap semiconducting

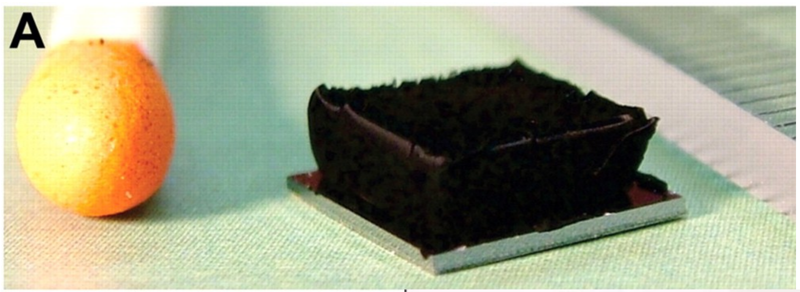


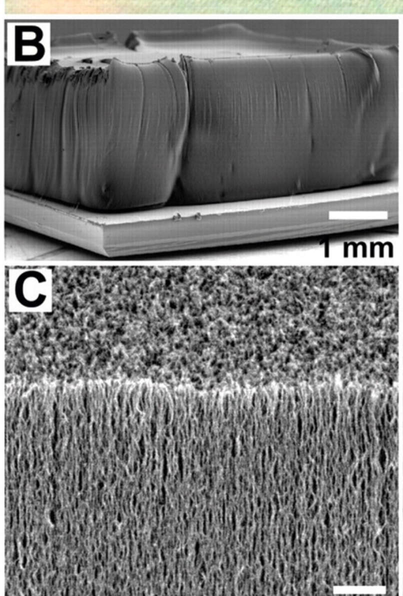





# VANTA black

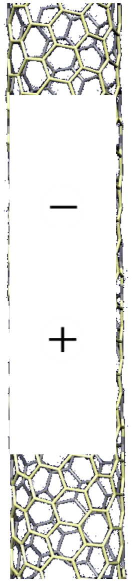
- **V**ertically **A**ligned **N**ano**T**ube **A**rray
- Absorbs 99.965% of visible light

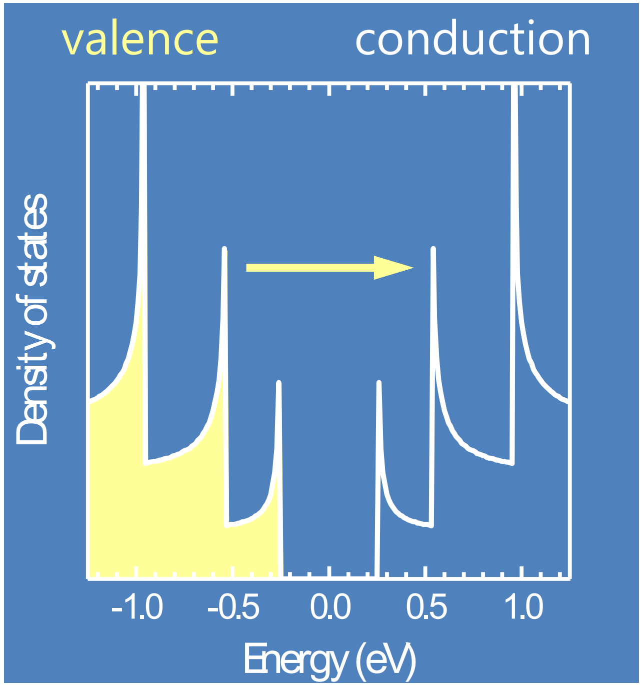


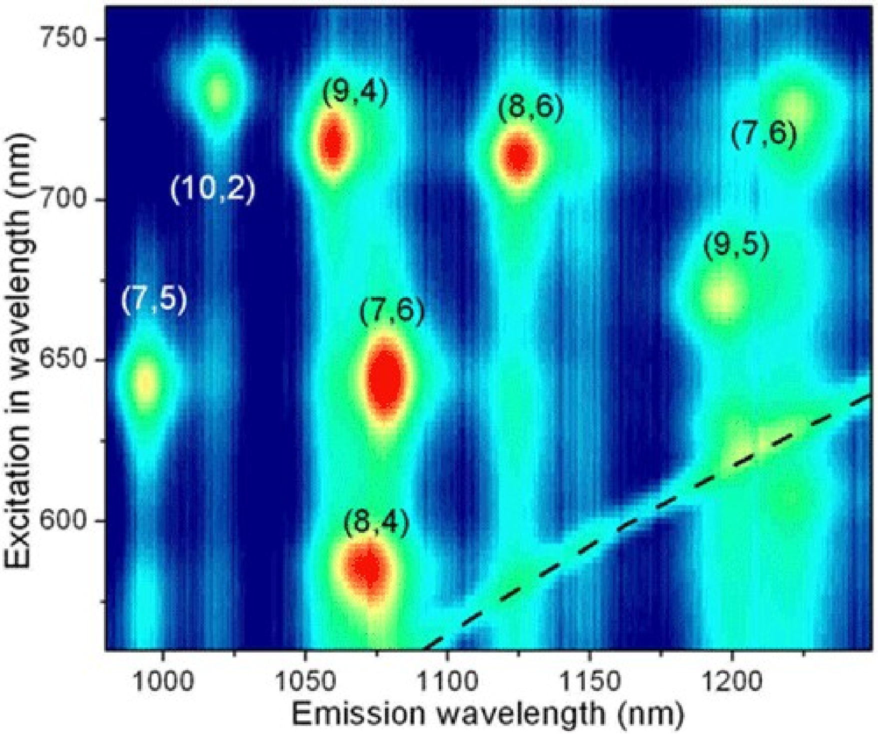




# Determination of type

- Photoluminescence with varying excitation λ
- Every (*n*,*m*) nanotube has specific pairs of transition energy



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# Gate length scaling

\+ Increased speed -> lower gate delay (CV/I), higher transconductance ($g_m$) and cut-off frequency ($f_T$)

\+ Reduced power consumption - > lower energy delay product ($CV/I \cdot CV^2$)

\+ Higher packing density -> less interconnect delay, cheaper

\- Short channel effects (drain potential influence the channel) -> poor subthreshold slope, DIBL, high output conductance ($g_d$).

ITRS 2015 - 3 nm node: $L_g$=10 nm, $L_c$=11 nm, spacer=4 nm -> footprint =40 nm

Need to reduce gate dielectric thickness, increase dielectric constant or change geometry.

# Different gate geometries

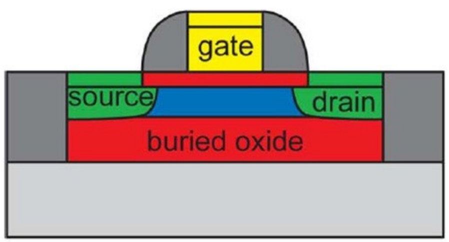
- $\lambda$ = screening length, reduced by higher gate dielectric constant or thinner channel

- $L_g > 5\lambda$ to avoid short channel effects

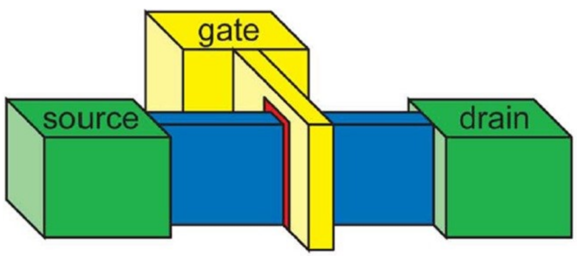
- More "wrapping" of the channel reduces $\lambda$ -> enables $L_g$ scaling

- CNTs and graphene allows for very good gate length scaling

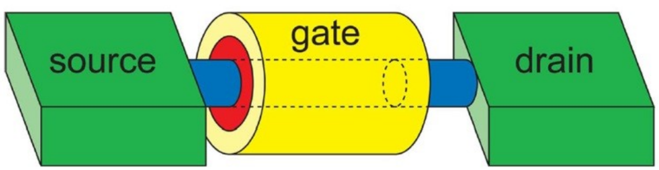
planar




trigate



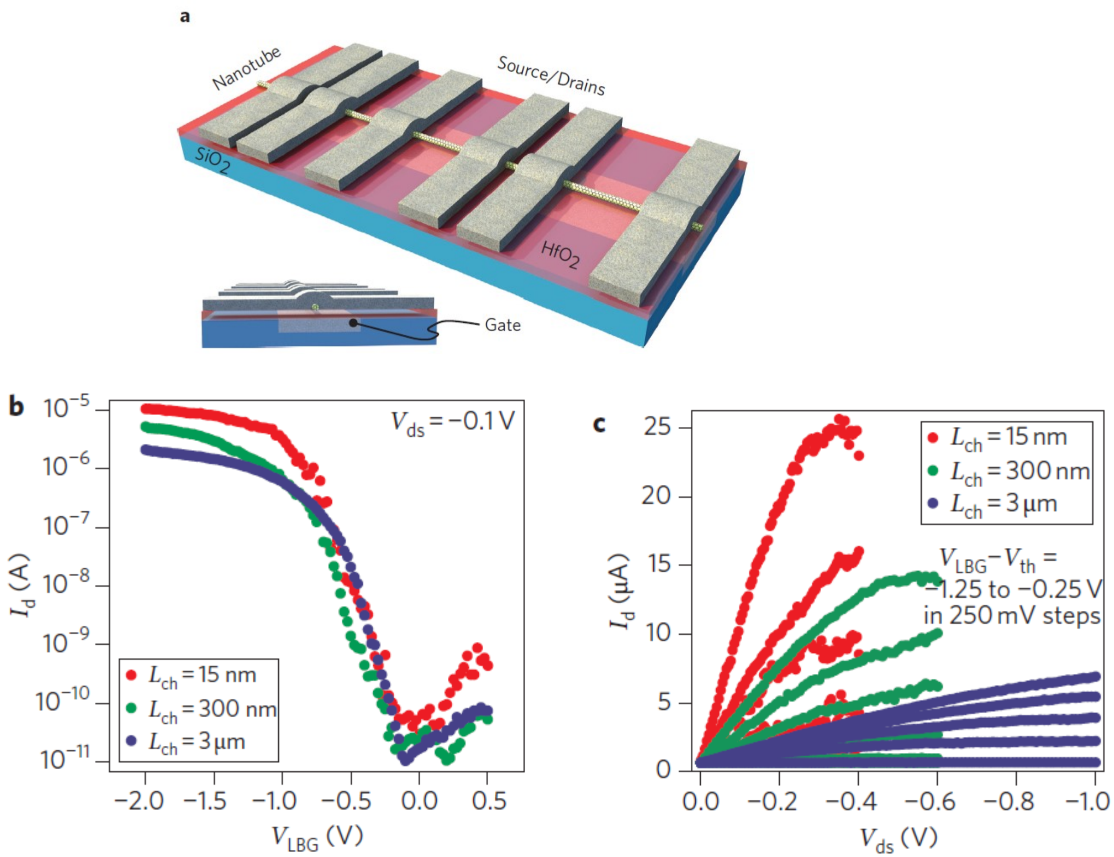

gate-all-around

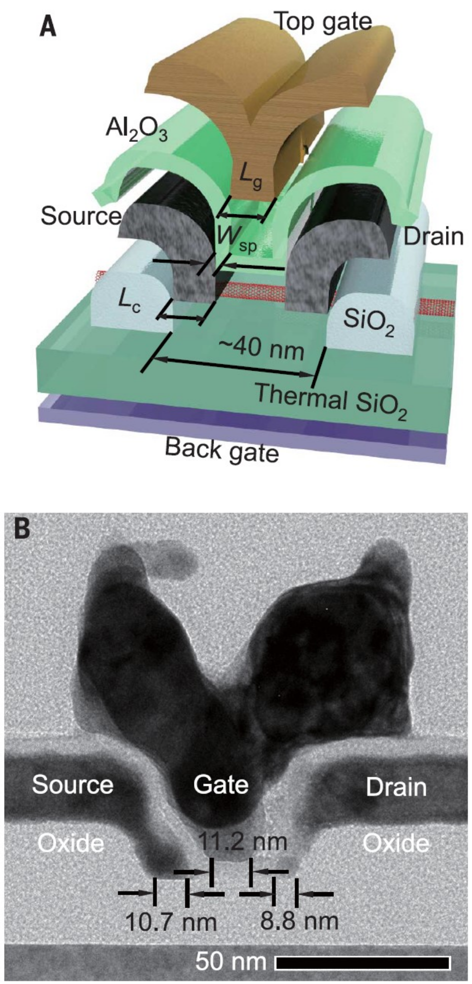



$$\lambda_1 \approx \sqrt{\frac{\varepsilon_{ch}}{\varepsilon_{ox}} t_{ox} t_{ch}} \quad > \quad \lambda \approx \sqrt{\frac{\varepsilon_{ch}}{2\varepsilon_{ox}} t_{ch} t_{ox} \left(1 + \frac{\varepsilon_{ox}}{4\varepsilon_{ch}} \frac{t_{ch}}{t_{ox}}\right)} \quad > \quad \lambda \approx \sqrt{\frac{\varepsilon_{ch}}{4\varepsilon_{ox}} t_{ch} t_{ox} \left(1 + \frac{\varepsilon_{ox}}{4\varepsilon_{ch}} \frac{t_{ch}}{t_{ox}}\right)}$$

# Gate length scaling

- No short channel effects (DIBL, SS degradation) down to $L_g$=15 nm
- $I_{on}$ = 0.9 mA/µm -> normalisation ?
- on/off ratio = $10^5$
- SS = 90 mV/dec also for short devices



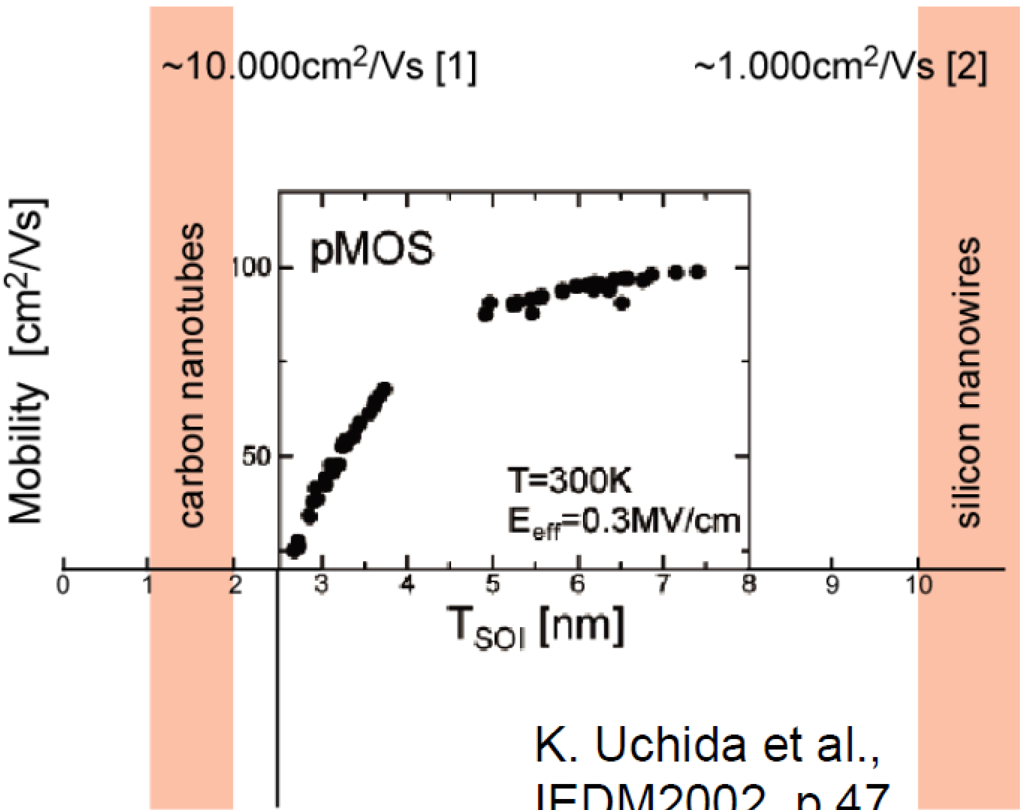



Franklin et al. *Nature Nanotechnol.* **5**, 858–862 (2010)

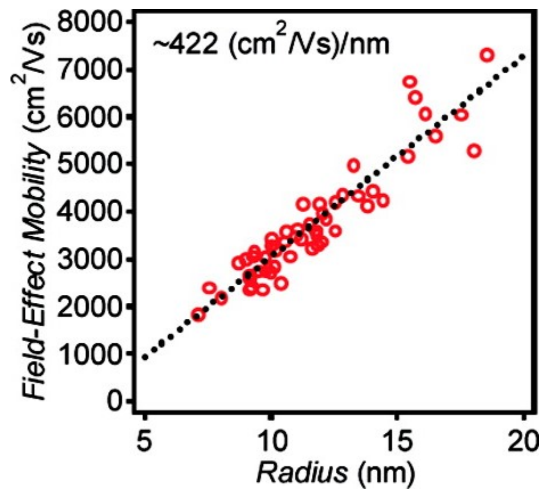
Cao et al., *Science* 356, 1369–1372 (2017)

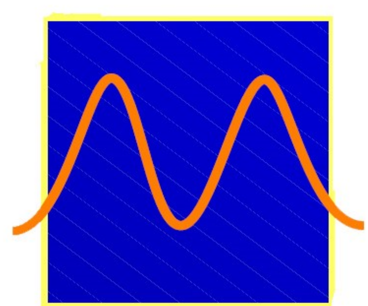
# Surface scattering

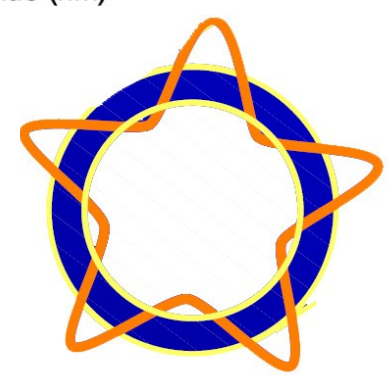
- Need to reduce channel thickness to be able to reduce $L_g$
- Surface roughness scattering gives $\mu \sim t^6$ for SOI MOSFETs
- Not a problem for CNTs – no unsaturated bonds / no roughness




K. Uchida et al., IEDM2002, p.47

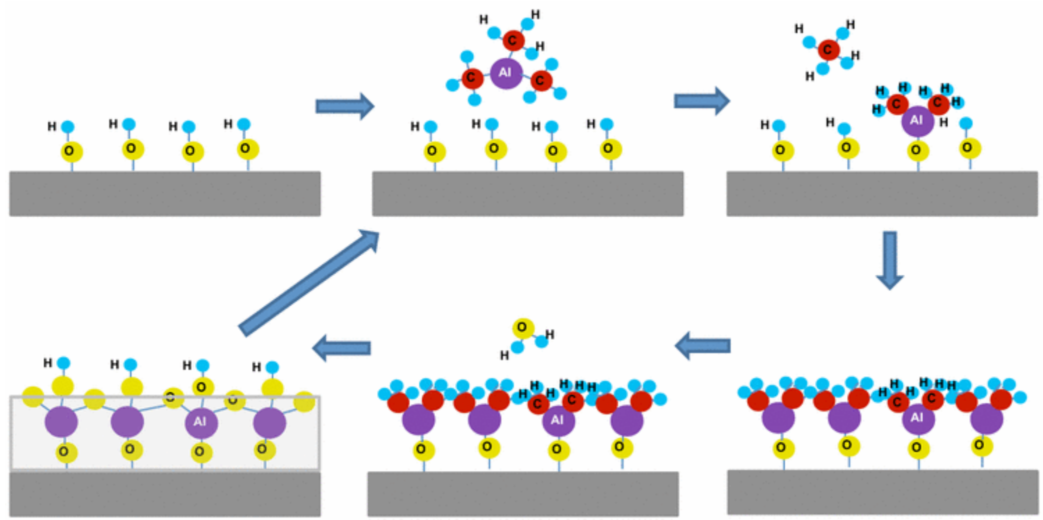


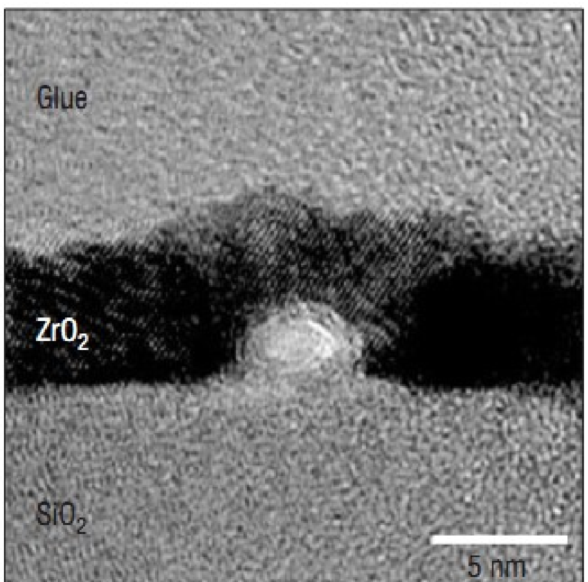



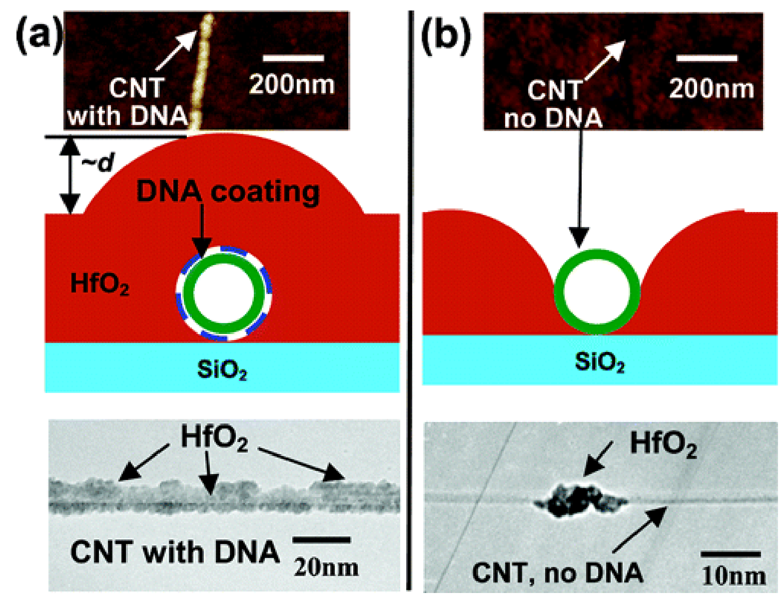


# High k gate dielectrics

- Need OH groups for ALD.
- Overgrow from surface or functionalize CNT.
- No dangling bonds give nice interface? Traps in oxide?





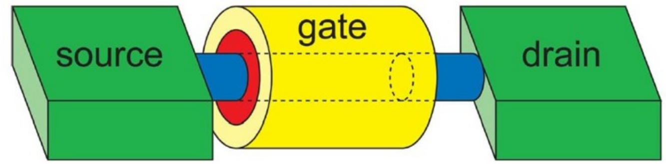

Javey et al. *Nature Materials,* 1 (4), 241-246, 2002

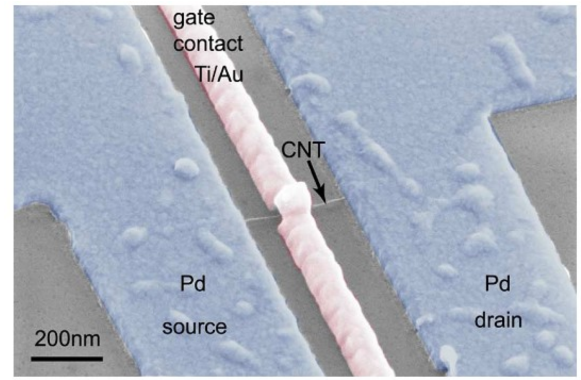
Lu et al. *J. Am. Chem. Soc.*, 128, 3518–3519, 2006

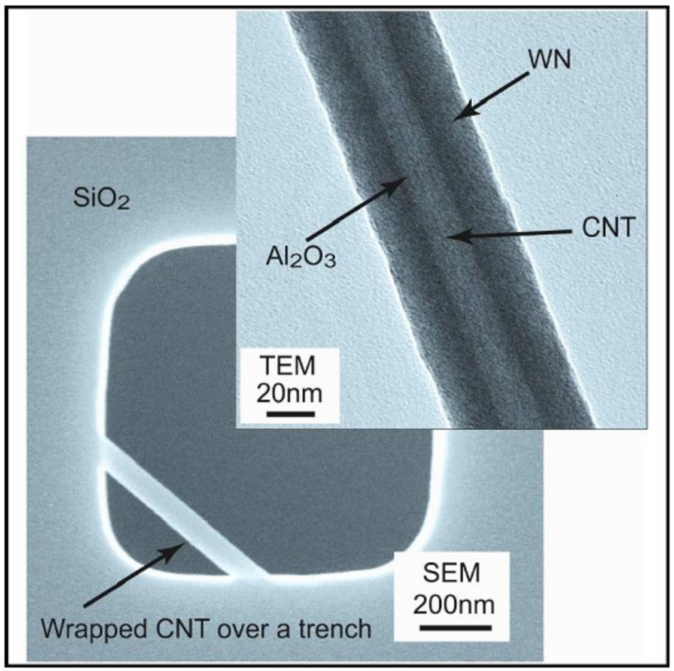
# Gate-all-around CNTFET

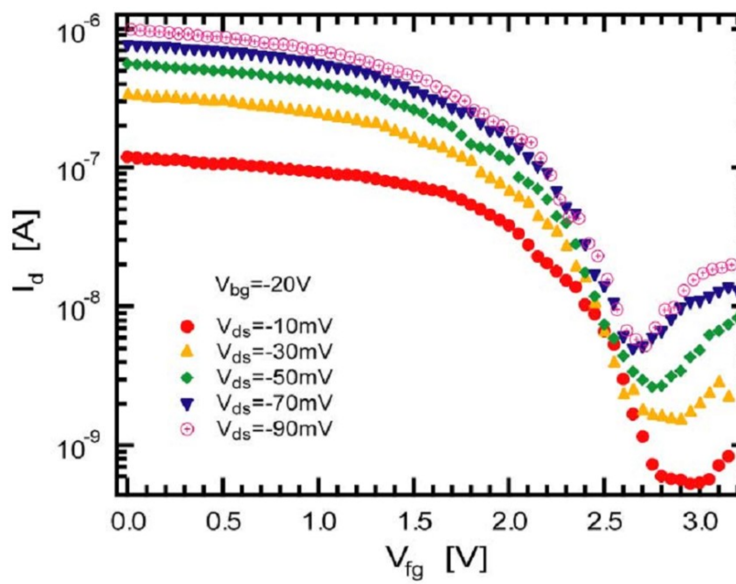
- Wrap CNT in Al2O3 and WN using ALD

- Poor subthreshold swing due to interface traps and short channel effects



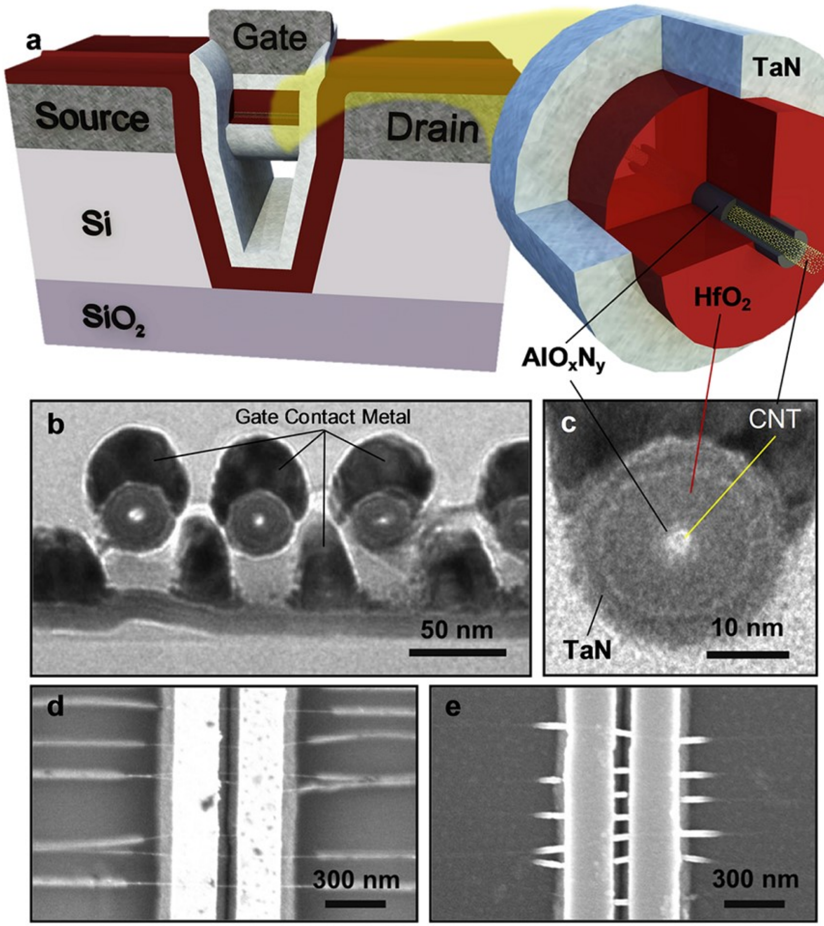



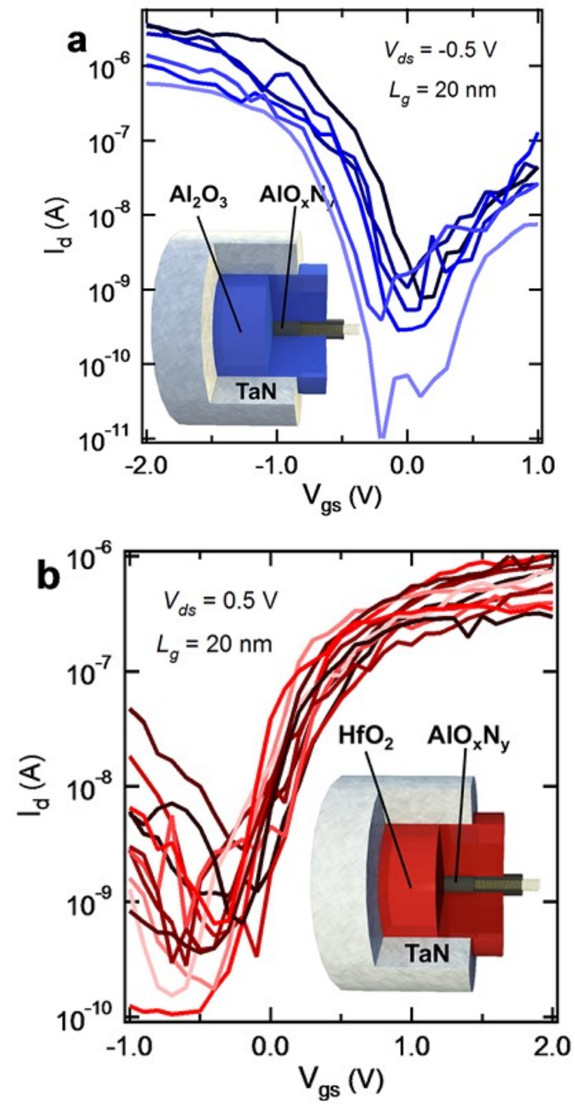




Chen et al. *IEEE Electron. Dev. Lett*. **29**, 2 (2008)

# Different high-k

- Control p or n-type by different high-k



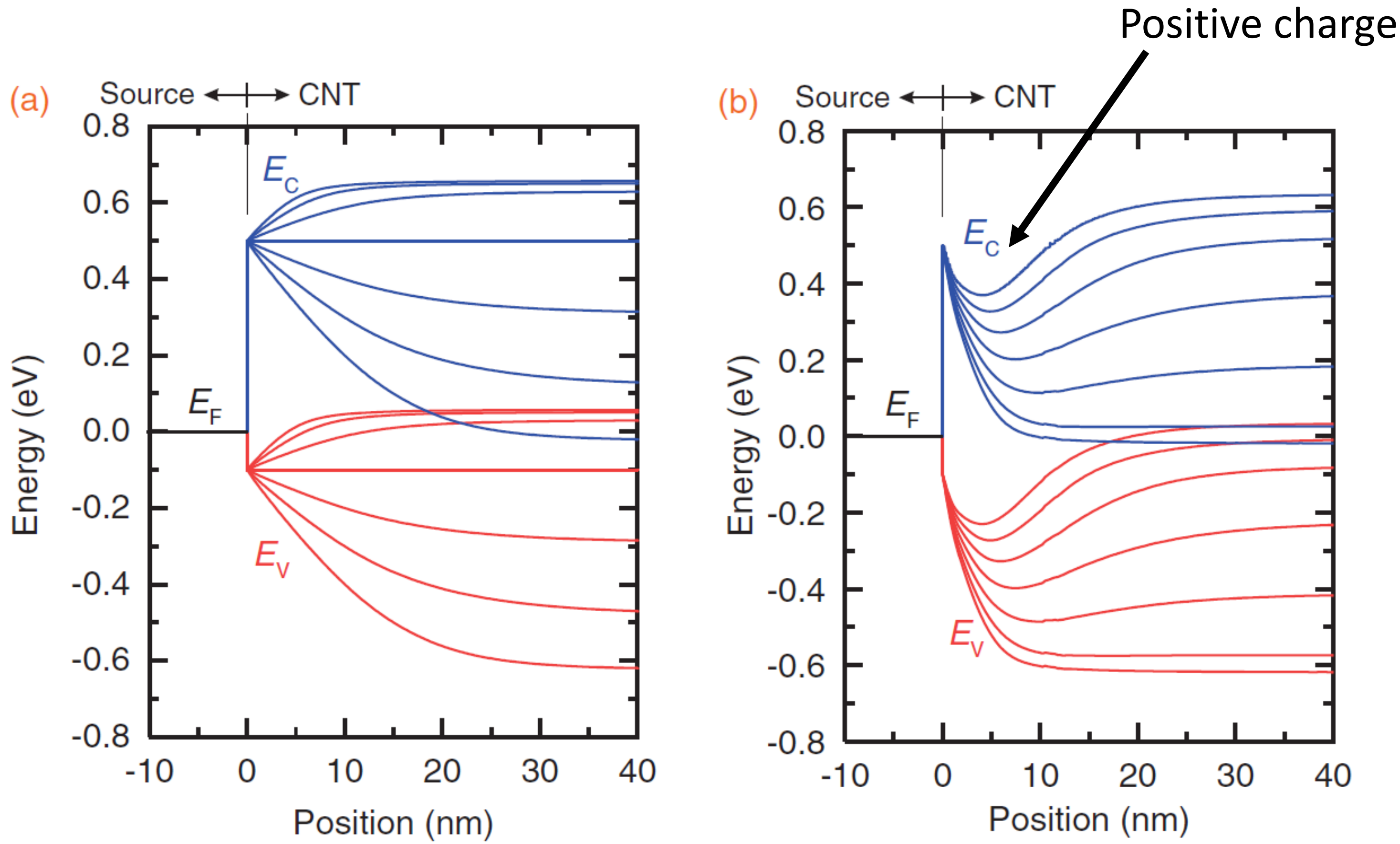






Franklin et al. *Nano Lett.* 13 (6), (2013)

# Conversion from p- to n-type

- High work function metal -> low Schottky barrier to valence band
- Positive charge (in e.g. oxide) close to contact increases barrier to valence band and thins down barrier to conduction band.

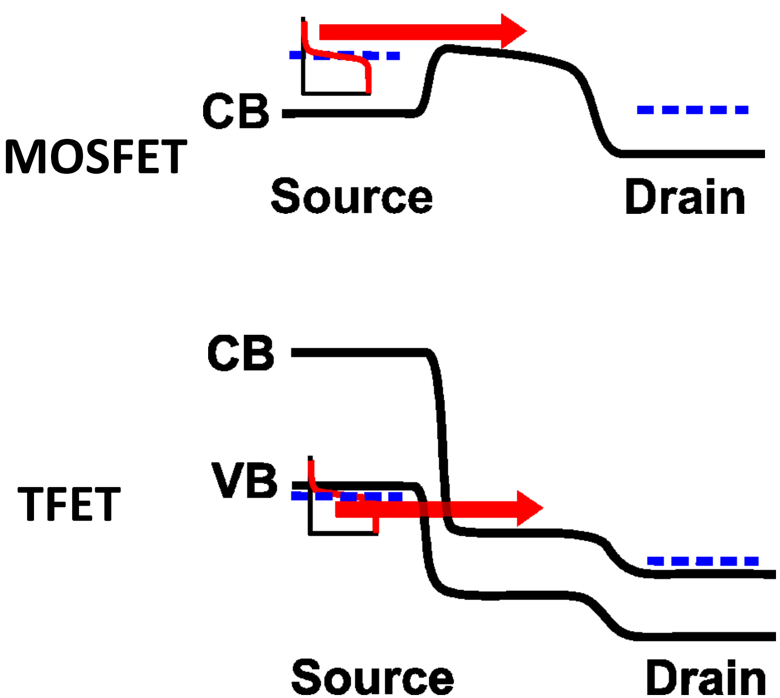


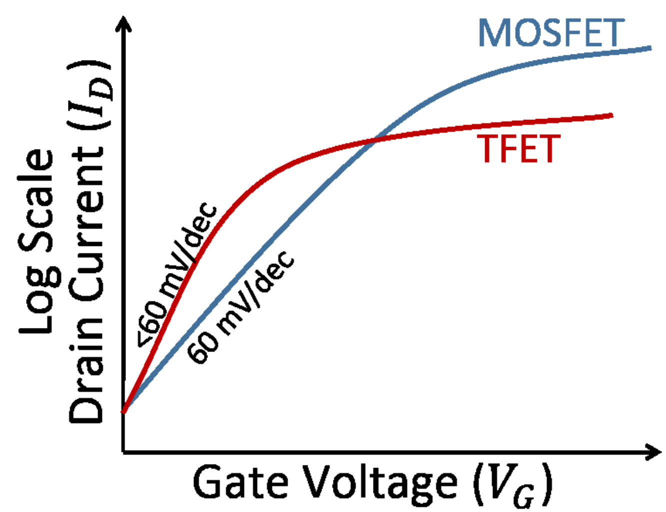

Suzuki, Appl. Phys. Express 6 (2013)

# Improving the inverse subthreshold slope

- ”conventional” FETs rely on thermionic emission over a barrier
- SS ≥ ln(10) $k_B T$ = 60 mV/dec at room temperature
- A decreased SS enables a lower $V_{dd}$ while keeping the same on/off ratio -> increased speed and reduced power consumption

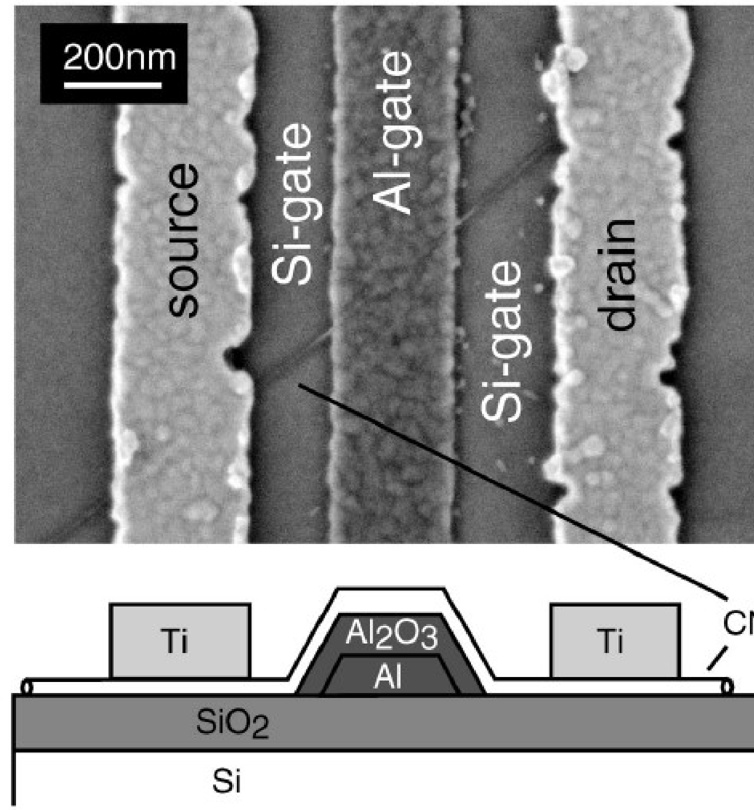
$$S = \left( \frac{d log_{10}(I_d)}{dV_g} \right)^{-1}$$



# Band-to-band tunneling transistor

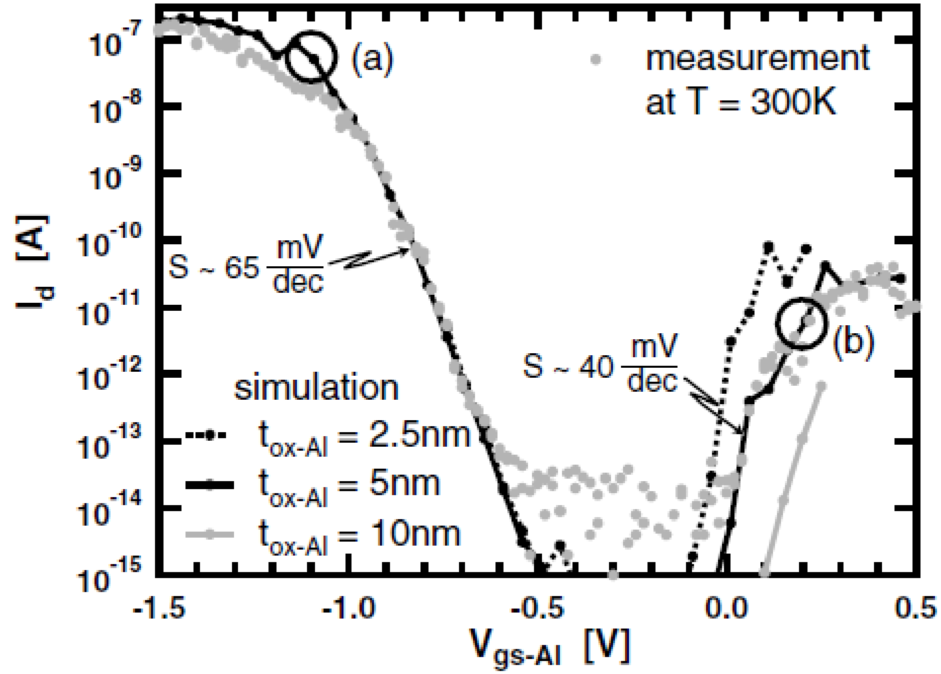
- + λ is a few nm in CNT - > sharp band bending
- + Low effective mass
- + Long mfp
- + Same effective mass of electrons and holes
- + Direct band gap

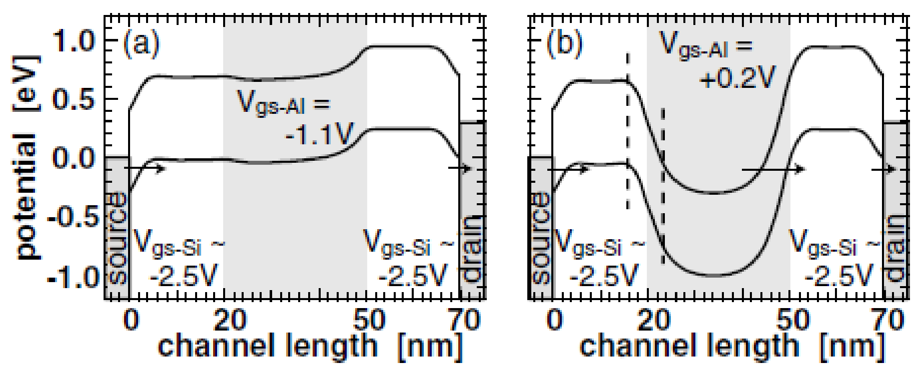



Appenzeller et al. *PRL*. **93**, 196805 (2004)

# Electrical characteristics

- Back gate to form p-type regions
- Al gate to switch FET
- Ambipolar characteristics
- SS=40 mV/dec for the n-branch
- Band-to-band tunneling at the border between the gates



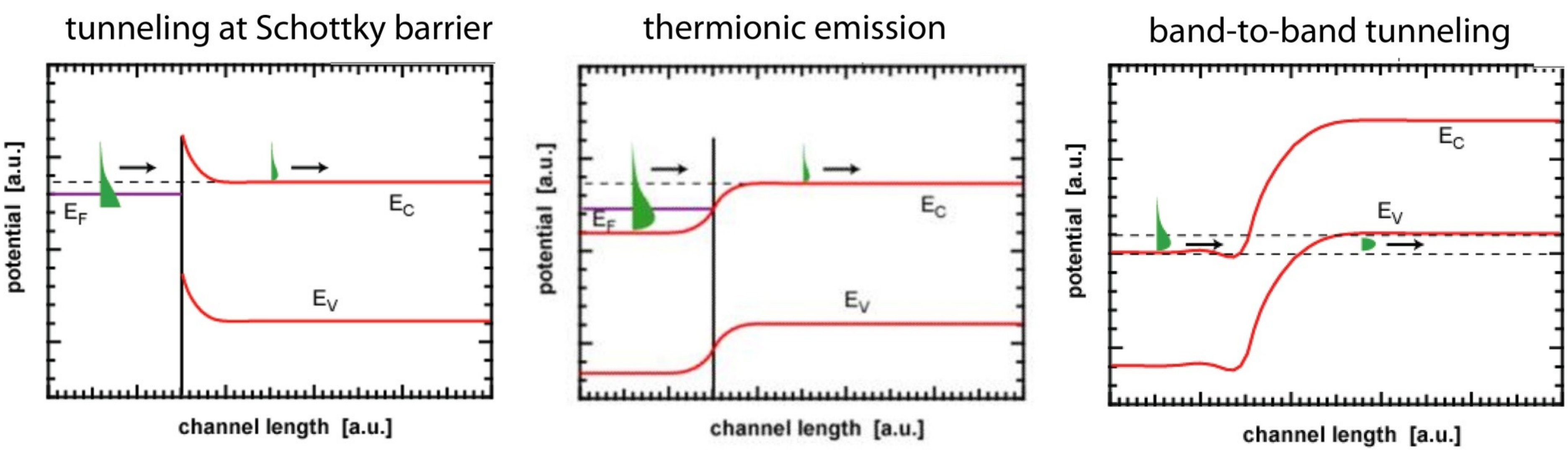



# Mechanism of SS reduction

- Only high energy tail of Fermi-Dirac distribution is transferred in thermionic emission or in tunneling through Schottky barrier

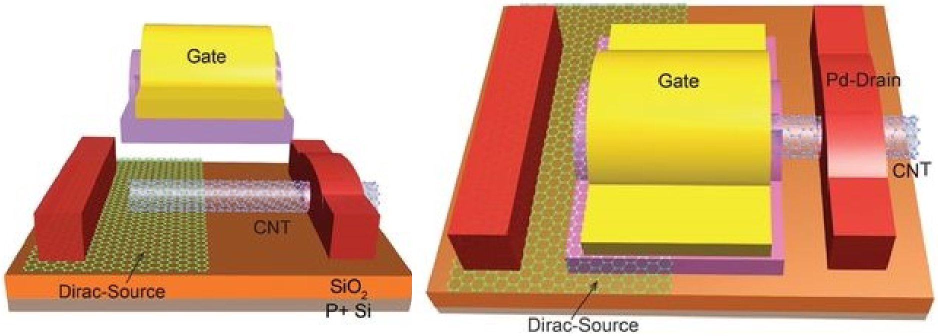
- Band-to-band tunneling ”filters” the Fermi-Dirac distribution

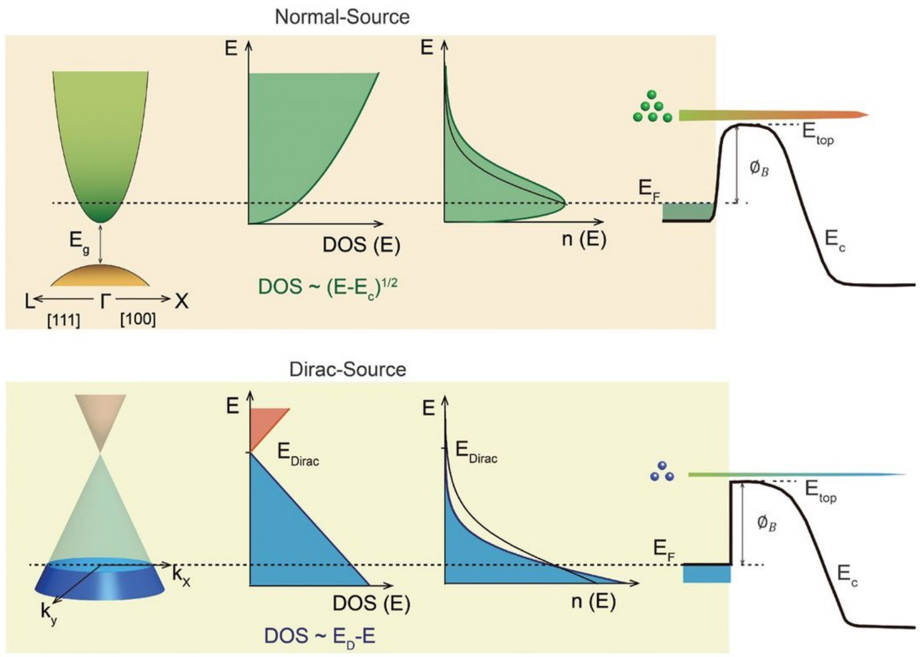
- For BTB tunneling, small movement of bands give large change in current i.e. small SS

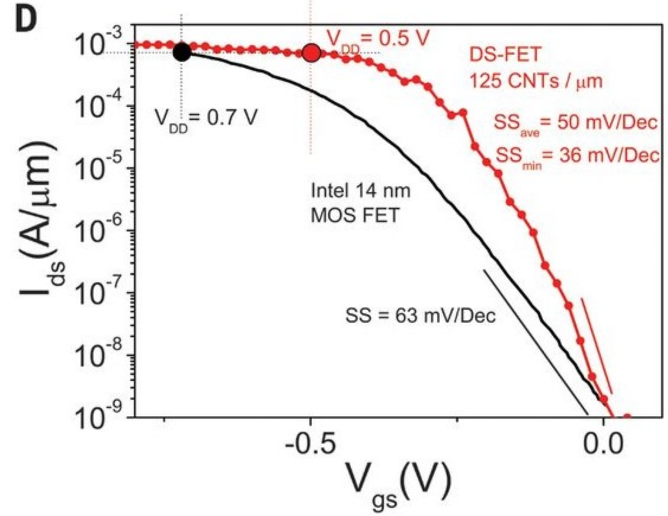


# Graphene source for steep switching

- Use linear DOS of graphene to get ”sharper” carrier distribution in source.
- $SS_{min}$ = 36 mV/dec as good as TFETs but higher current




Chenguang Qiu et al. Science, **361**, 387-392 (2018)

# Outline

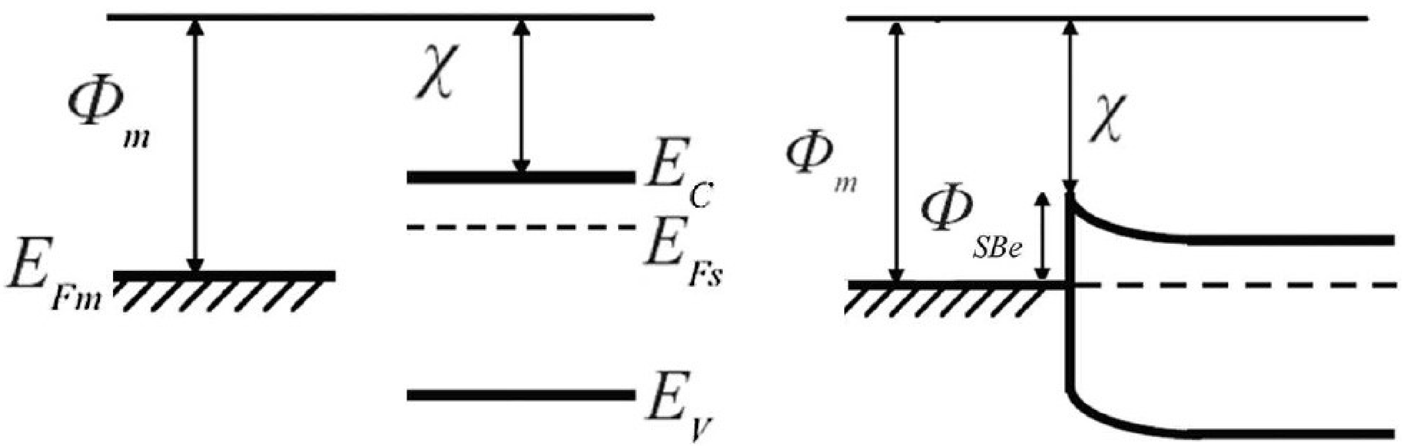
- Basics of graphene and CNTs
  - Structural
  - Electronic
  - Production of CNTs
- Advantages of CNTs for FETs
  - Electrostatics -> length scaling
  - High-k compatibility
  - Band-to-band tunneling
- Challenges of CNT integration
  - Contacts
  - Doping
  - Positioning
  - Chirality control
- Towards integration
  - Flexible electronics
  - High frequency performance

# Schottky barrier basics

- Potential barrier between metal and semiconductor
- Gives rectifying behaviour
- Change metal work function -> change SB height
- Too simple !!!

$$\Phi_{SBe} = \phi_m - \chi$$

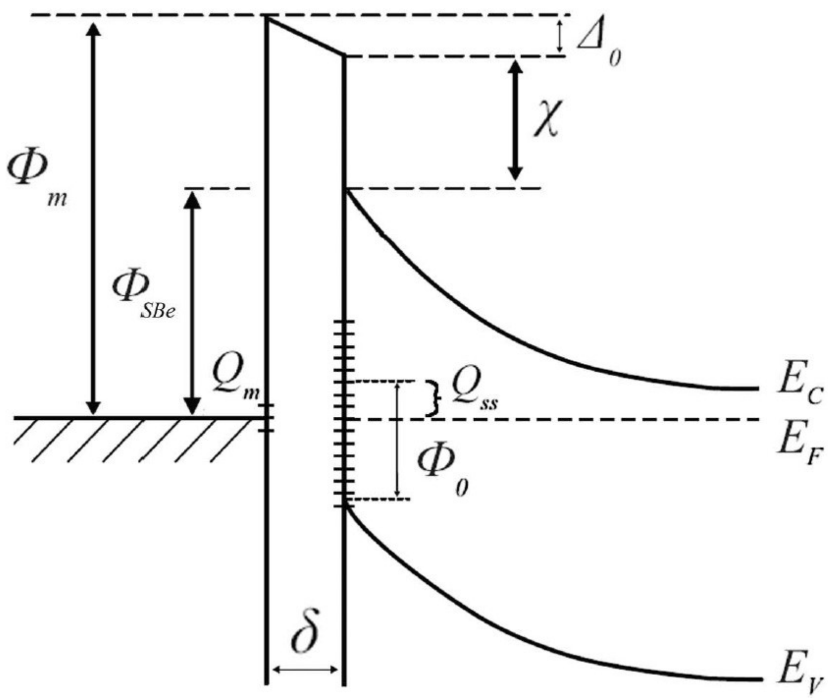
$$\Phi_{SBh} = \chi + E_g - \phi_m = I_s - \Phi_m$$

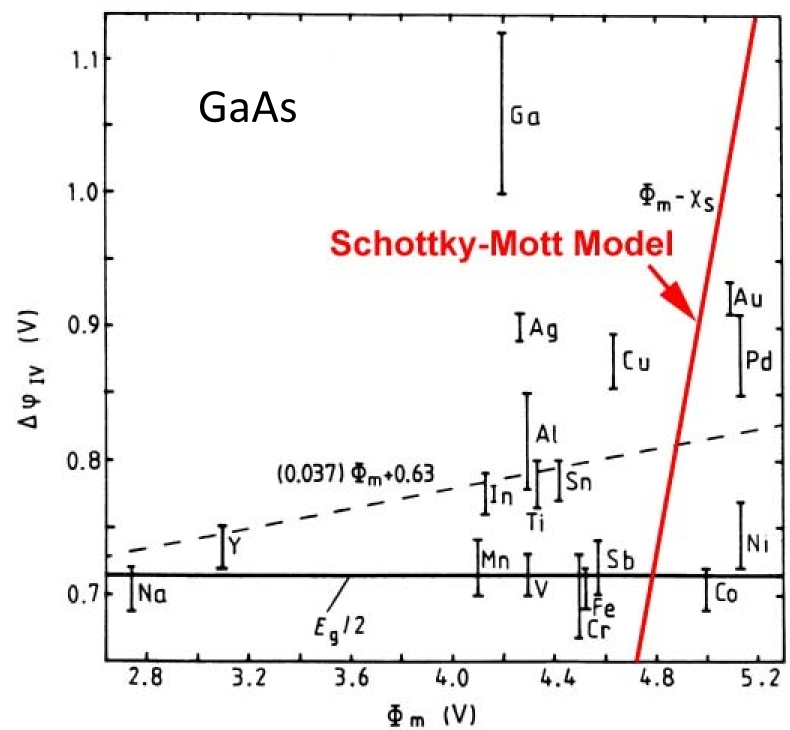


# Fermi level pinning

- Interface states form dipoles that shift bands
- SB height often independent on metal work function

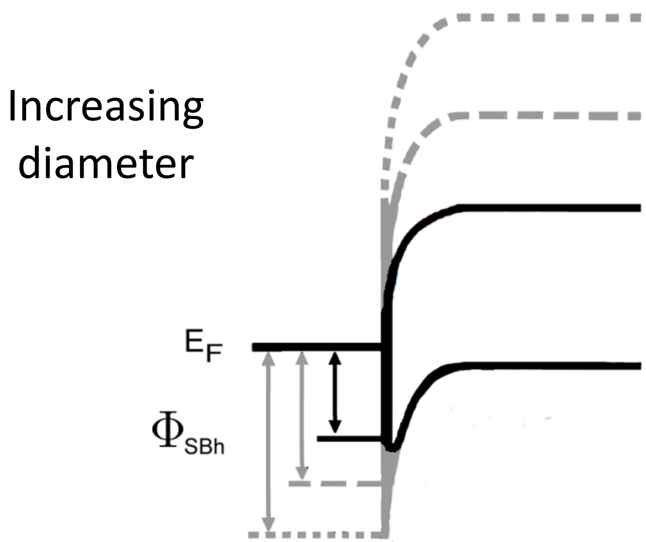
$$\Phi_{SBe} = \gamma(\Phi_m - \chi) + (1-\gamma)(E_g - \Phi_0) \qquad \gamma = \frac{1}{1 + \frac{qD_{it}\delta}{\epsilon_i}}$$

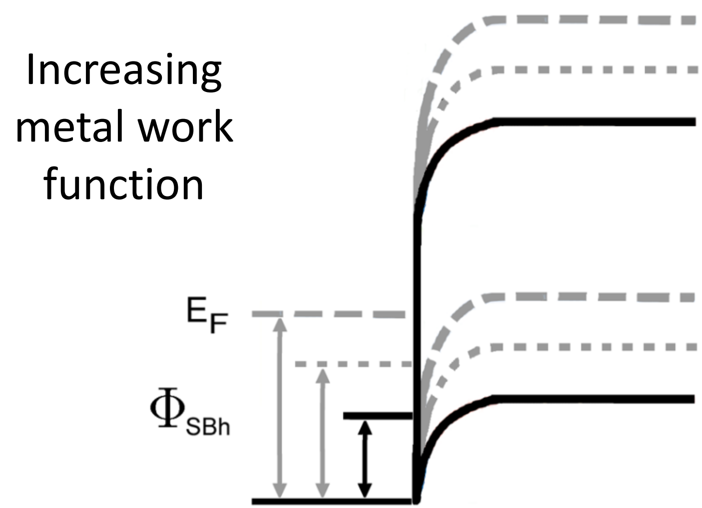


# Schottky barrier to CNTs

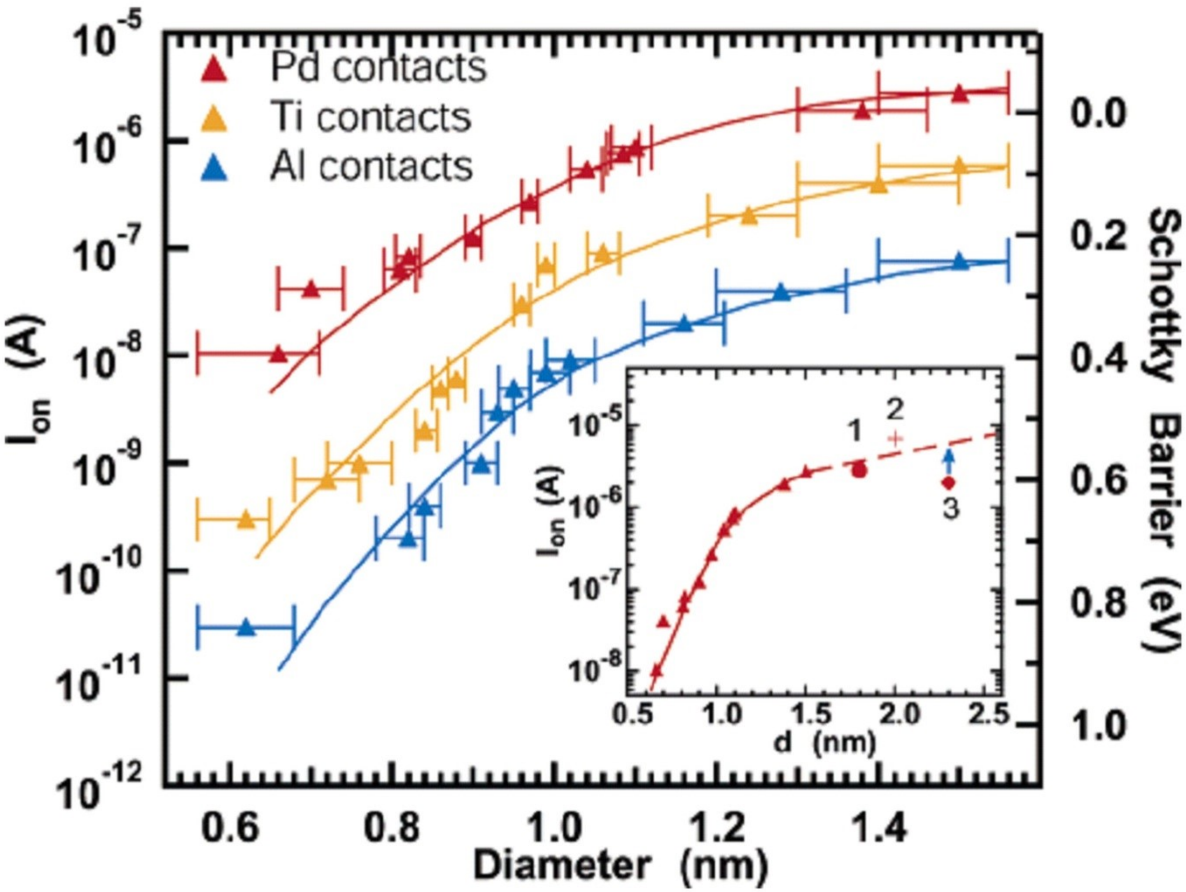
- Theoretically predicted that interface states have no influence on CNT-metal contacts
- Increasing CNT diameter gives lower barriers
- Increasing metal work function gives lower hole barriers



# Different contact metals

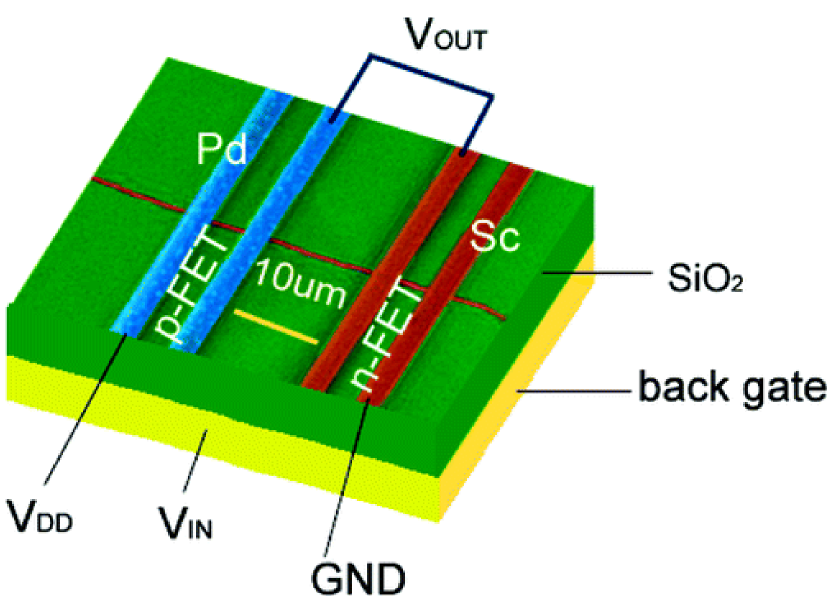
- Increasing $I_{on}$ with larger CNT diameter
- Increasing $I_{on}$ with higher work function
- No or small effect of Fermi level pinning

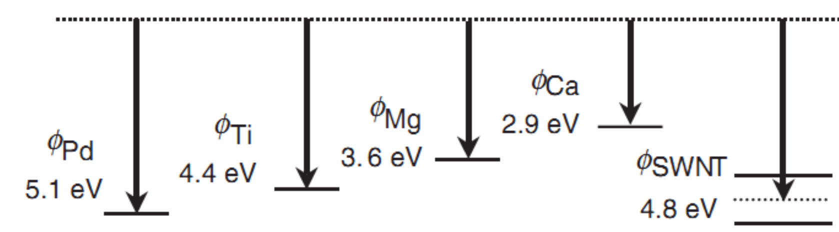


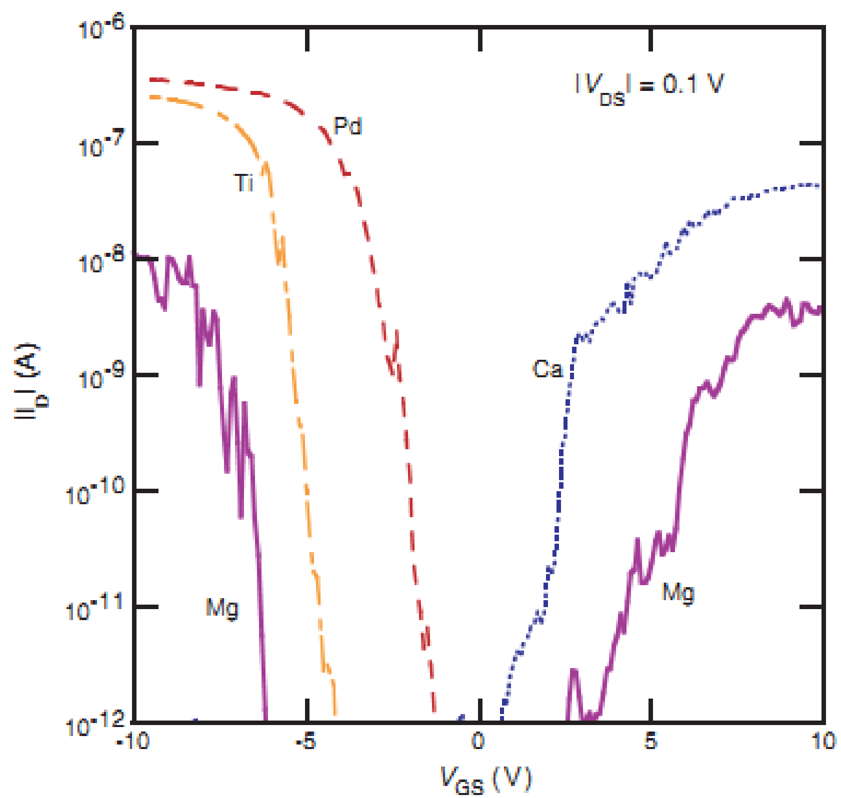

Chen et al. *Nano Lett.* **5,** 1497–1502 (2005)

# Impact of metal work function

- Can form n or p-type devices using different metals
- Pd best for p-type
- Sc best for n-type



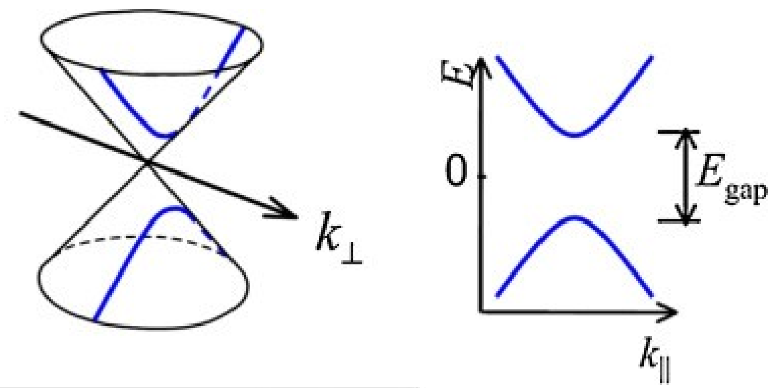



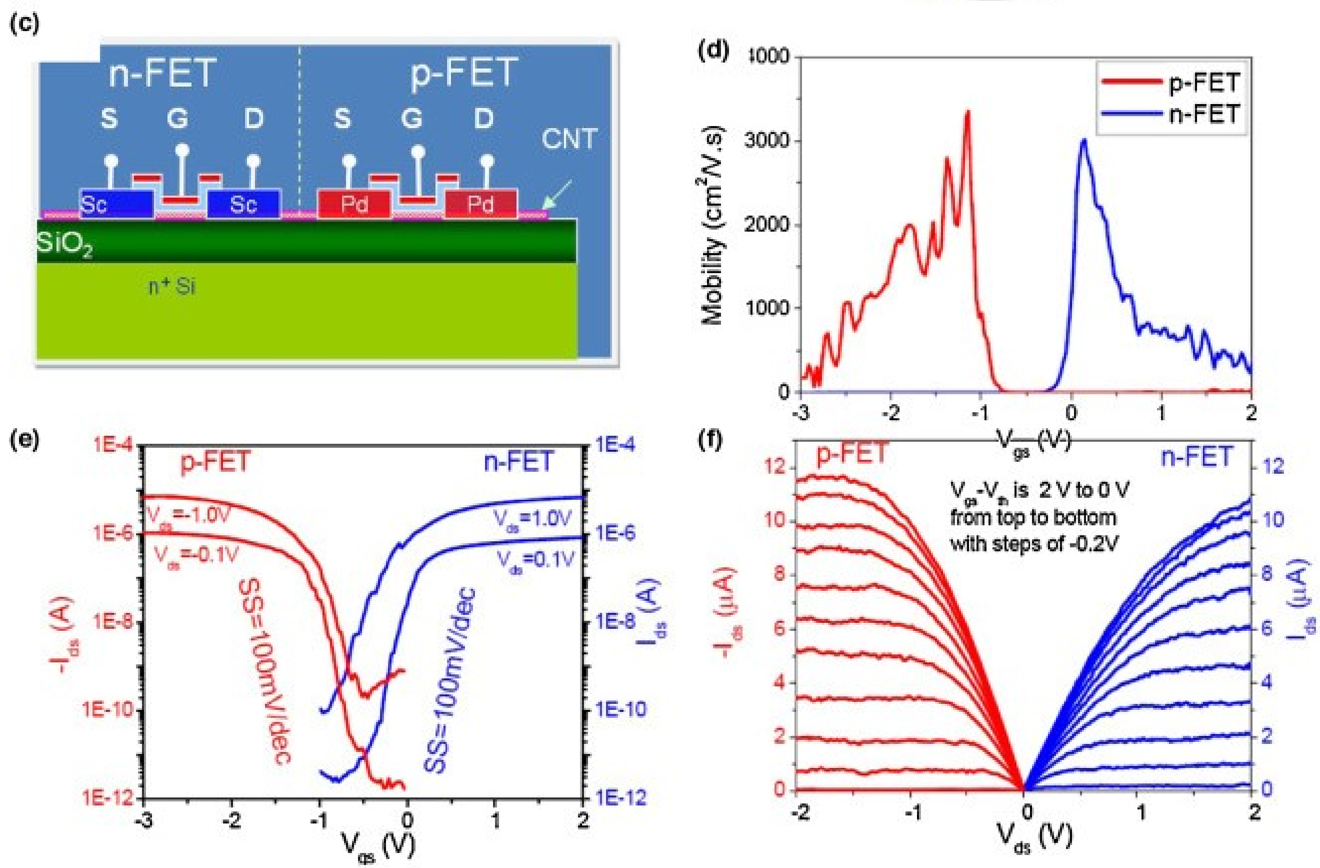

Nosho et al. *Nanotechnology* **17** , 3412 (2006)

# CNTFETs for CMOS

- For most semiconductors $\mu_e > \mu_h$

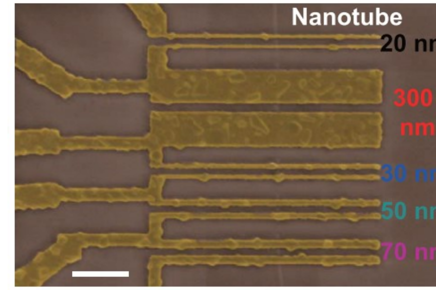
- Symmetric valence and conduction bands give similar PMOS and NMOS performance for CNTFETs

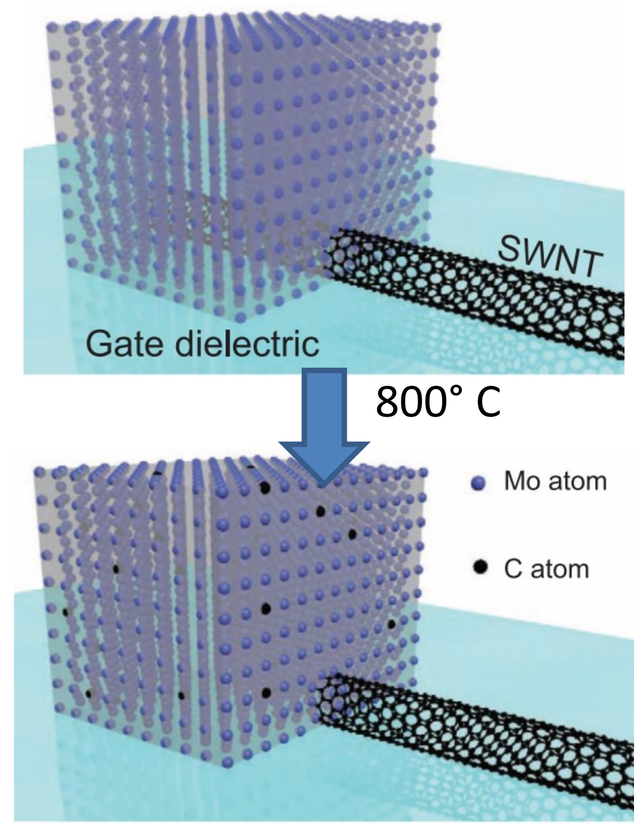


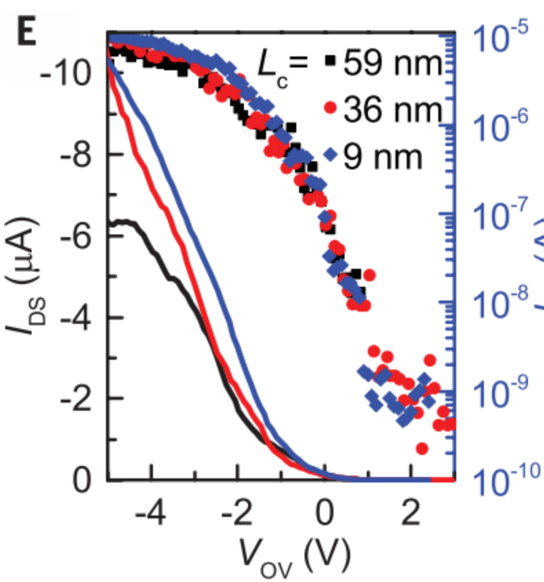



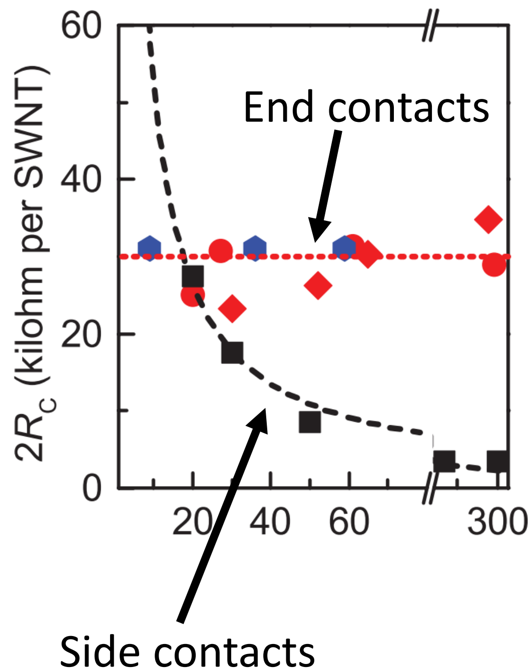
# End bonded contacts

- Mo contacts heated to 800°C forms $Mo_2C$
- Sidecontact transformed to end contact
- Contact only 2 $nm^2$
- Useful for very dense circuits



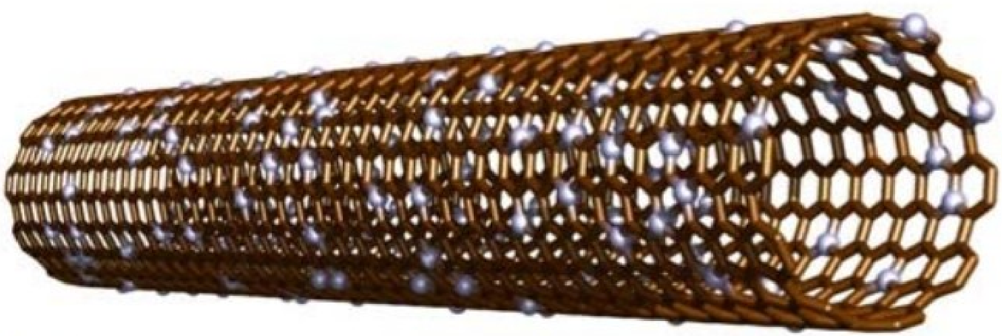



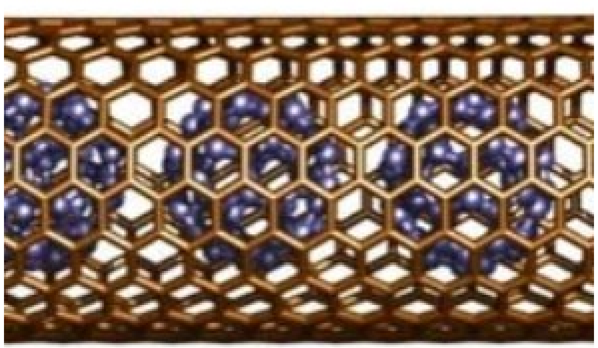

Cao et al. *Science* **350**, 68-72 (2015)

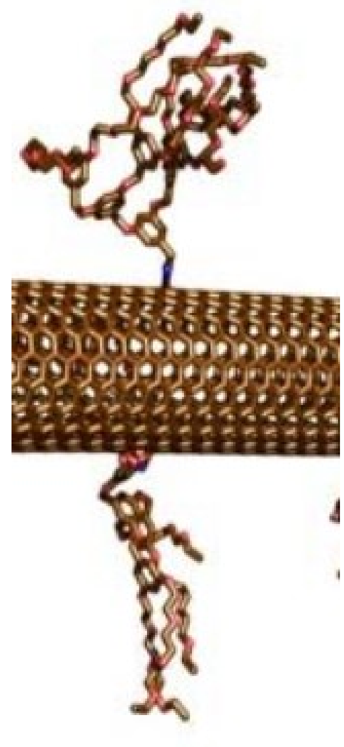
# Doping

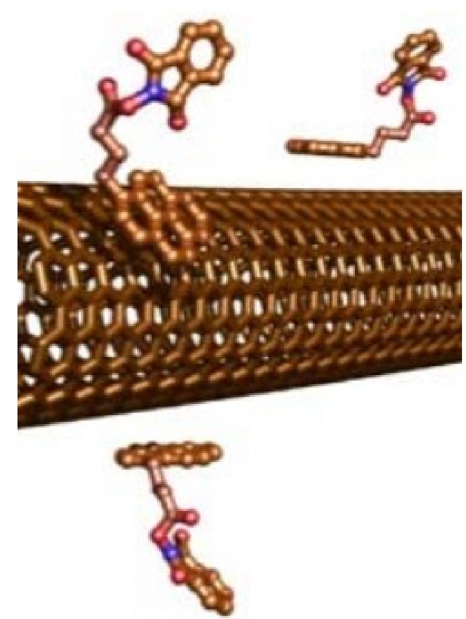
- Important for CMOS, pn-junctions and good contacts.
- Substitutional doping is difficult without destroying CNTs.

c)







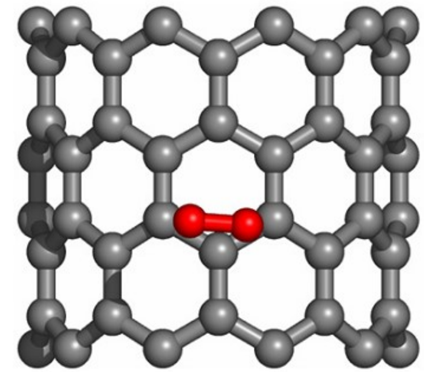


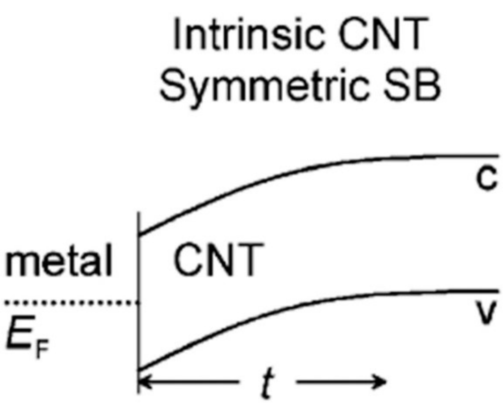
# CNTFETs in air

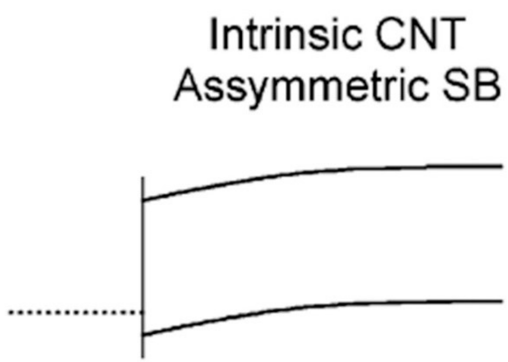
- Physisorbed oxygen p-dopes CNT

  OR

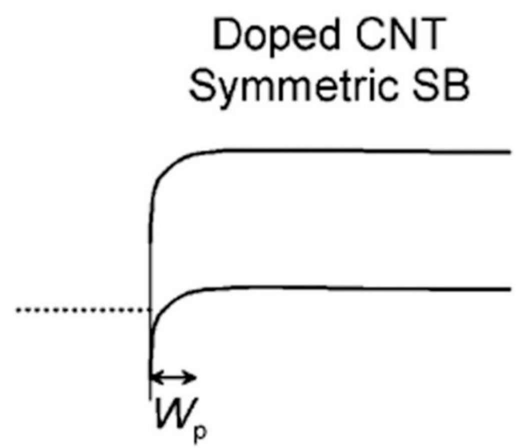
- Increases metal work function of contact






**Contact metal**
**work function change**

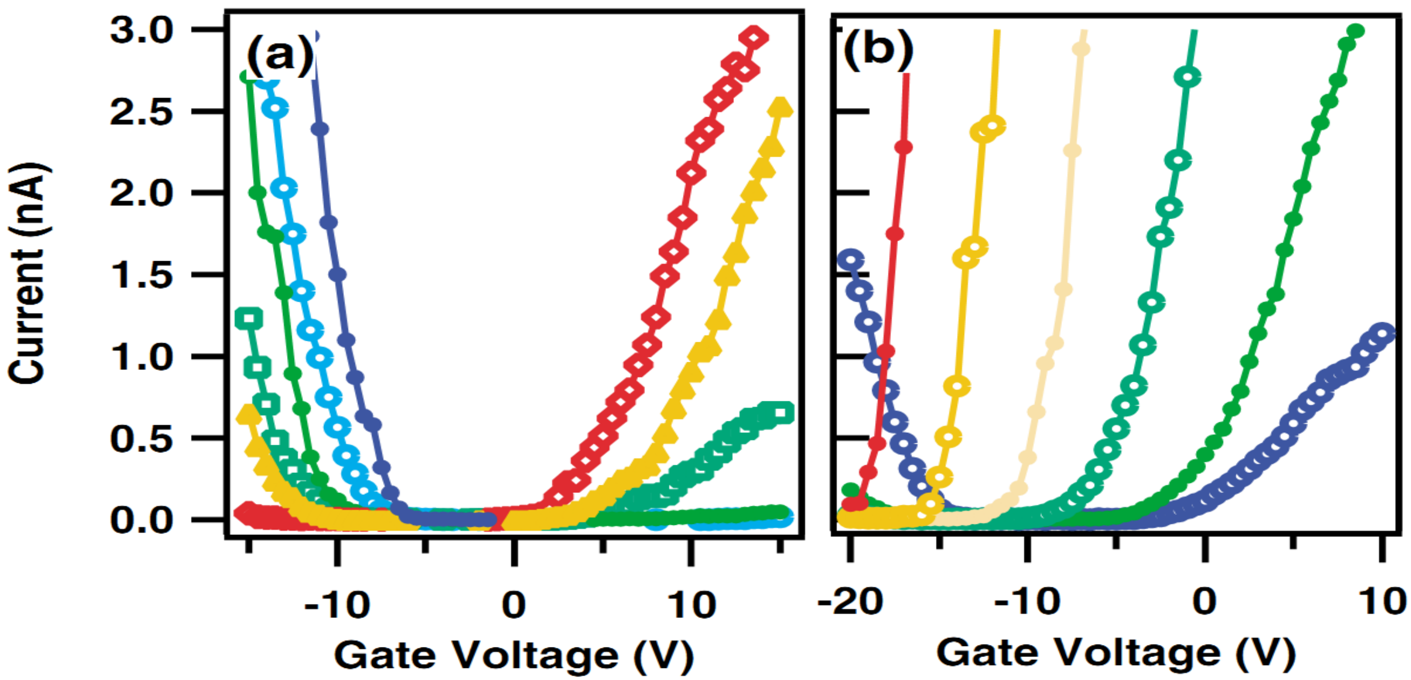



**p-doping -> thinner**
**Schottky barrier for holes**

# Potassium doping

- O exposure -> p-branch is lowered, n-branch is increased, no $V_{th}$ shift
- K physisorbed on CNT n-dopes by charge transfer -> $V_{th}$ shift
- O: changes work function // K: dopes CNT

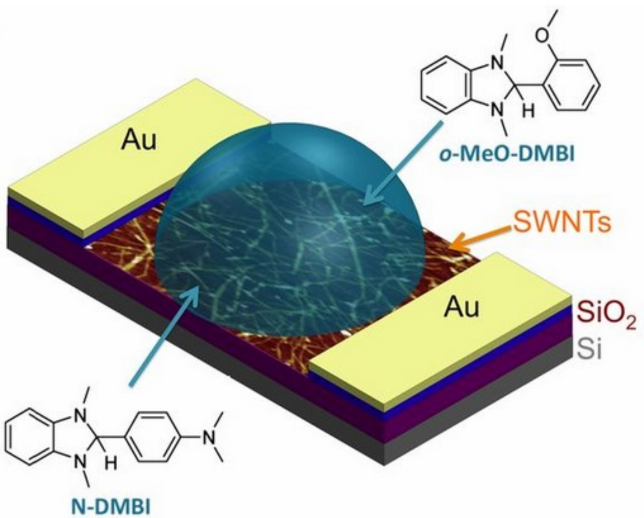
Oxygen exposure (red-> blue) K doping (blue->red)

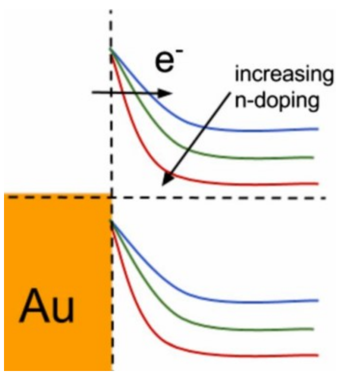


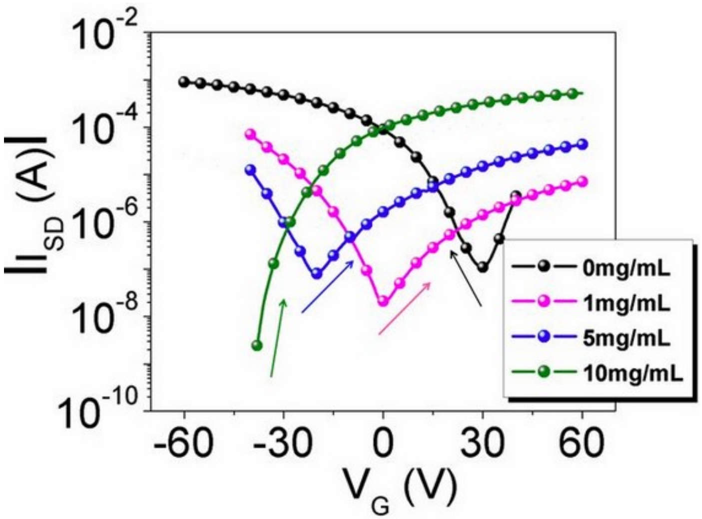

Heinze et al. *PRL*, **89**, 10 (2002)

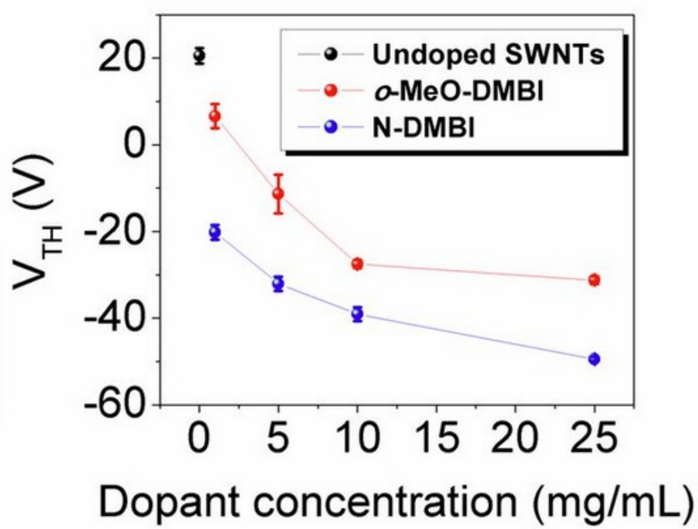
# Doping of thin film CNTFETs

- Organic molecules are deposited on CNT network
- n-doping lower Schottky barrier for holes and shifts $V_{th}$



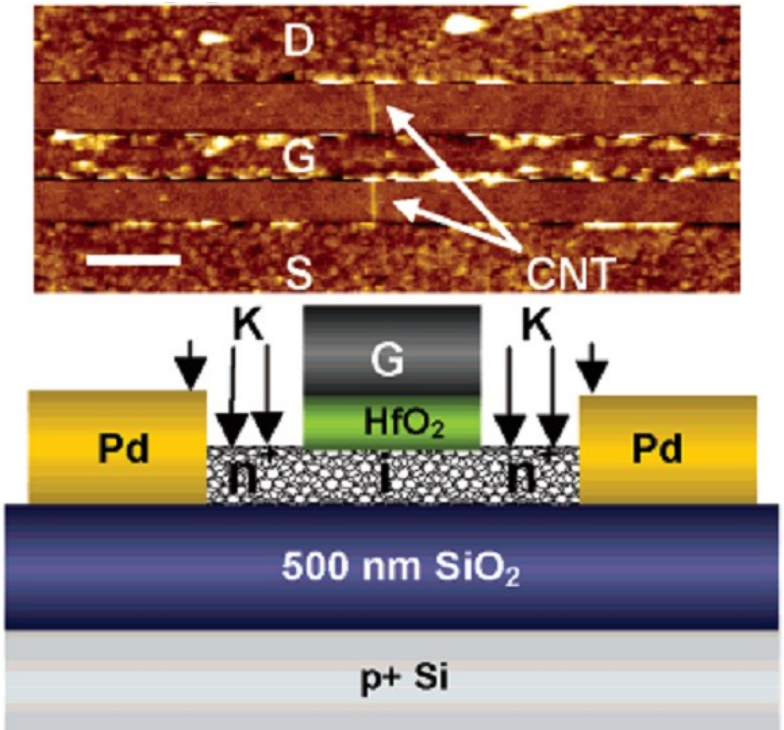



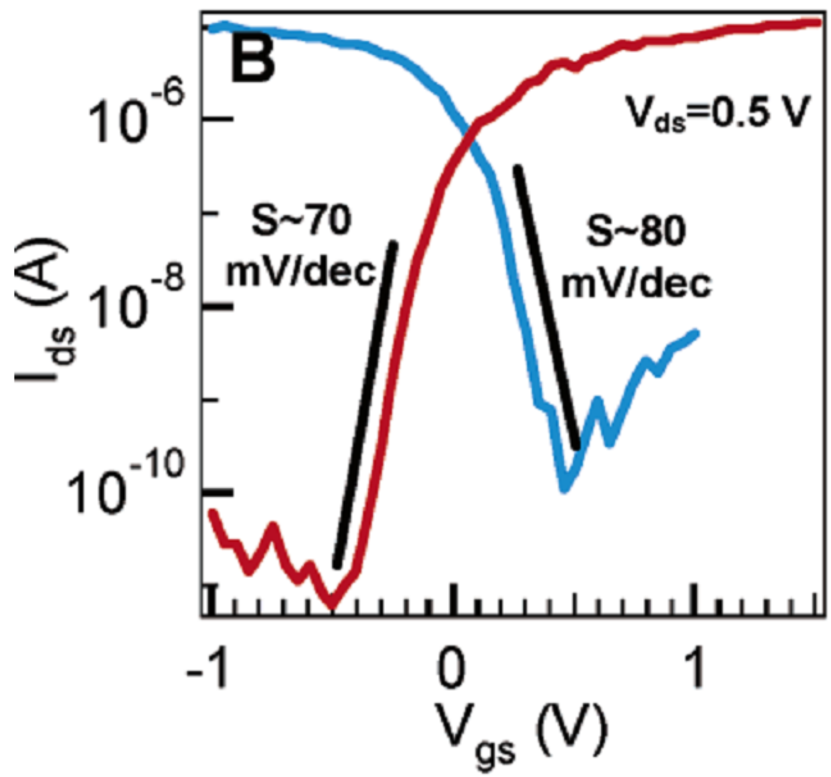




Wang et al. *PNAS*, **111**, 4776–4781 (2014)

# Doped contacts

- n - dope outer CNT segments using K
- Removes influence from Schottky barrier at metal contact

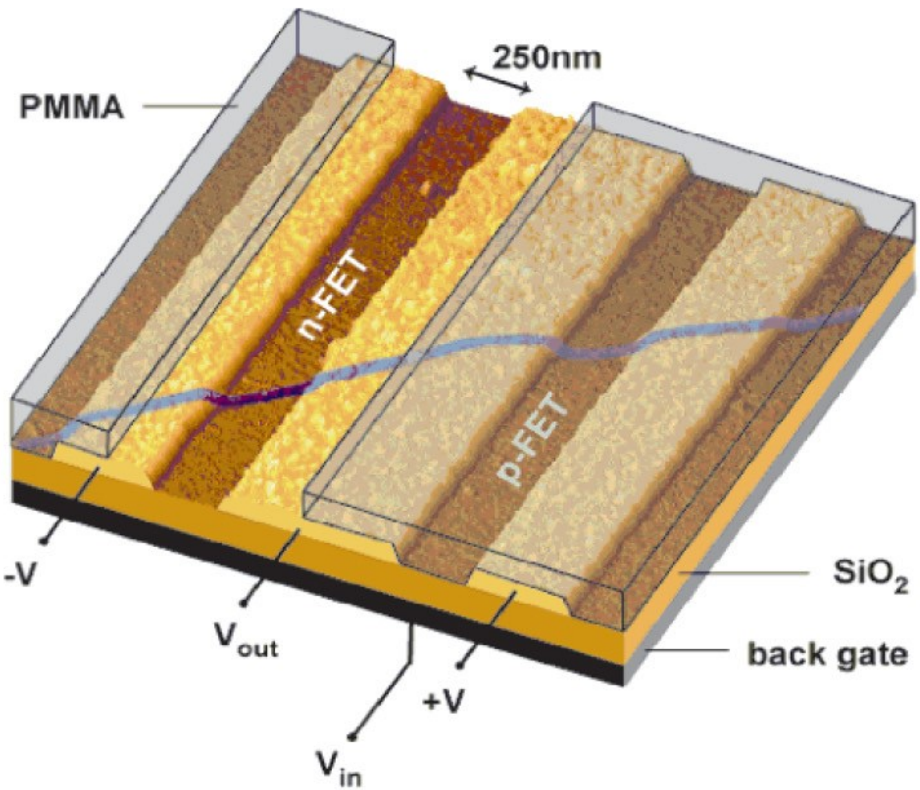


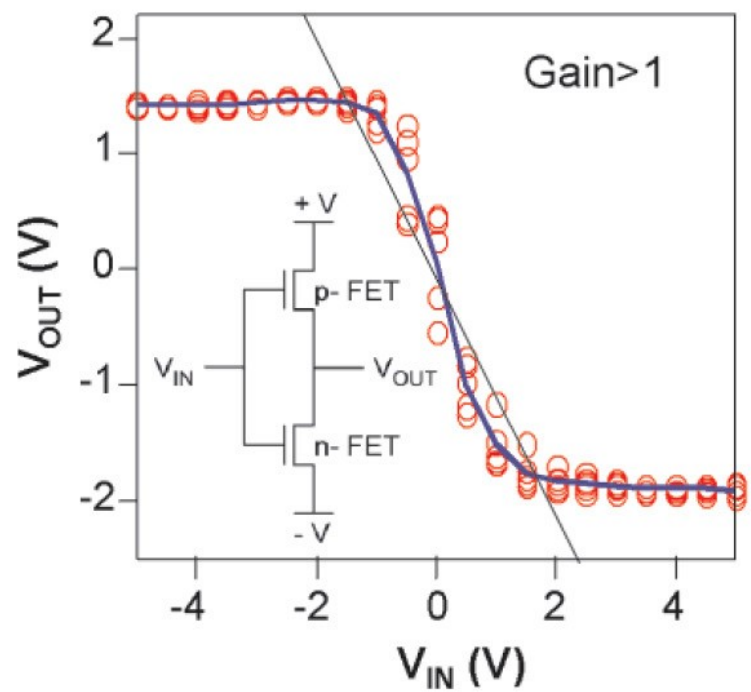




Javey et al. *Nano Lett.*, **5**, 345-348 (2005)

# Logic gate on single CNT

- Inverter from p and n CNTFET on the same CNT
- Use K doping or annealing to form n-CNTFET

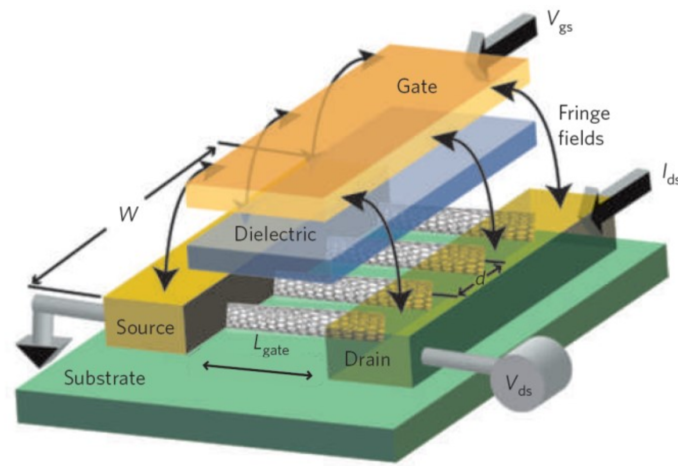


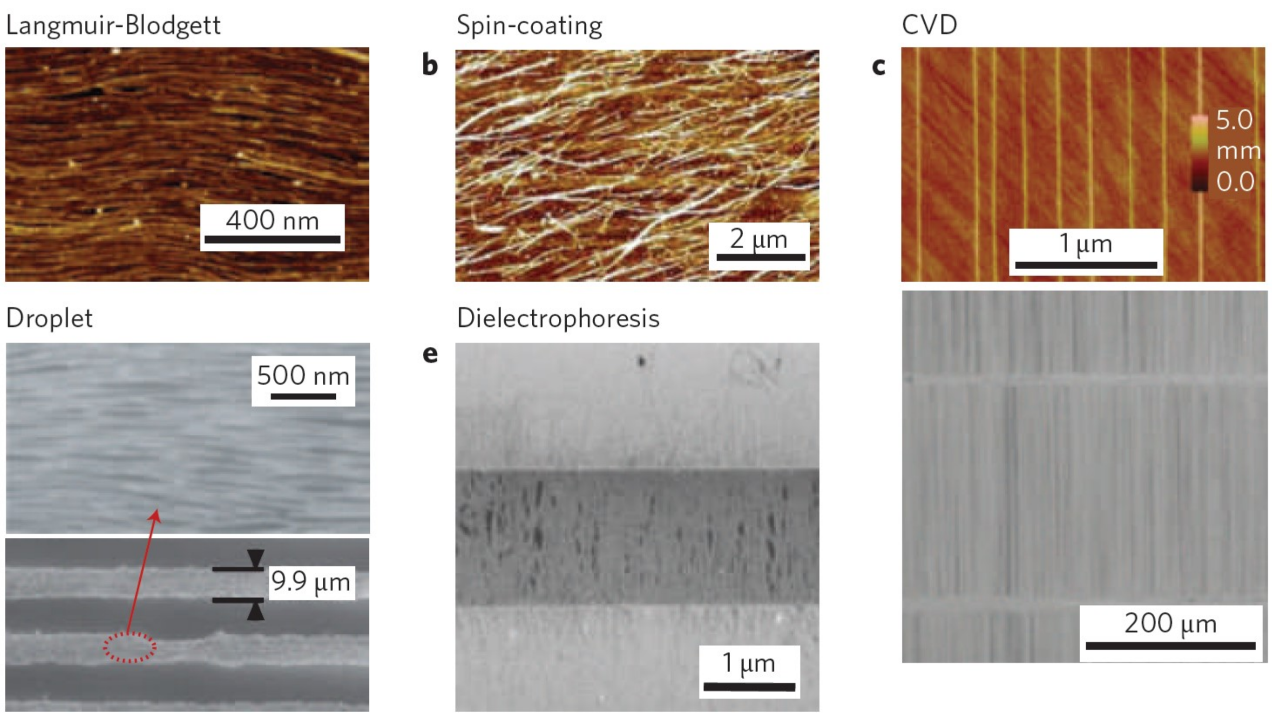




Derycke et al. *Nano Lett.* **1** , 453–456 (2001)

# Positioning

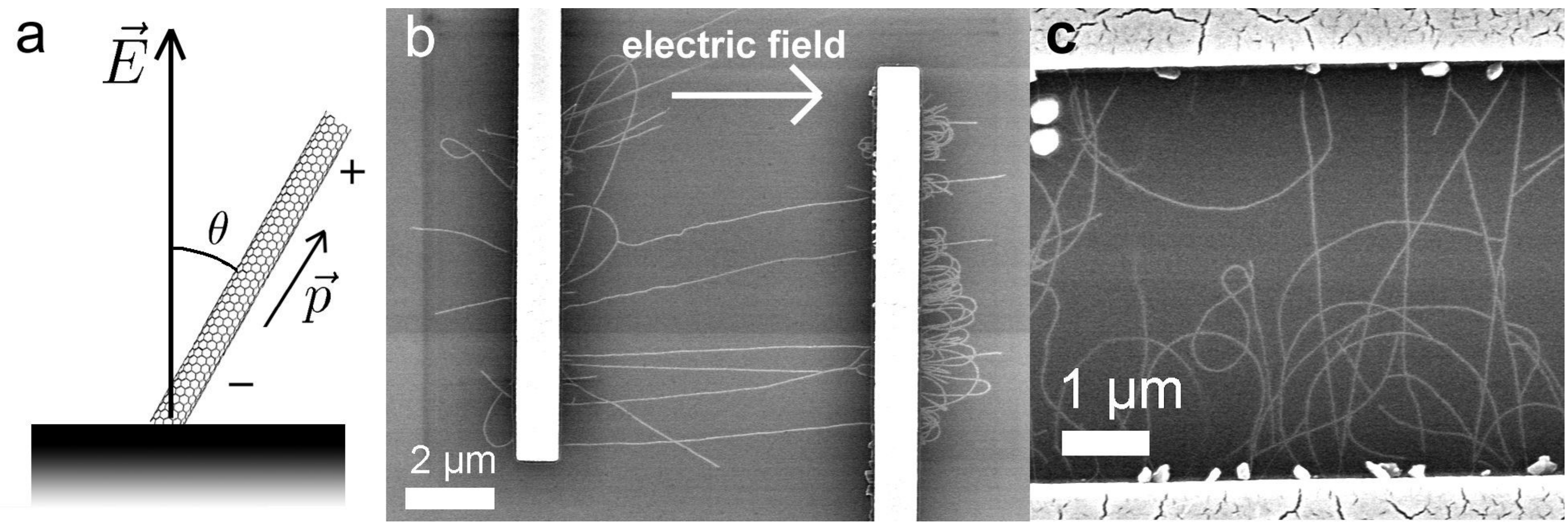
- Multiple parallell CNTs in each FET increases $I_{on}$, $g_m$
- Dense packing reduces parasitic capacitances
- Need to control position and orientation of CNTs pre- or postgrowth



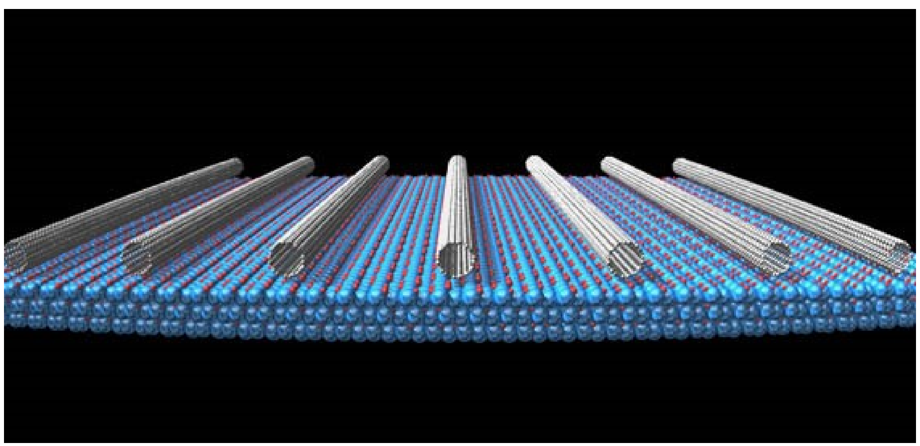
# Electric field alignment

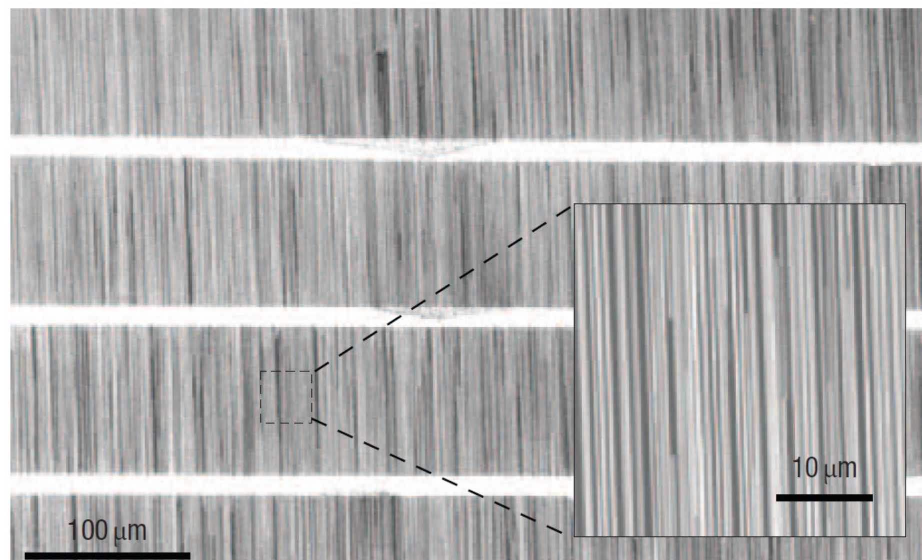
- Apply voltage to electrodes during CVD
- Dipole in CNTs align them with field lines
- Difficult to implement for large scale circuits



# ”epitaxial” alignment

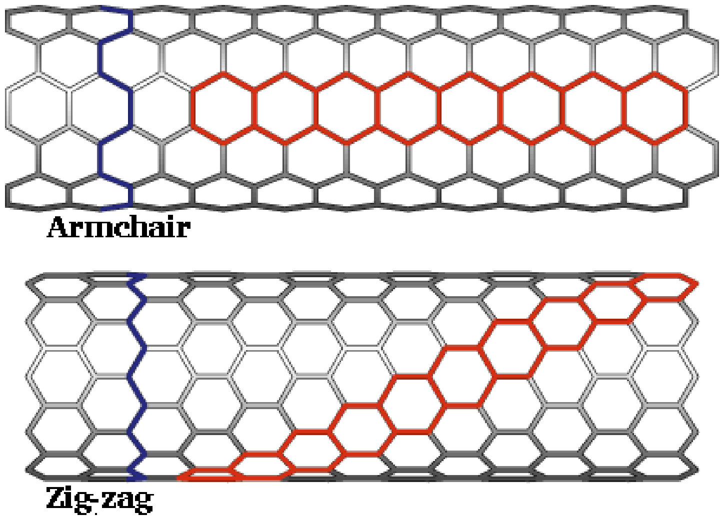
- CNTs align in certain crystal orientations of sapphire ($Al_2O_3$) or quartz substrates
- CNTs align at atomic steps
- Strong attractive interaction between CNTs and Al atoms
- 99.9% are aligned within 0.01°
- 10 CNTs / µm





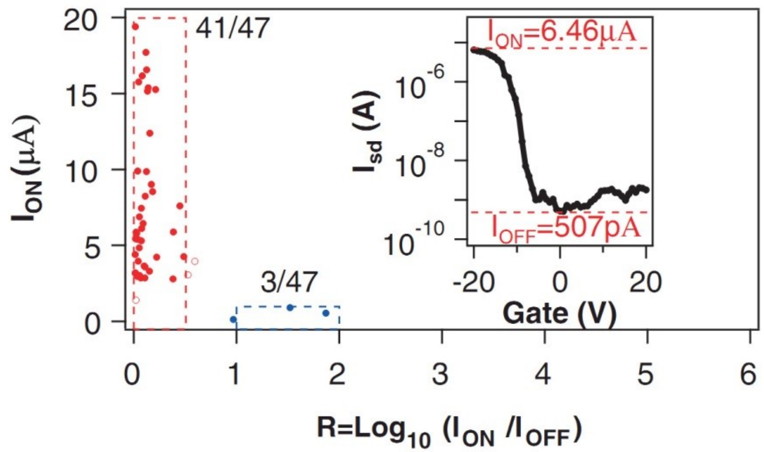
# Chirality control

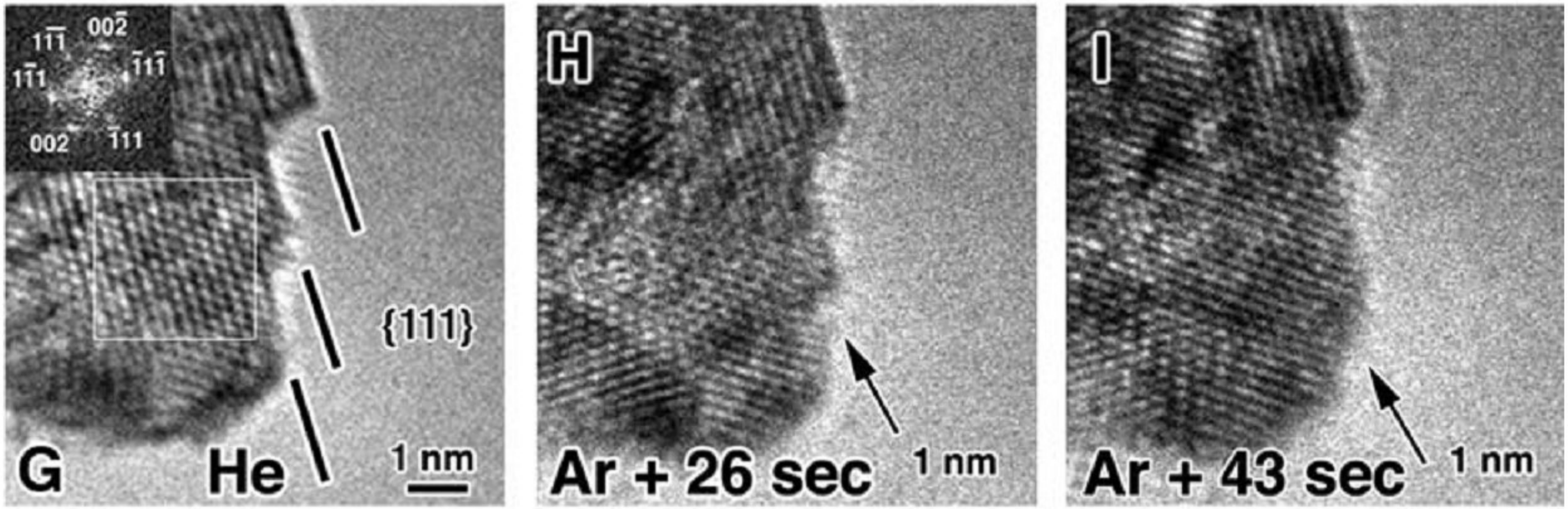
- Metallic CNTs in FETs -> leakage currents - > poor on/off ratio
- Need chirality control or at least control of CNT type
- Need to either:
  - Selectively grow only metallic or semiconducting
  - Separate the two types
  - Selectively destroy one type



# Selective growth

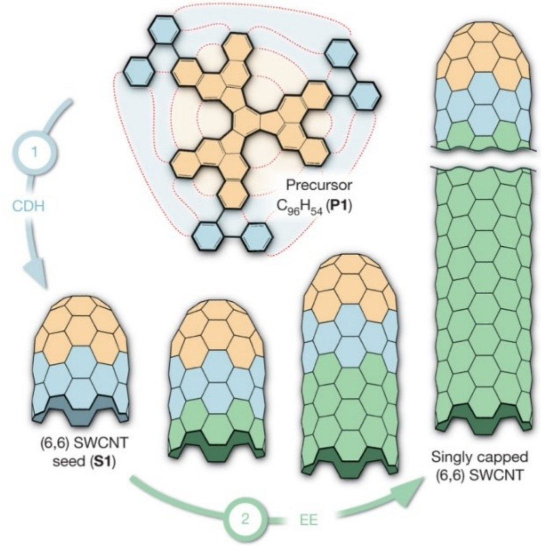
- Anneal metal catalyst in Ar, He or $H_2$
- Increased metallic CNT part from 33% to 91%
- Strong facets when annealed in He
- Steps in particle important for chirality control?
- Not well understood!



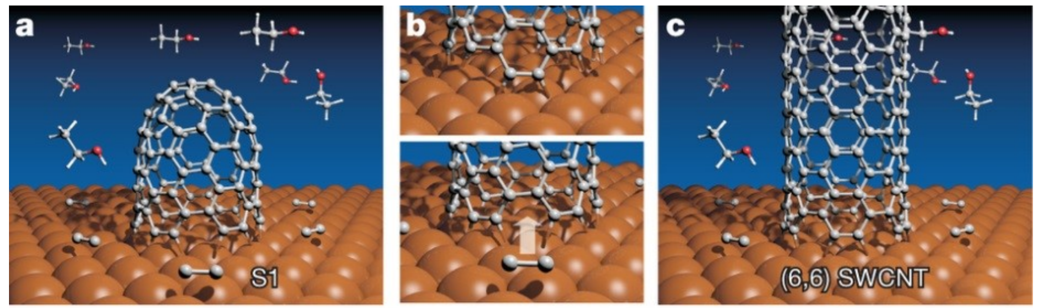



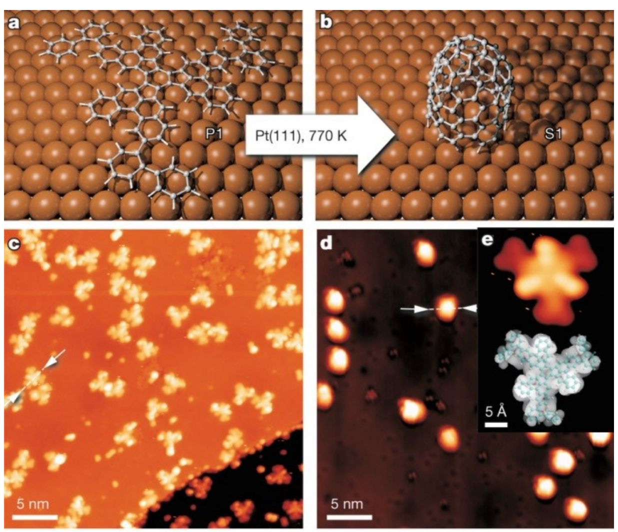

Harutyunyan et al. *Science,* **326**, 116-120 (2009)

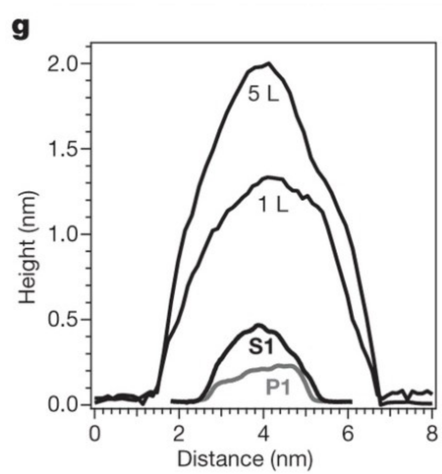
# Templated growth

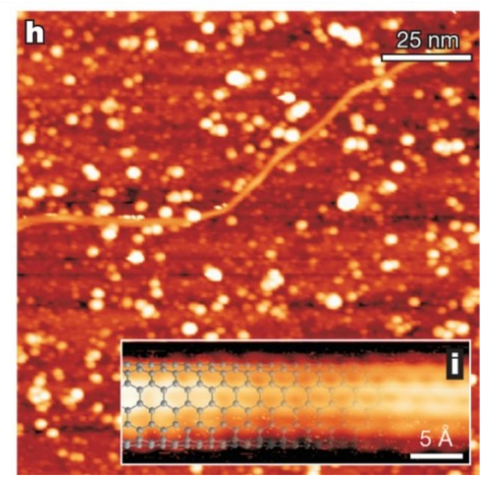



- Molecule defines cap
- Only (6,6) CNTs i.e. ”real” metallic



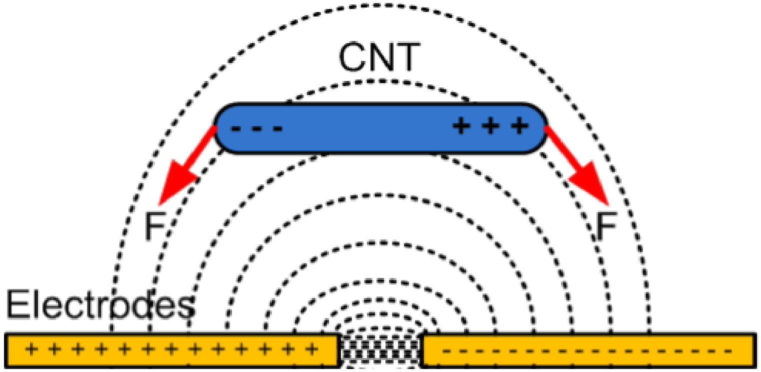



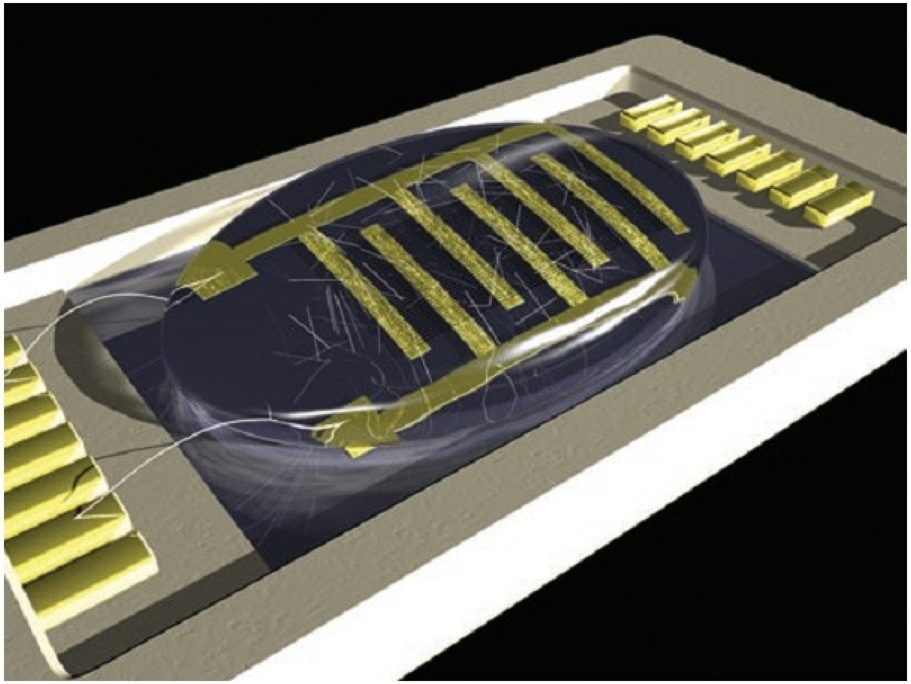



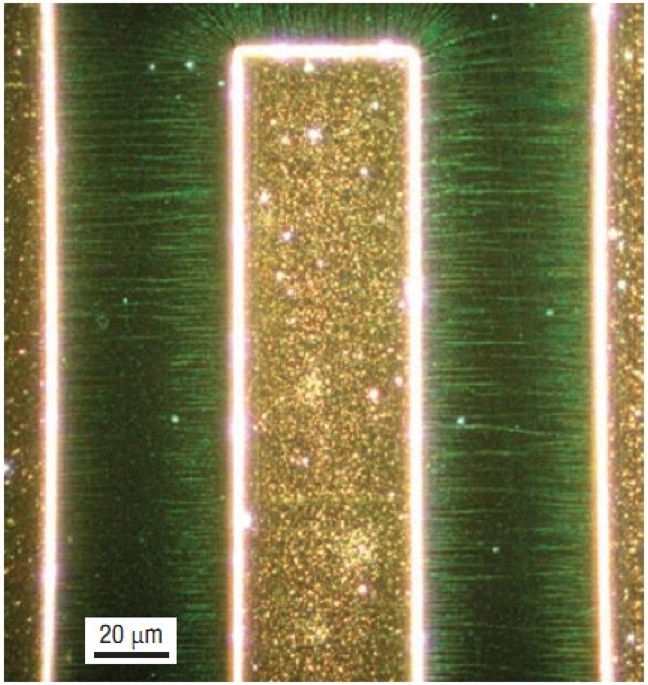

Sanchez-Valencia et al. *Nature 512, 61–64 (2014)*

# Separation by dielectrophoresis

- AC voltage between electrodes
- Metallic CNTs attracted to electrodes and removed from suspension
- Only small scale (nanograms)



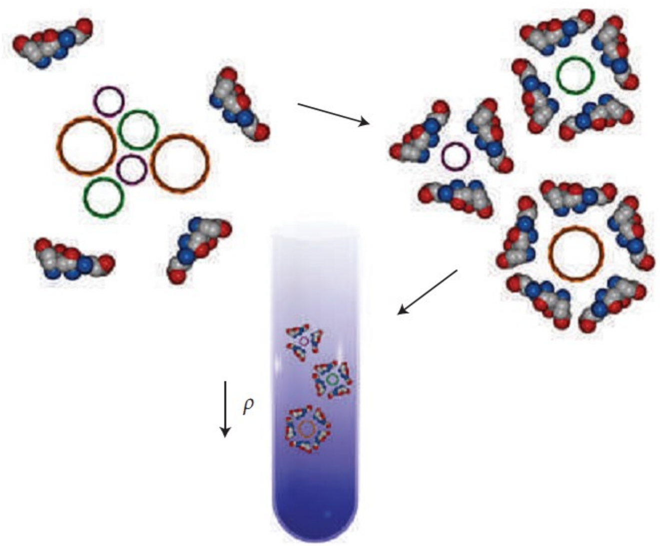



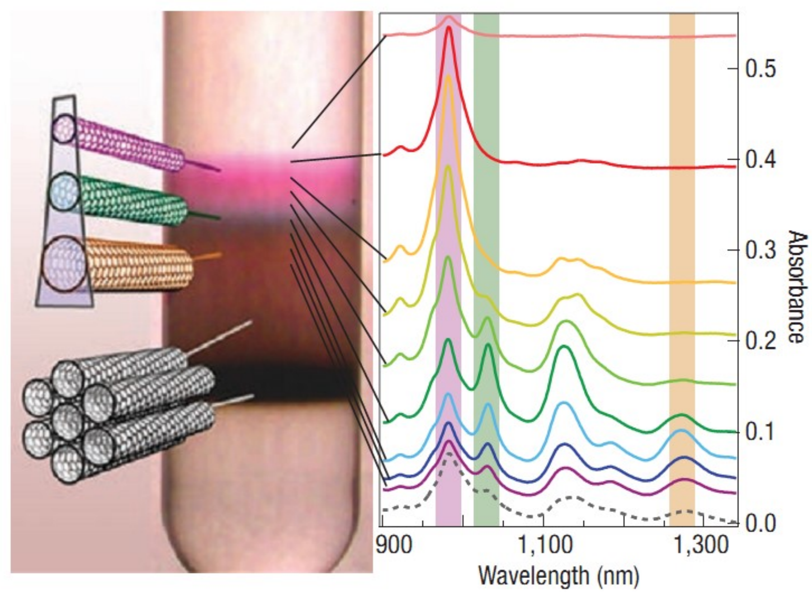


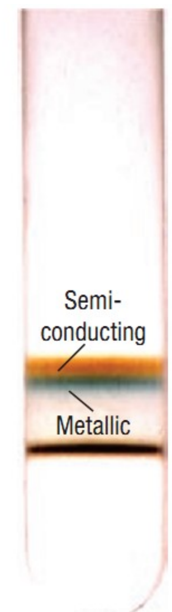

Krupke et al. *Science*, **301**, 344–347 (2003)

# Separation by centrifugation

- Centrifuge CNT suspension at 64000 rpm -> 200000 g
- CNTs are sorted according to density
- Pick up some part of vial and repeat
- 97% of CNTs are within 0.2 Å of mean diameter



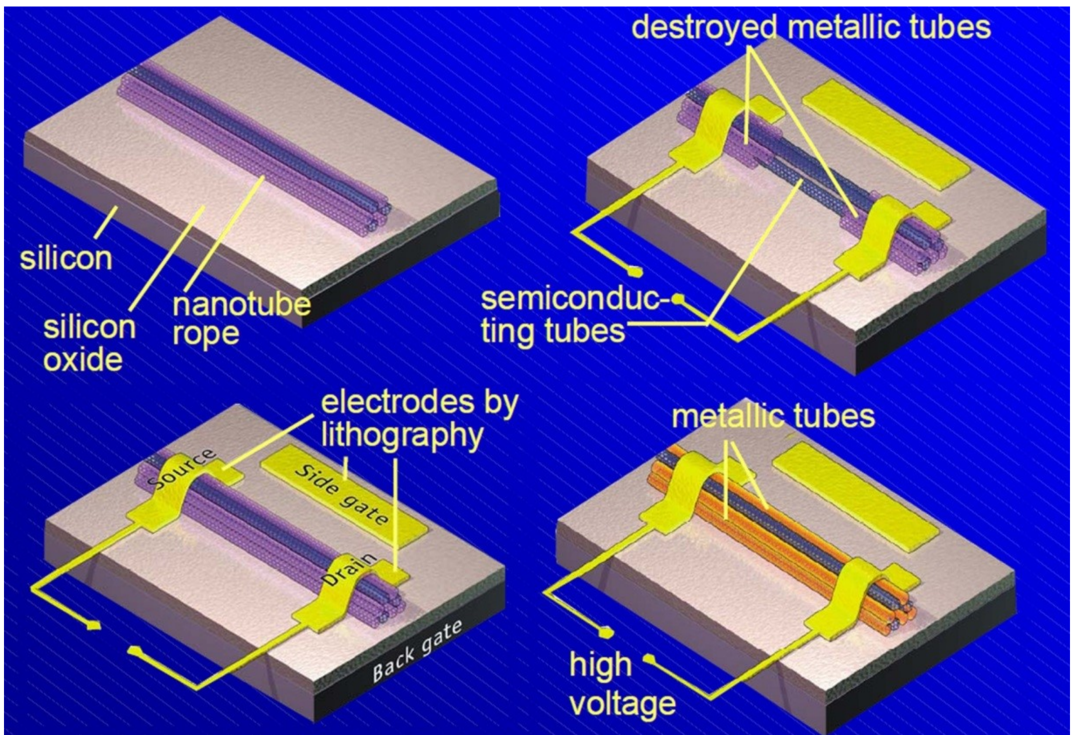



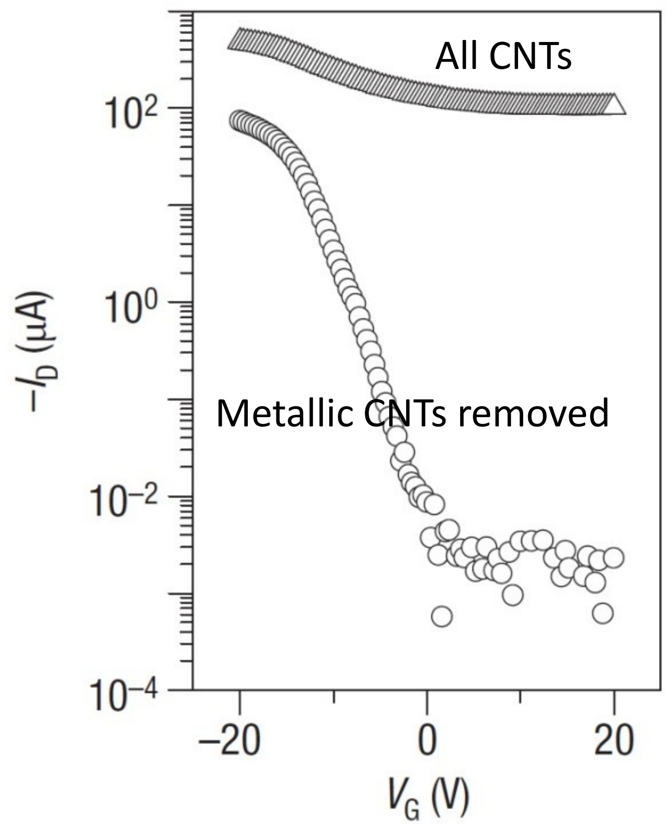




Arnold et al. *Nature Nanotech.* **1**, 60–65 (2006)

# Selective destruction

- Apply gate voltage to switch off semiconducting CNTs
- Apply high S/D voltage
- Metallic CNTs are heated and destroyed
- Difficult for large scale circuits
- May destroy nearby CNTs



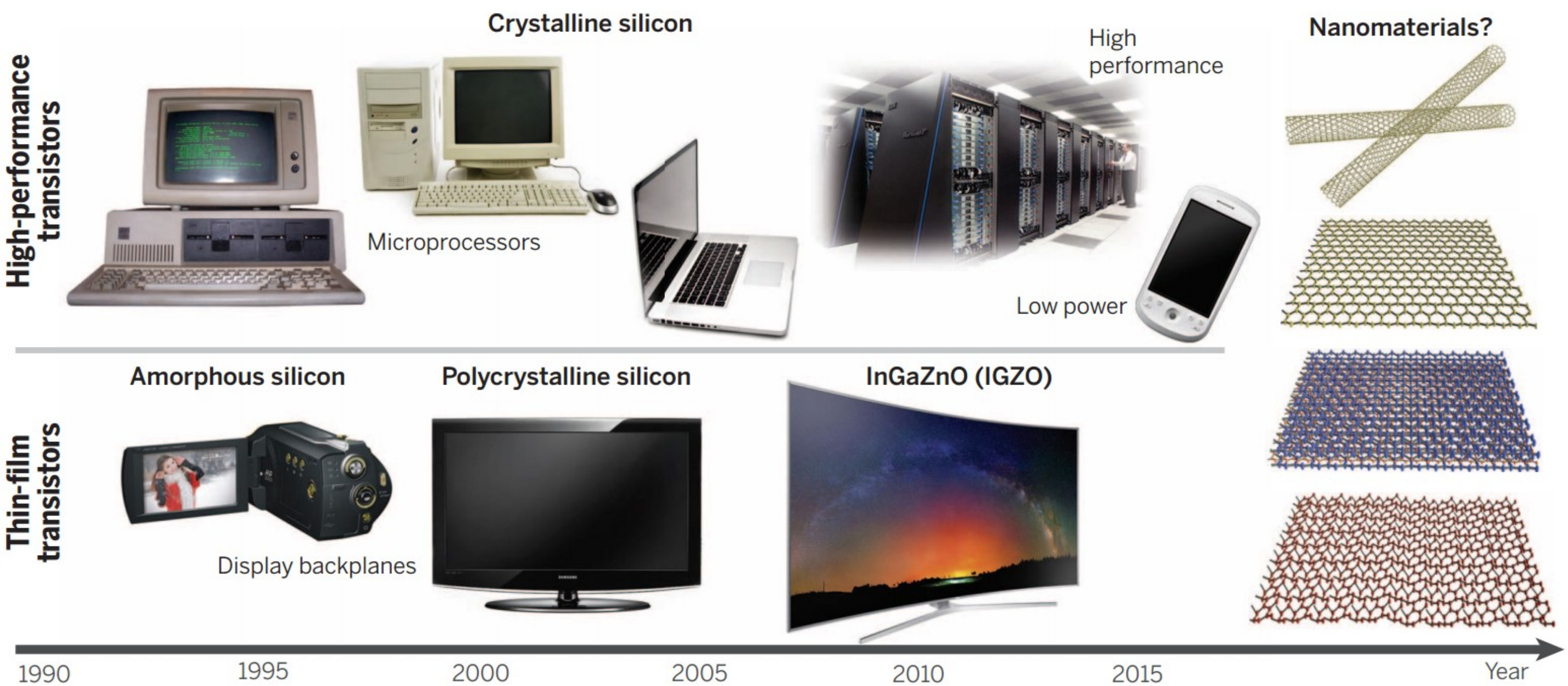



# Outline

- Basics of graphene and CNTs
  - Structural
  - Electronic
  - Production of CNTs
- Advantages of CNTs for FETs
  - Electrostatics -> length scaling
  - High-k compatibility
  - Band-to-band tunneling
- Challenges of CNT integration
  - Contacts
  - Doping
  - Positioning
  - Chirality control
- Towards integration
  - Flexible electronics
  - High frequency performance

# Thin film transistors

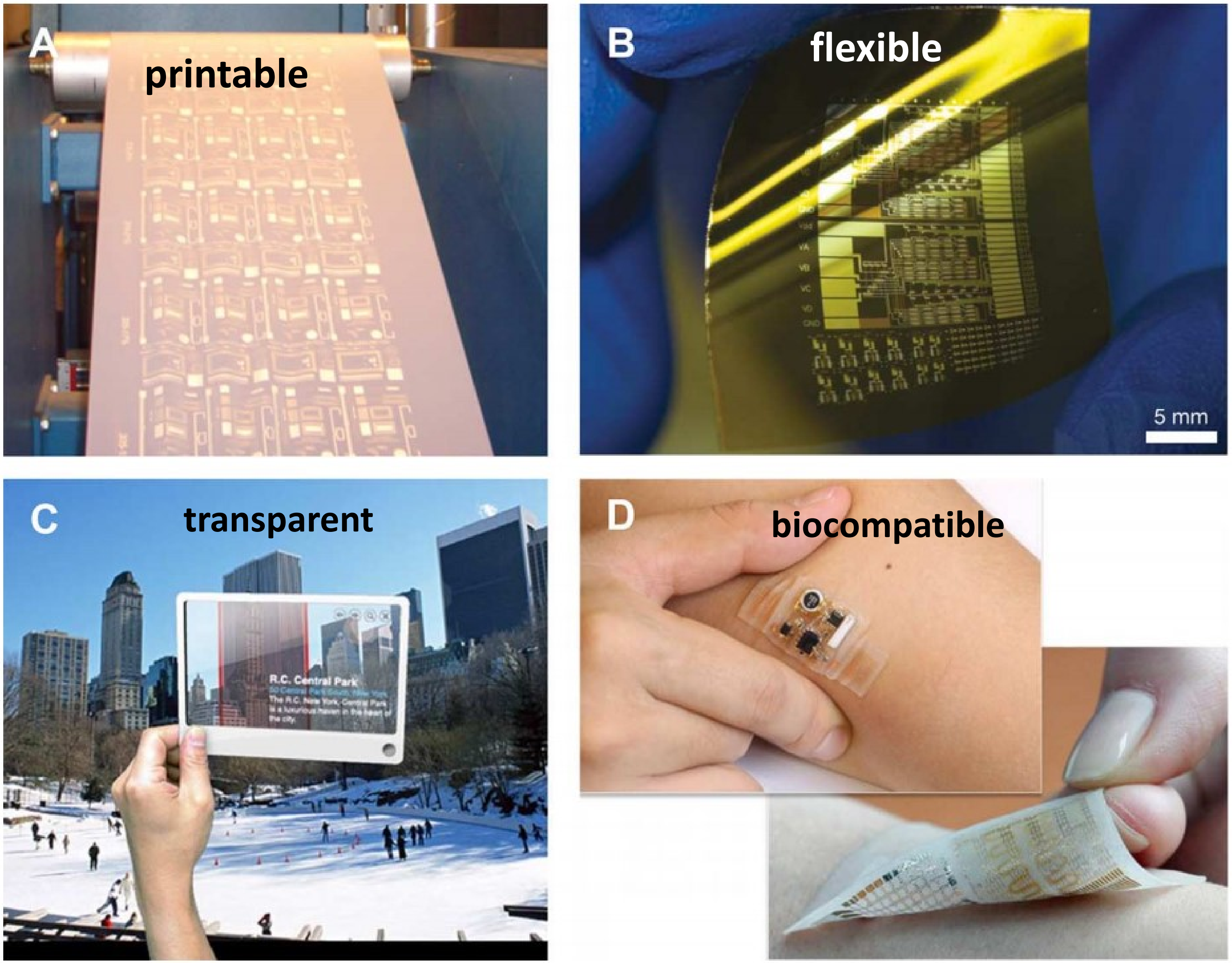
- Printed / flexible / transparent / biomedical electronics
- Lower requirements on size and speed
- More sensitive to cost and fabrication complexity
- Amorphous-Si, Poly-Si, InGaZnO, organic molecules





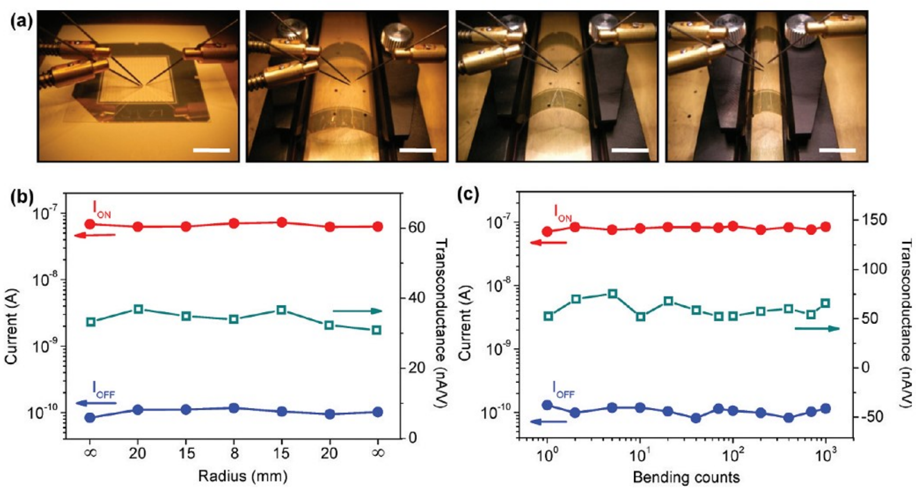

Franklin. *Science*, **349**, 6249 (2015)

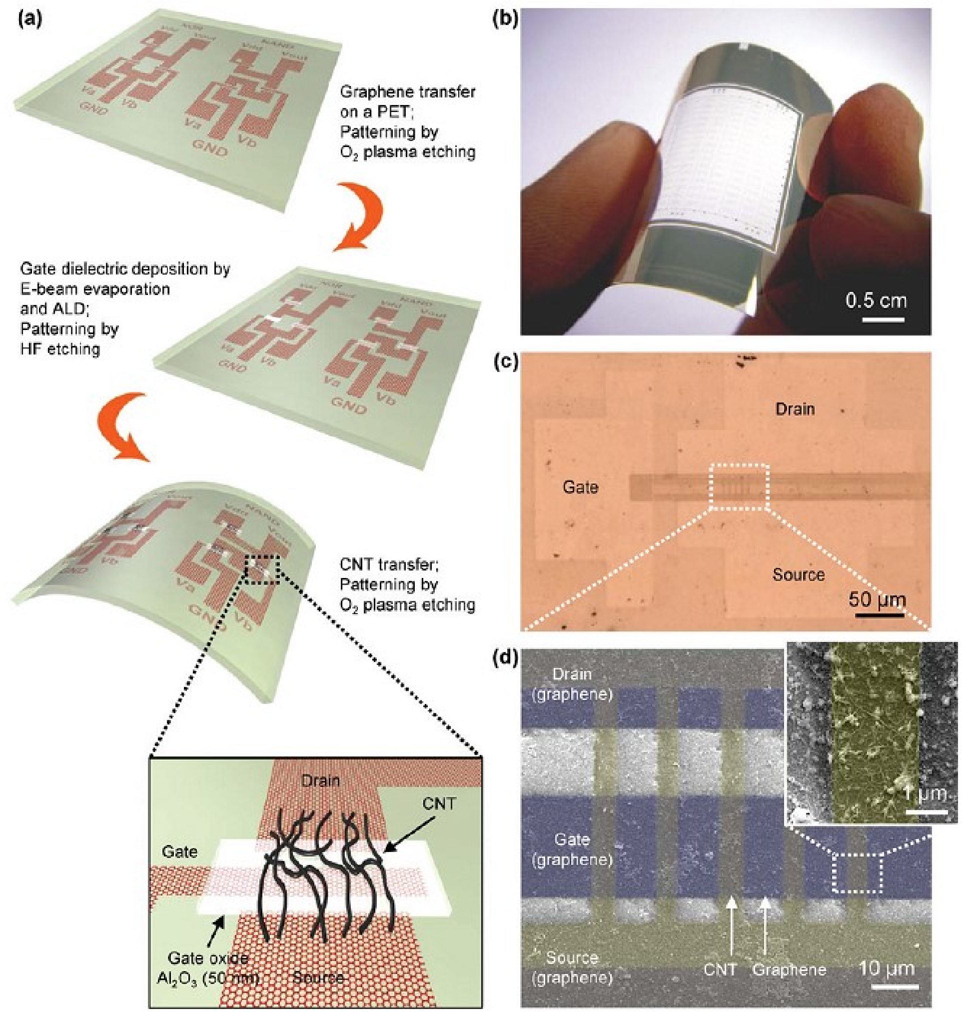
# Thin film transistors



# Flexible electronics

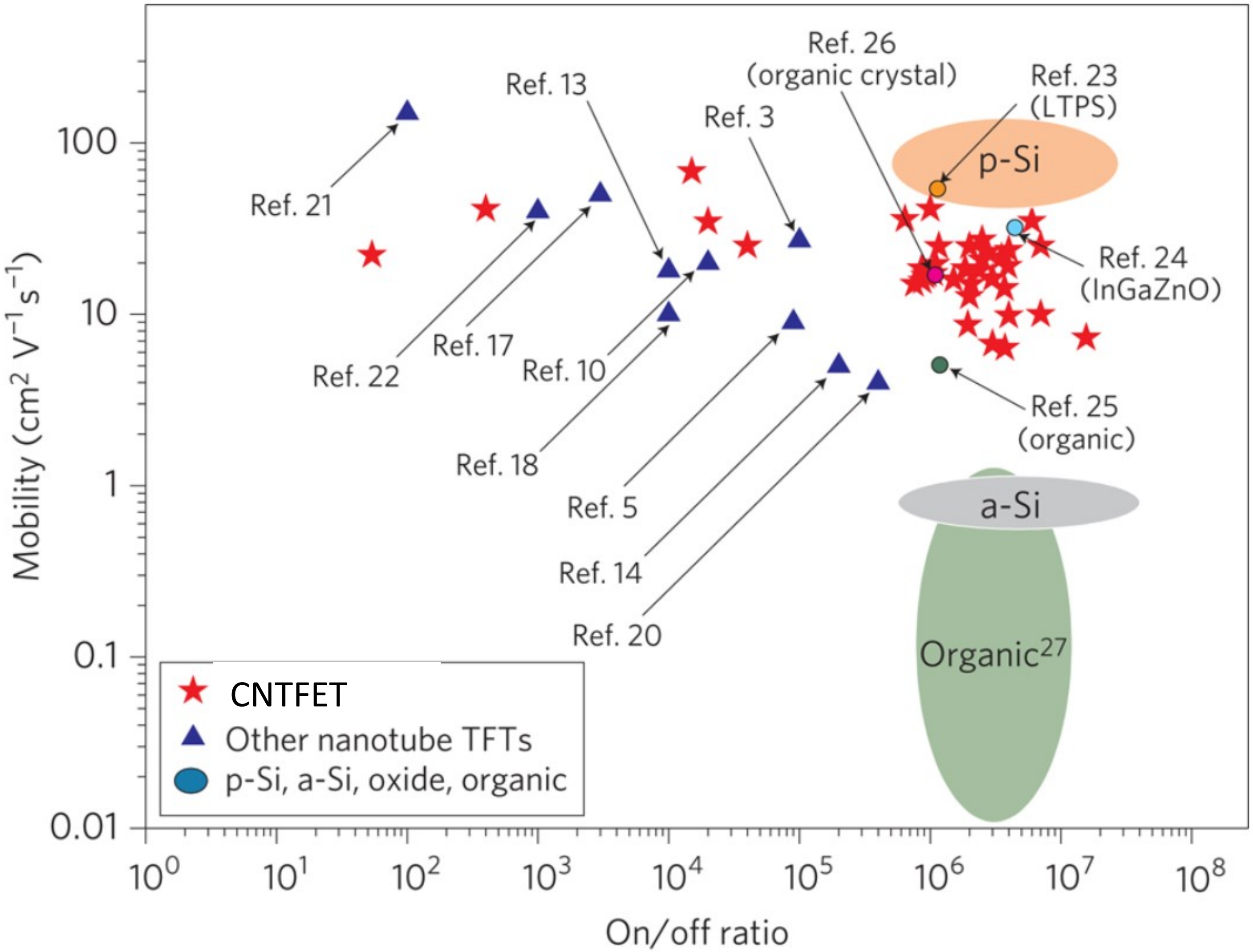
- Graphene for electrodes
- CNTs for channel
- No degradation when bent




Yu et al. *Nano Lett.* **11,** 1344–1350 (2011)

# Thin film transistors comparison

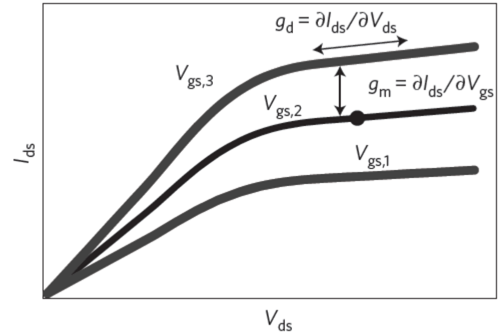


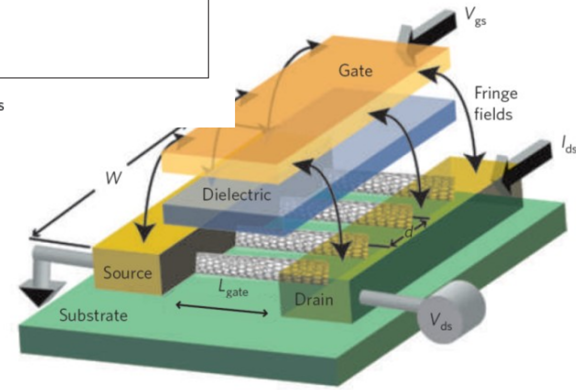

Sun et al. *Nature Nano*. 6, 156–161 (2011)

# Requirements for RF applications

- Need high $g_m$ and low $g_d$ -> only semiconducting CNTs

- Minimize paracitic capacitance / CNT -> dense array of CNTs




$$f_T = \frac{g_m}{2\pi}\frac{1}{(C_{gs}+C_{p,gs}+C_{p,gd})((R_{p,s}+R_{p,d})g_d+1)+C_{p,gd}g_m(R_{p,s}+R_{p,d})}$$

**Table 1 | Ideal parameter values for making a high-frequency field-effect transistor from single-walled nanotubes.**

| Property/parameter | Target value or range | Justification |
|---|---|---|
| Diameter | 1.5–2.0 nm | Current is largest in this range[54–55]. |
| Chirality | Semiconducting and same (*n*,*m*) | To obtain identical transport properties. |
| Purity | >99% semiconducting nanotubes | No metallic nanotubes for high gain and high $f_{max}$. |
| Length | >1 μm | Nanotube length must be longer than the intended channel length. |
| Density | >10 nanotubes μm$^{-1}$ | Reduces the parasitic capacitance per nanotube; increases current carrying capacity; improves impedance matching. |
| Alignment | All parallel | Results in higher transconductance and denser nanotube packing. |
| Uniformity | Wafer scale | Essential for large-scale processing. |

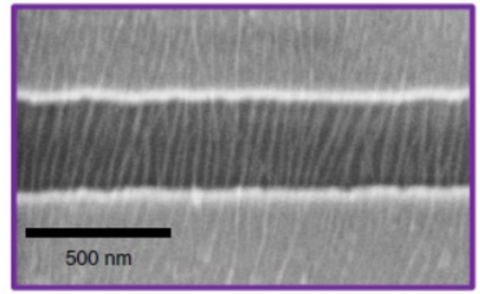
Rutherglen, *Nature nanotechnol*. **4**, 811 (2009)

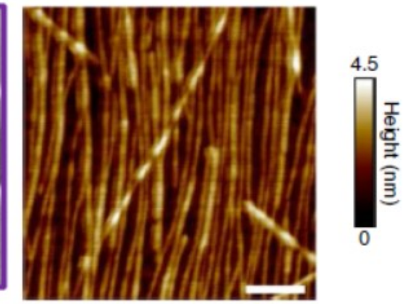
# RF performance

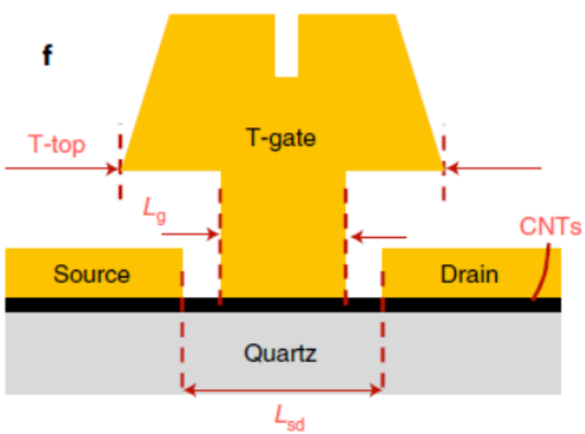
- Can not use single CNT due large parasitic capacitance (and impedance mismatch)

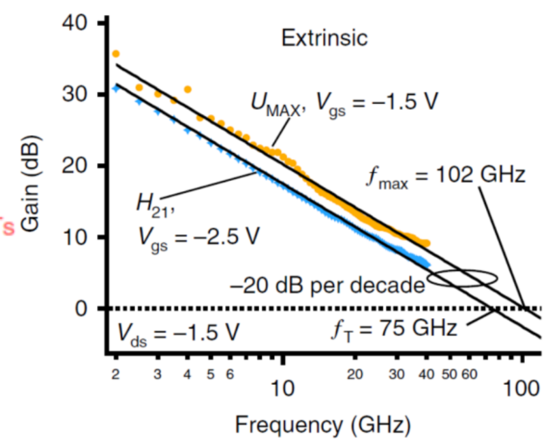
- Use semiconducting CNTs separated using centrifugation

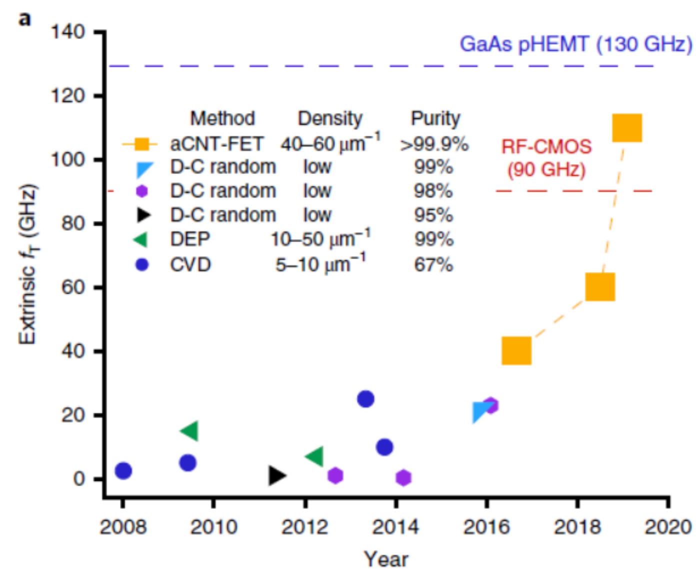
- $f_T$ / $f_{max}$ > 100 GHz




Rutherglen, *Nature electronics*. **2**, 530-539 (2019)

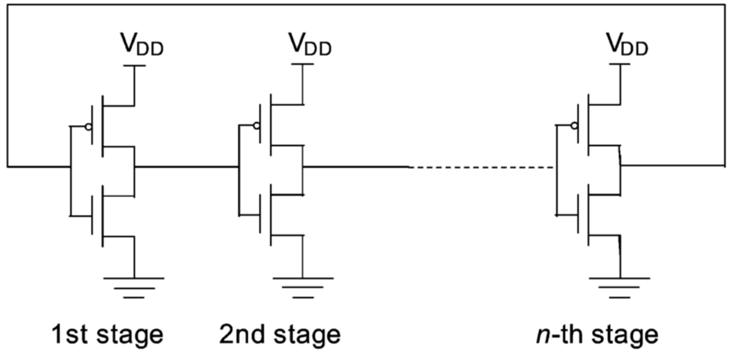
# Ring Oscillator

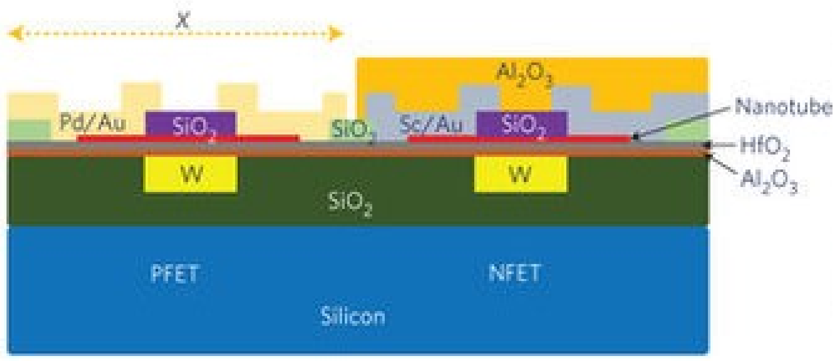
- Odd number of inverters in series, output connected to input.

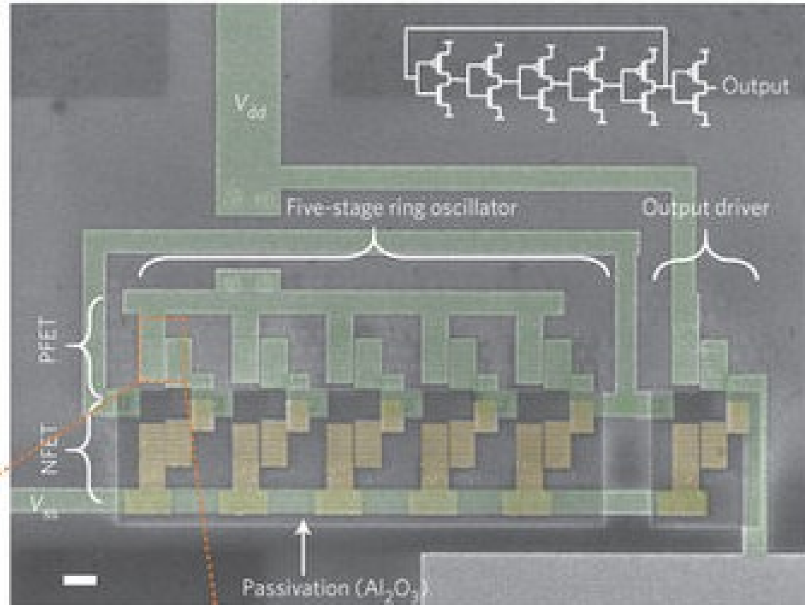
- Used to measure speed of digital technologies.

- Centrifuged NWs = 99.9% semiconducting

- Switching time = 355 ps /stage (2.8 Ghz)



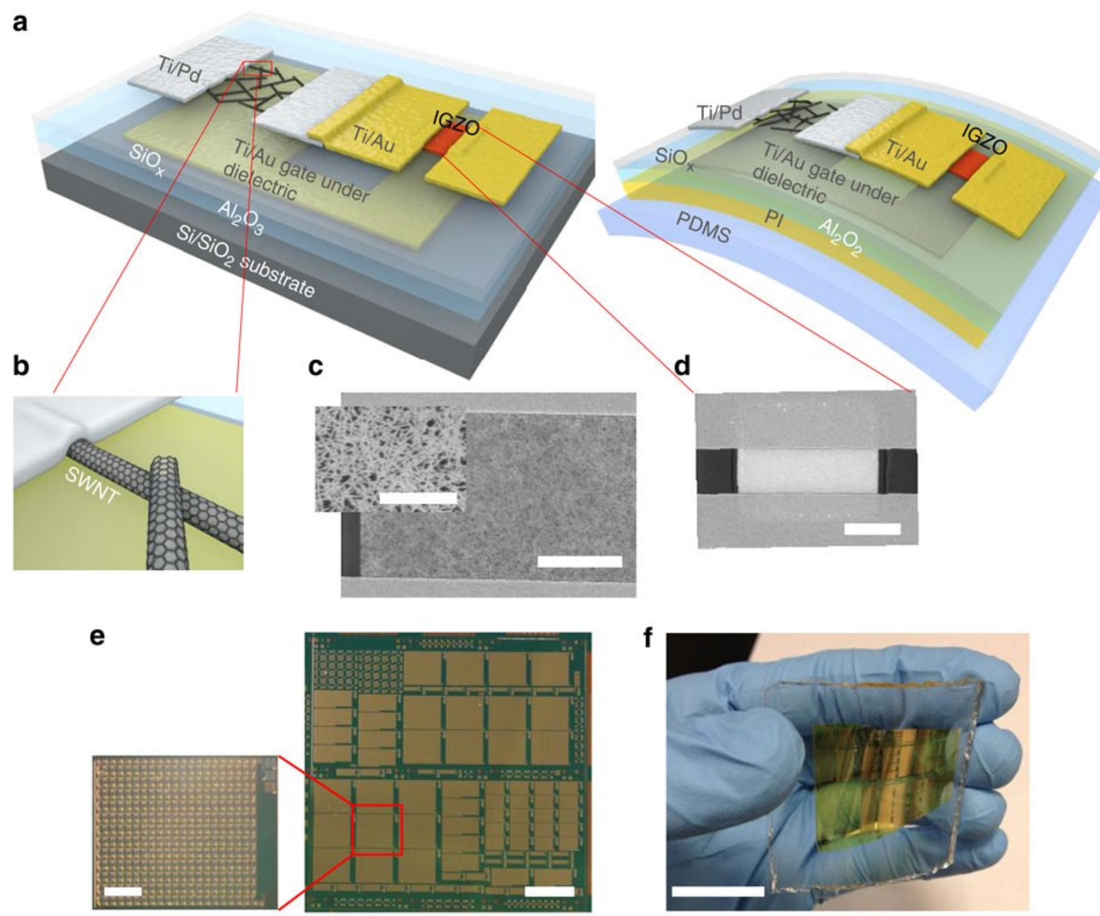



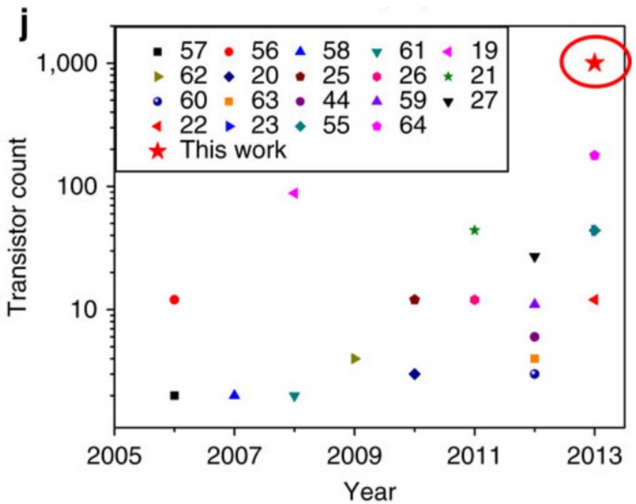




Han, *Nature Nanotechnology* **12**, 861–865 (2017)

# Large scale integration

- p-type CNTFETs (from centrifuged CNTs)
- n-type InGaZnO (sputtered)
- Flexible substrate
- 501 stage ring oscillators
- >1000 transistors

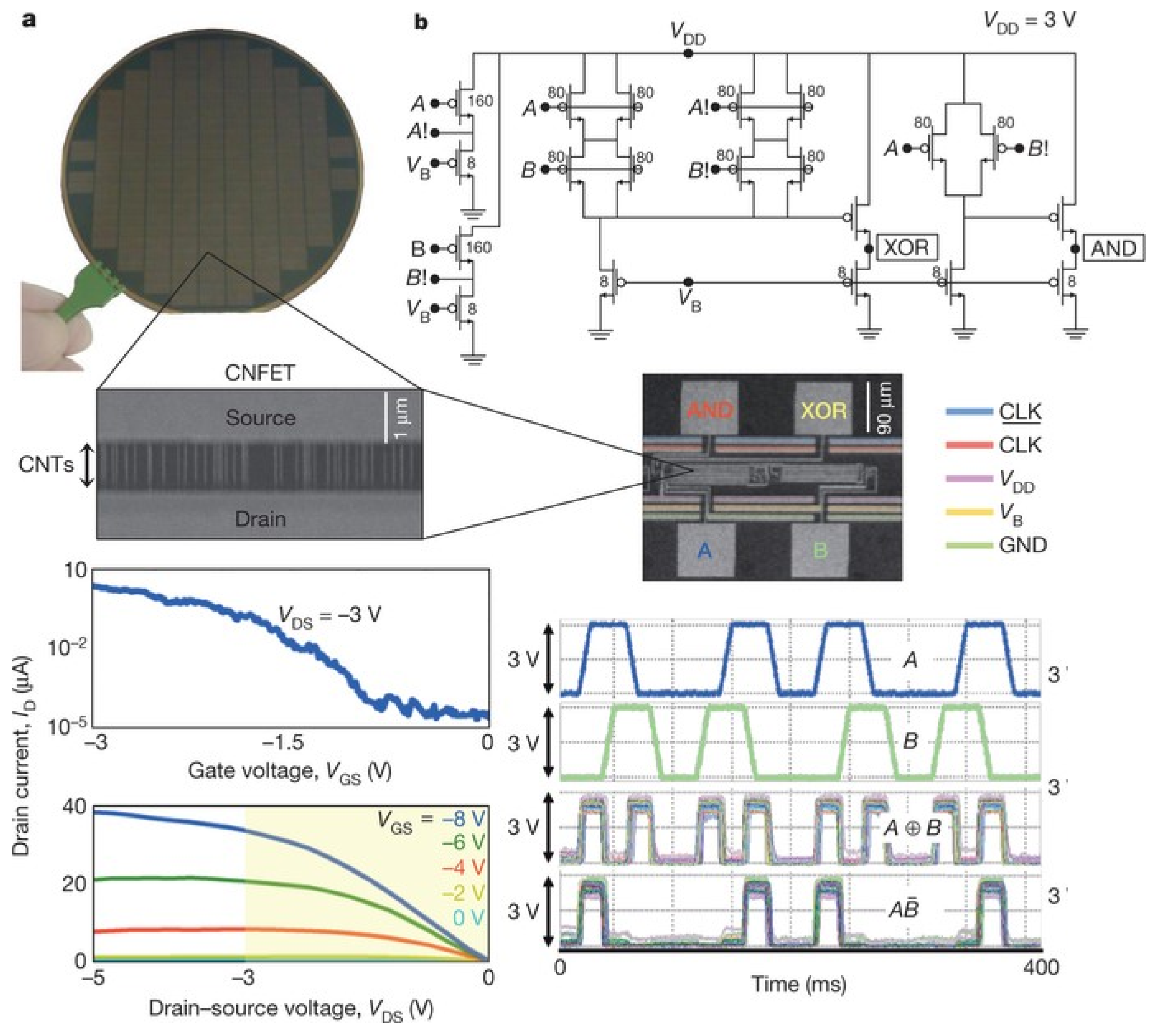



Chen et al. *Nature Comm.* 5, 4097 (2014)

# CNT computer

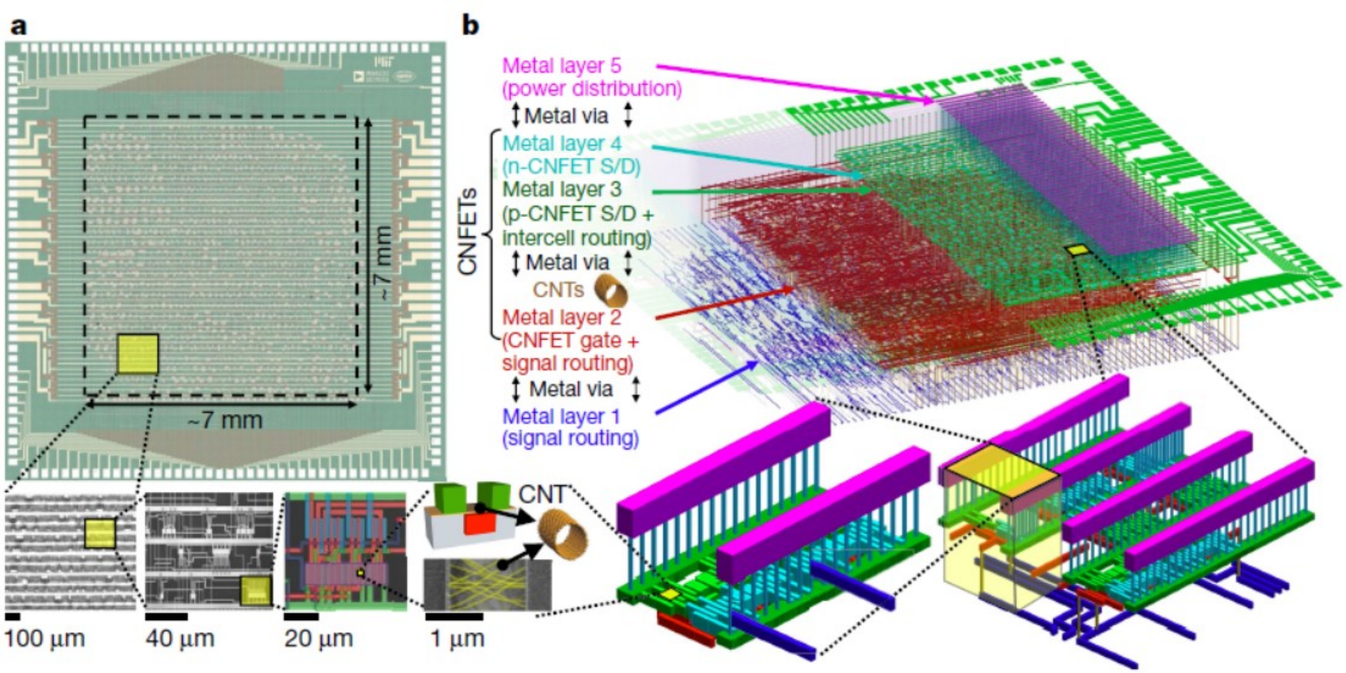
- 178  p-type CNTFETs. Aliged growth -> transfer -> burn-off
- Not CMOS, only p-type.
- Counting and number sorting.
- 1980’s level.

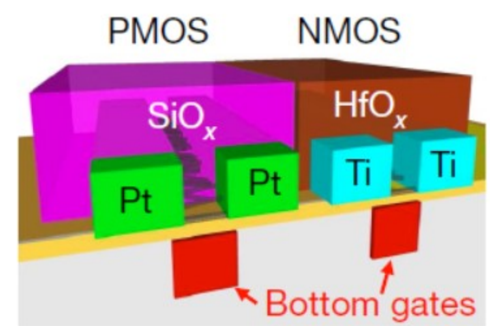


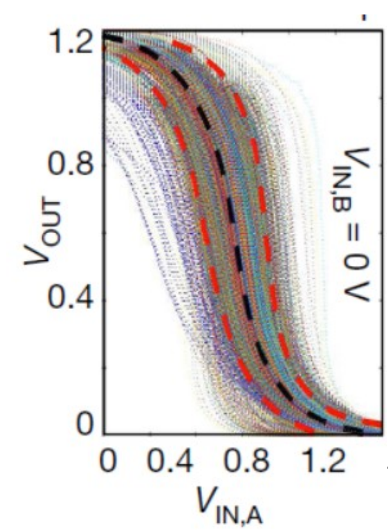

Shulaker et al. *Nature*, **501**, 526-530 (2013)

# Larger CNT computer

- 16-bit microprocessor with 14 000 CNTFETs
- n and p by varying contact work function and ALD oxide conditions
- Use stacked layers with n/p and routing
- Use circuit design to reduce effects of metallic CNTs (only 99.99 % semiconducting CNTs)




Hills et al. *Nature*, **572**, 595 (2019)

# Summary

- **Individual CNTs have great electronic properties**
  - High mobility
  - Coaxial gate + thin gives good electrostatics -> scaling
  - Compatible with high-k dielectrics
  - No surface scattering

- **CNTs are difficult to integrate in large scale circuits**
  - Schottky barriers at contacts
  - Unstable doping
  - Poor position control
  - Semiconducting / metallic mix