Carbon-Based Electronics:
Will there be a carbon age to follow the silicon age?

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Solid State Seminar

9-13-13

Outline

- Review of development of Carbon Nanotube (CNT) transistors (for logic)
  - Issues, progress, prospects
- Advent of graphene
  - Recognition of promise of graphene nanoribbons (GNRs) for logic transistors
  - Issues, progress, prospects
- Summary of prospects for carbon transistors

C60: Birth of carbon Nanotech era

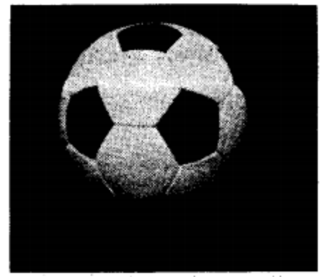
162 LETTERS TO NATURE NATURE VOL. 318 14 NOVEMBER 1985

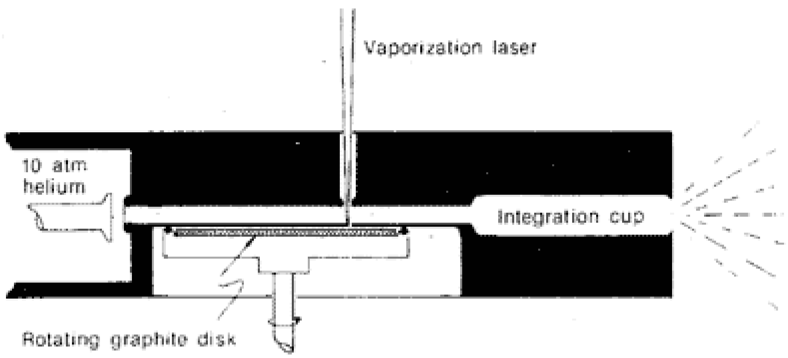
C_{60}: Buckminsterfullerene

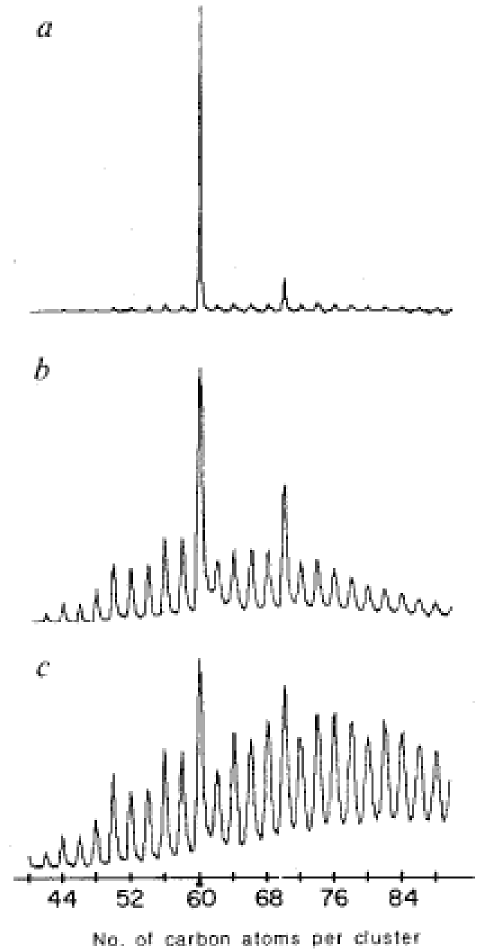
H. W. Kroto*, J. R. Heath, S. C. O'Brien, R. F. Curl & R. E. Smalley

Rice Quantum Institute and Departments of Chemistry and Electrical Engineering, Rice University, Houston, Texas 77251, USA

Fig. 1 A football (in the United States, a soccerball) on Texas grass. The C_{60} molecule featured in this letter is suggested to have the truncated icosahedral structure formed by replacing each vertex on the seams of such a ball by a carbon atom.





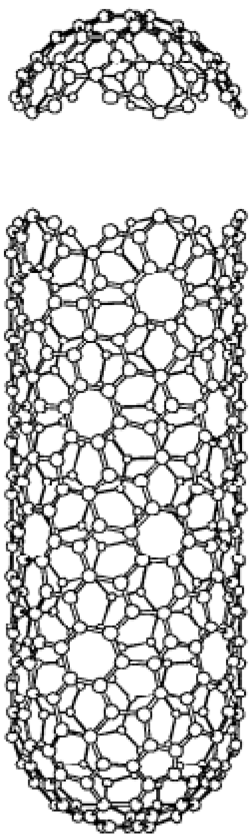


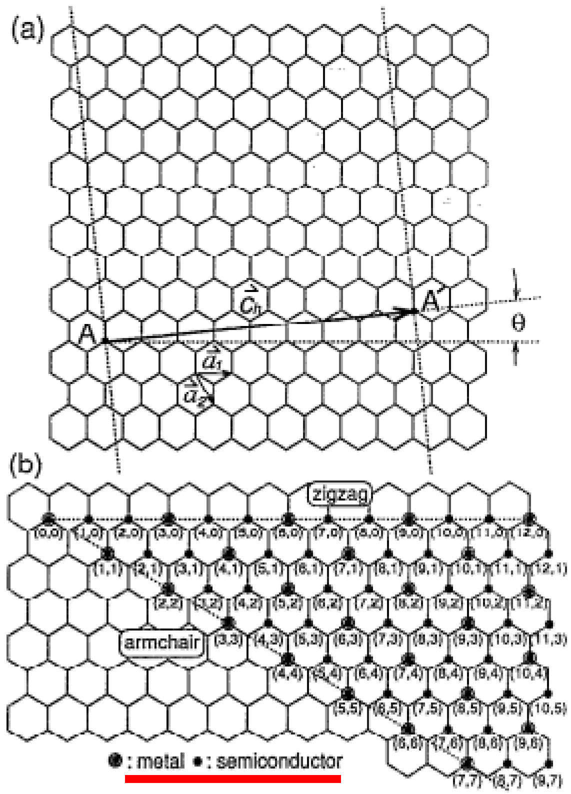
Main properties of carbon nanotubes predicted before discovery!

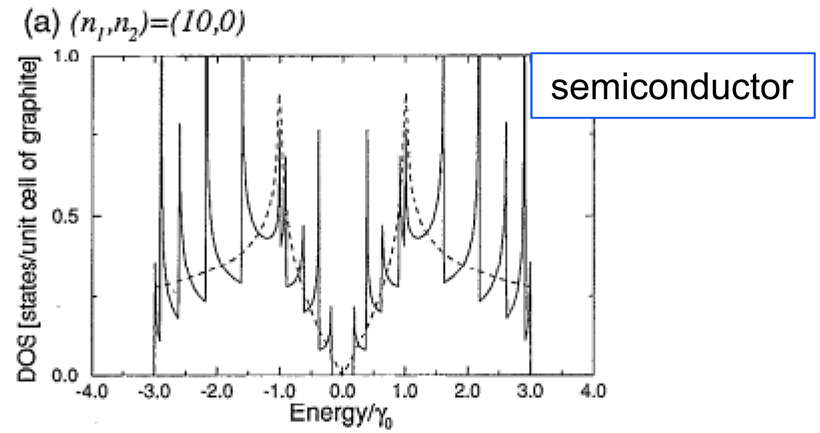
Electronic structure of chiral graphene tubules

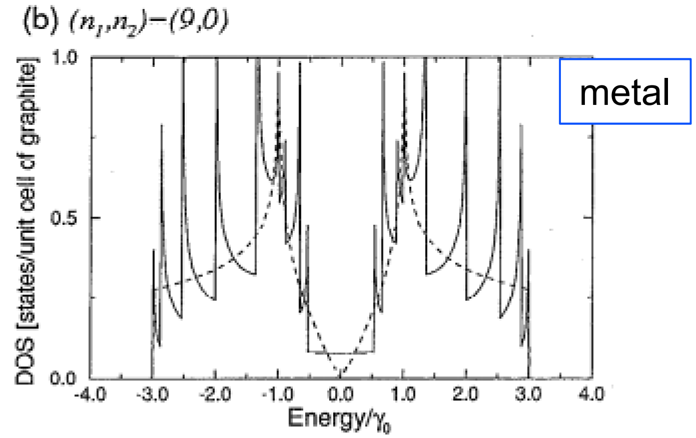
R. Saito, M. Fujita, G. Dresselhaus, and M. S Dresselhaus
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 27 January 1992; accepted for publication 4 March 1992)
Applied Physics Letters

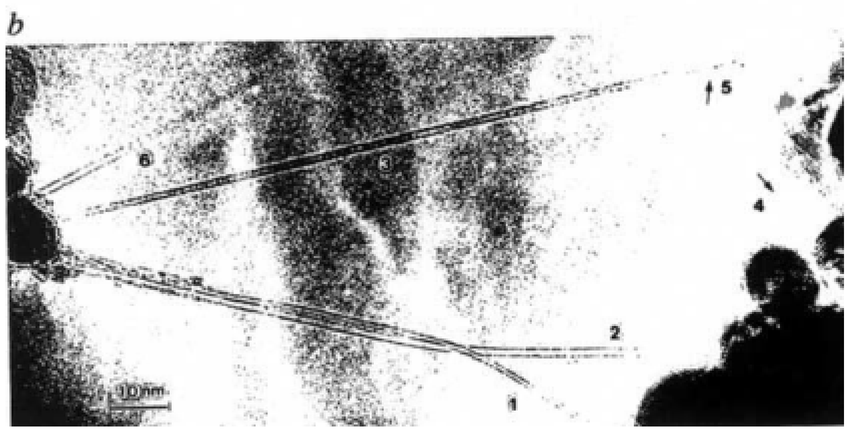


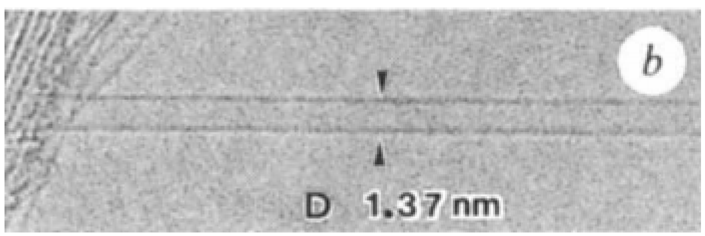


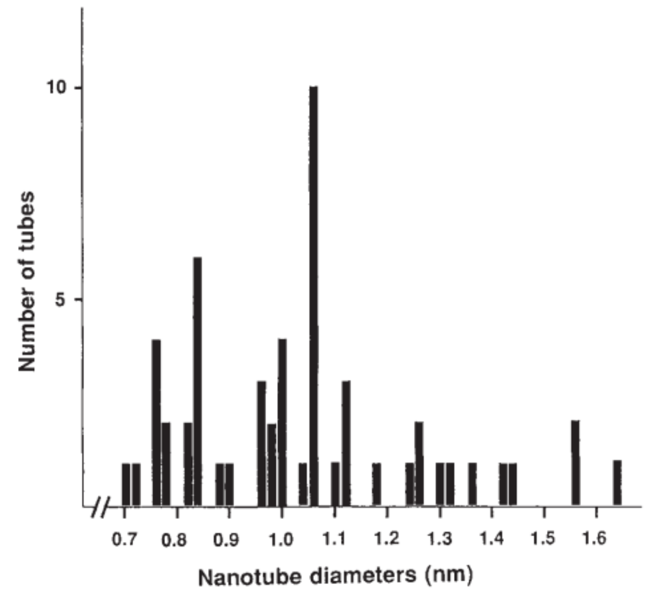




Single-wall carbon nanotubes discovered in carbon 'soot' by TEM



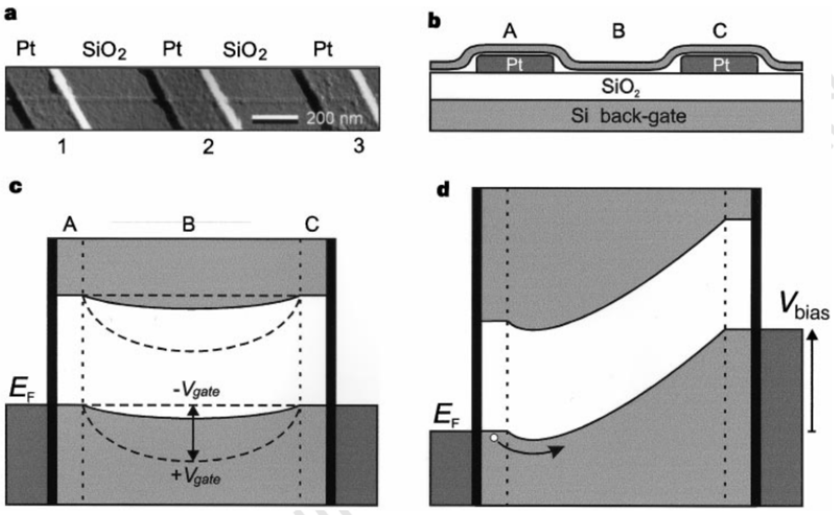


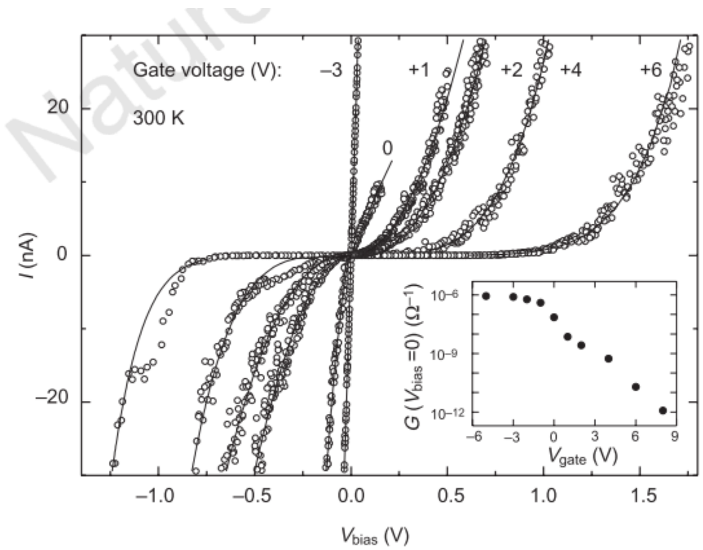


Iijima and Ichihashi, Nature (1993) [NEC]

CNT Transistor

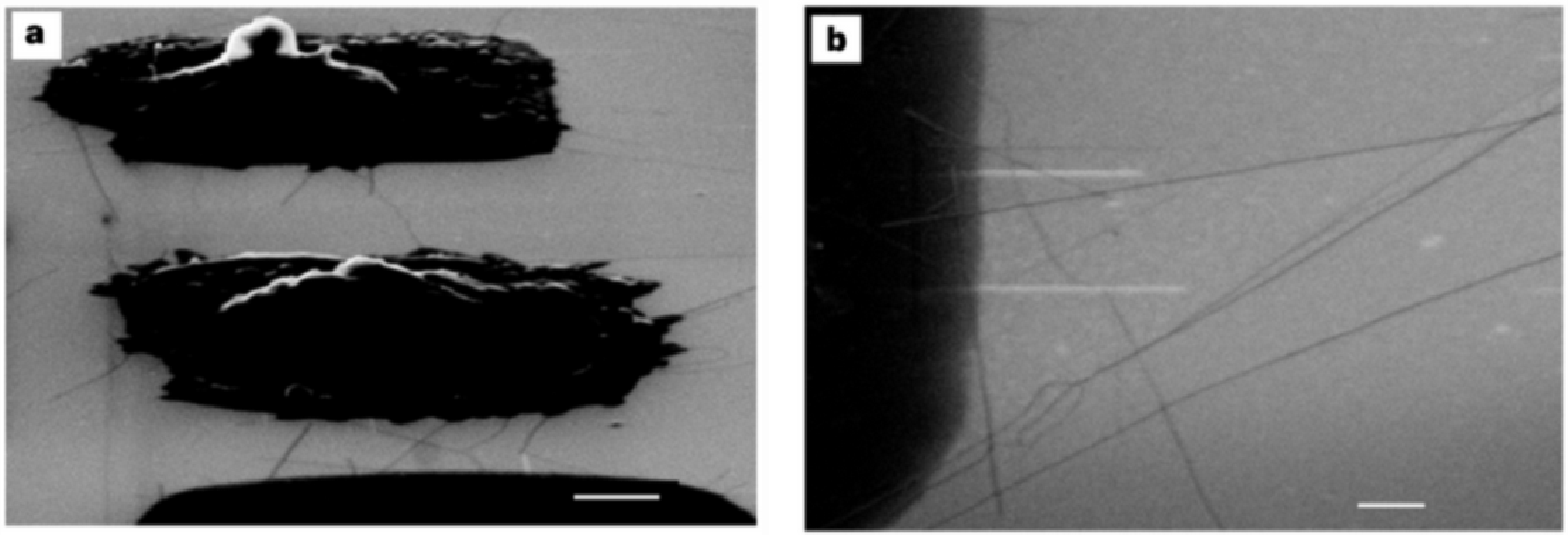
Laser vaporization method for CNT synthesis





Tans, et al., Nature (1998) [Dekker group, Delft]

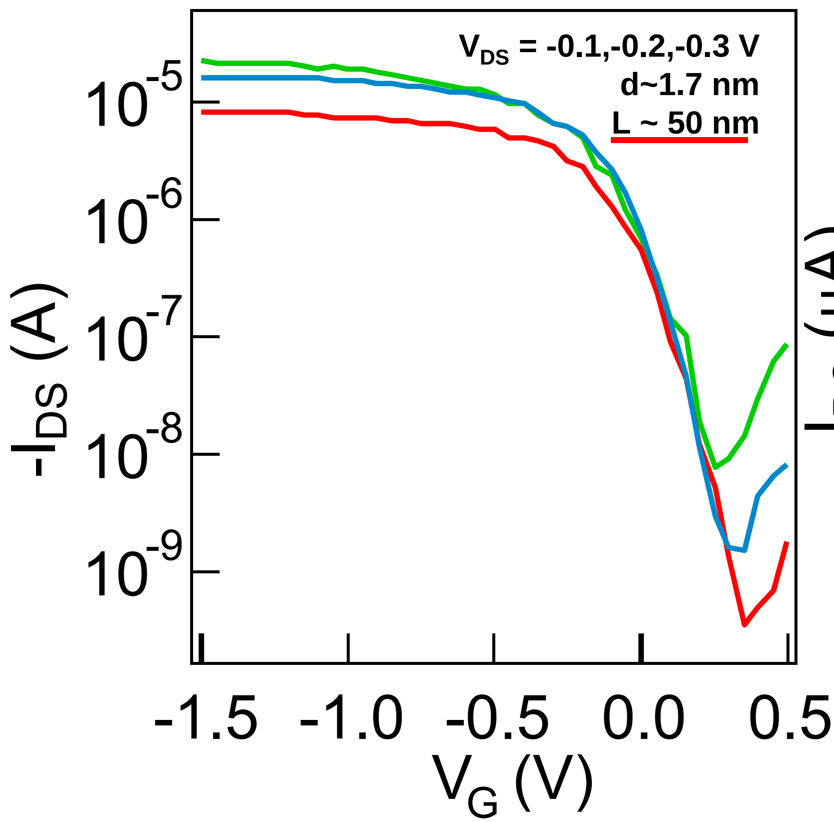
Catalytic CVD growth of CNTs on a surface

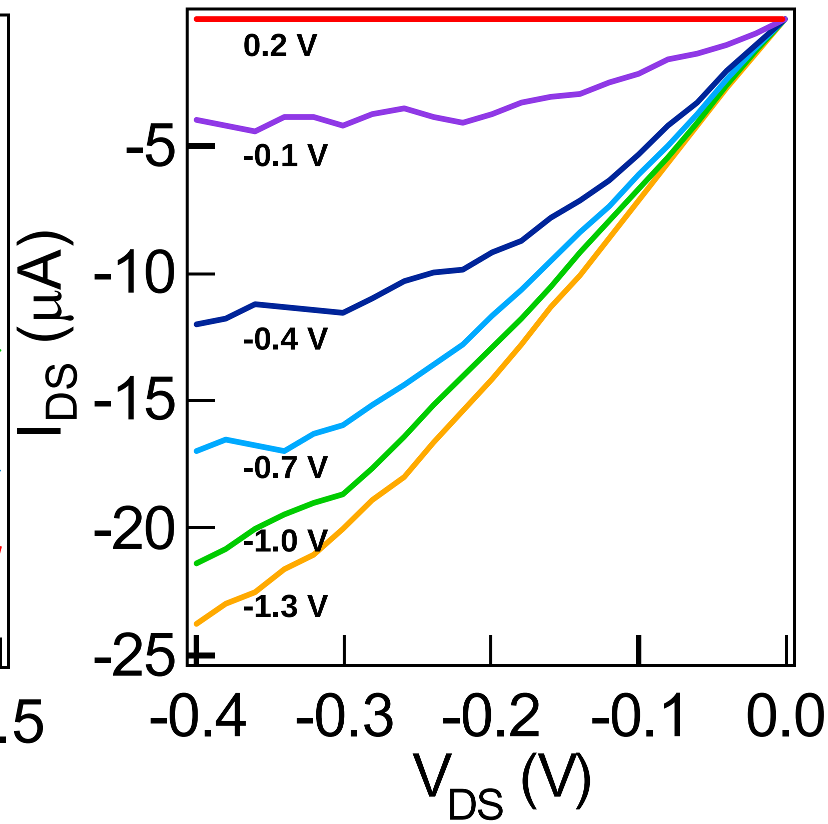


Catalyst: Fe(NO3)3·9H2O/alumina/methanol suspension
CVD at 1000C with methane

Kong, et al, Nature (1998) [Dai group, Stanford]

Self-Aligned Ballistic FETs w/High-k

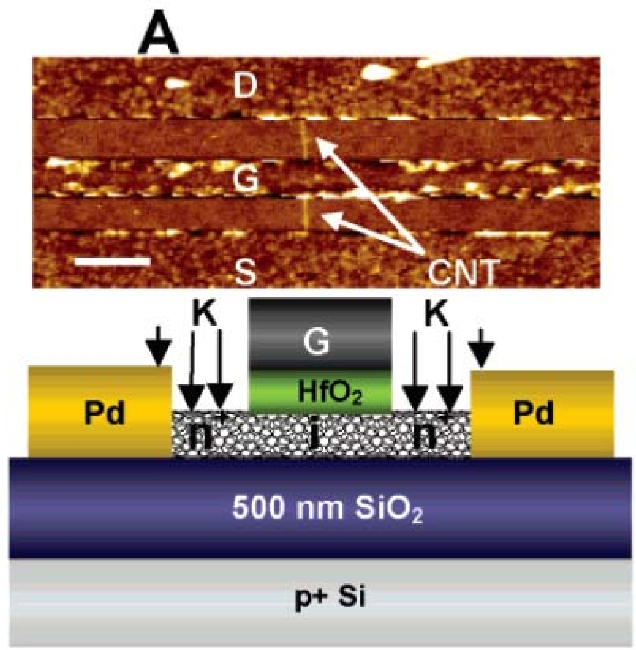


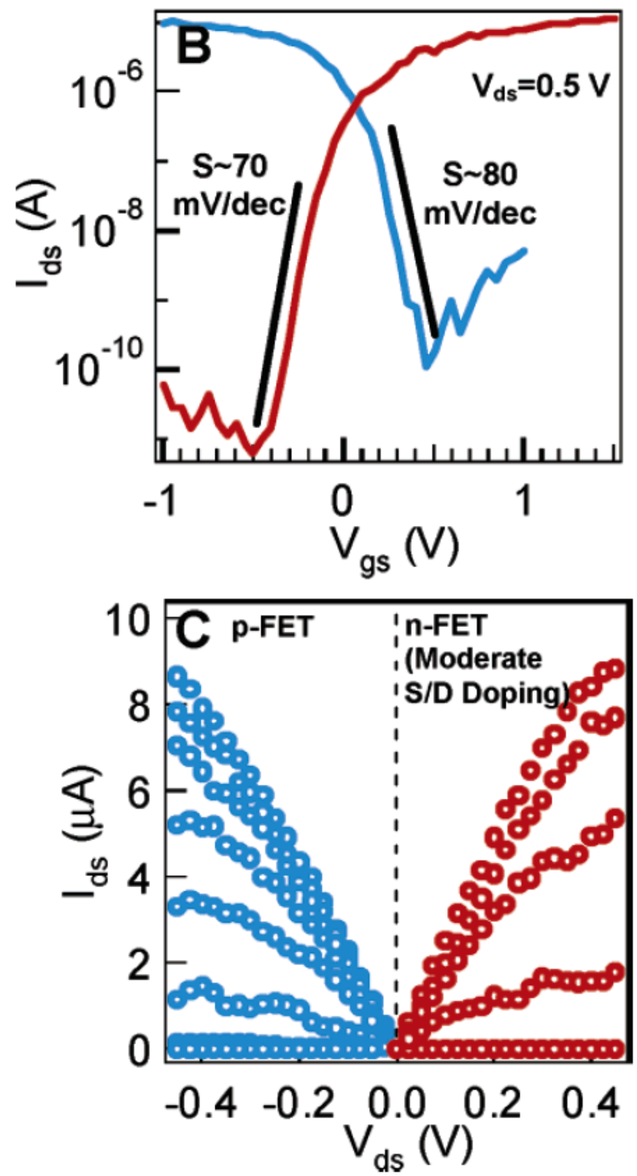


- Pd zero-barrier height contact
- > 5 mA/um at $V_g = V_{DS}$ =0.4V

Javey, et al, Nano Lett. (2004) [Dai group, Stanford]

High Performance p- and n-FETS

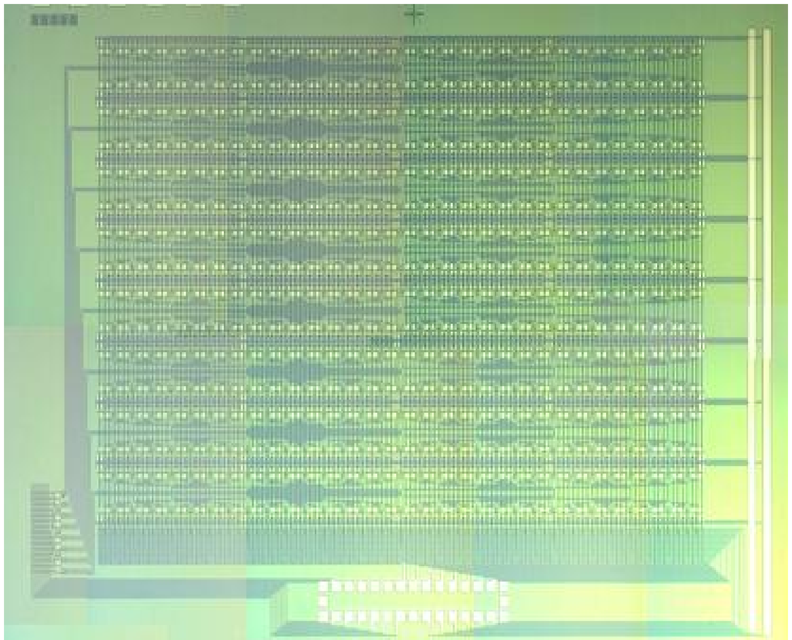


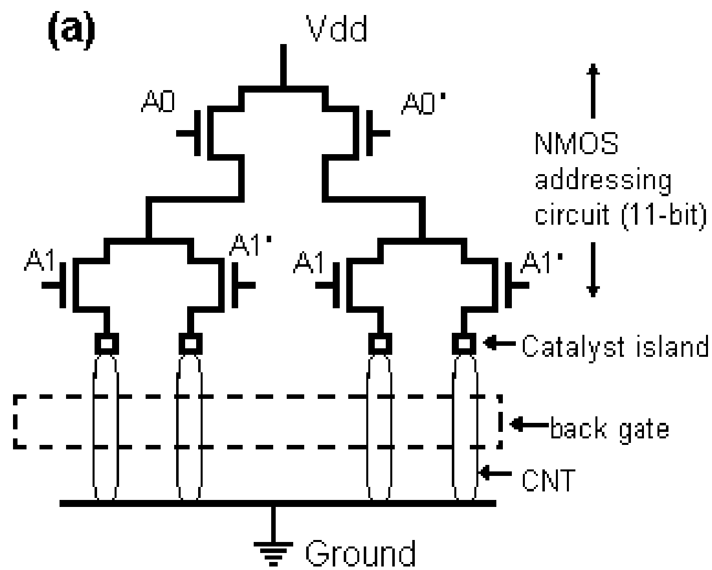


- Doping by adsorption
- Lg = 80nm

Javey, et al, Nano Lett. (2005)
[Dai group, Stanford]

CNT-CMOS Integration Chip

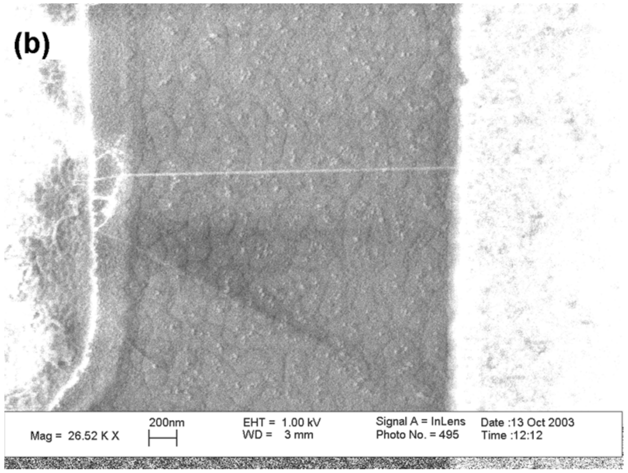


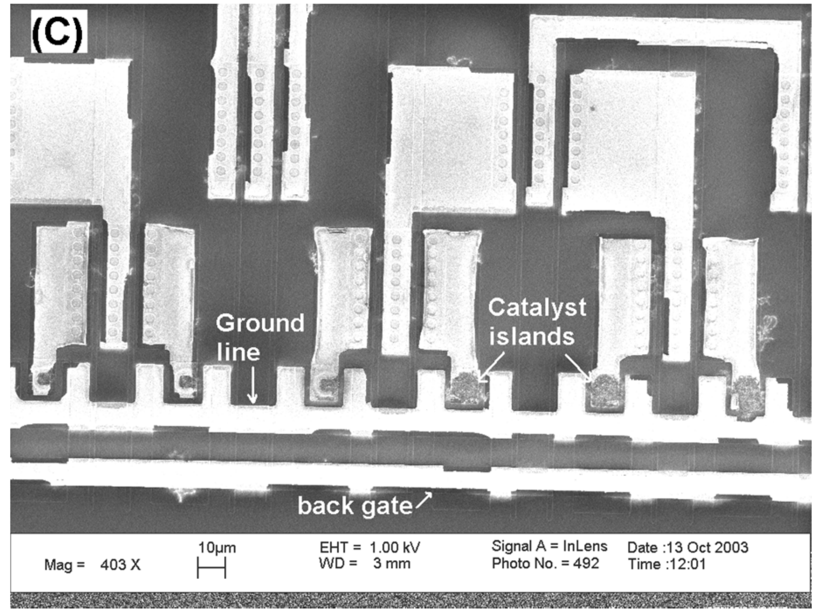


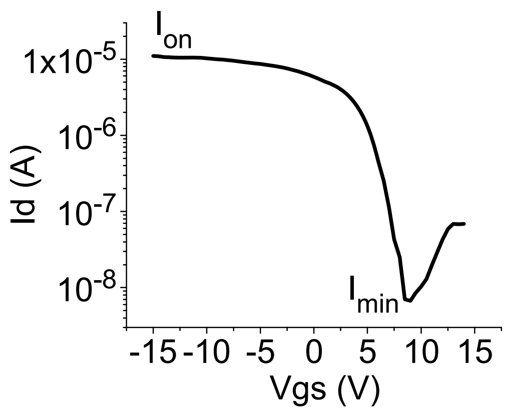
- **NMOS binary tree 11-bit decoder**
- **2048 back-gated CNT transistors**
- **>4000 Si NMOS transistors, 1 μm Microlab baseline process**

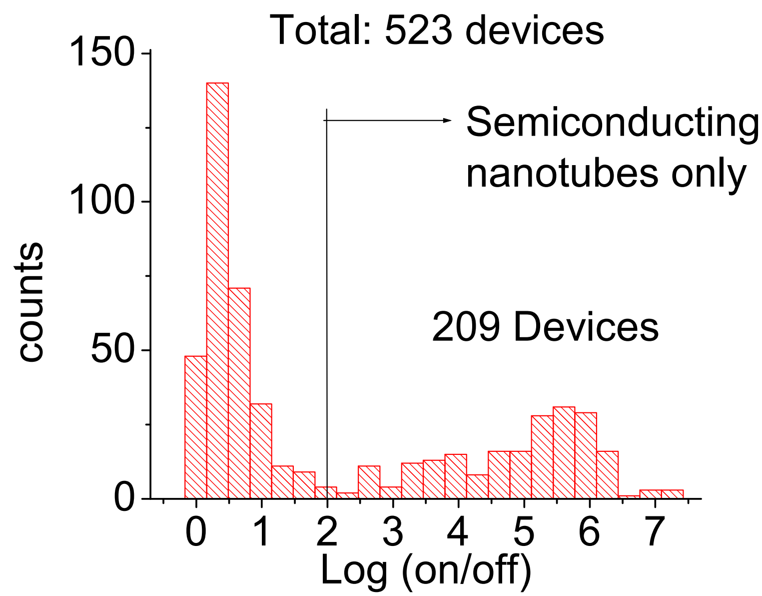
Tseng, et al, Nano Lett. (2004)
[UCB/Stanford, Bokor/Dai groups]

Carbon Nanotube + Silicon MOS Integrated Circuit



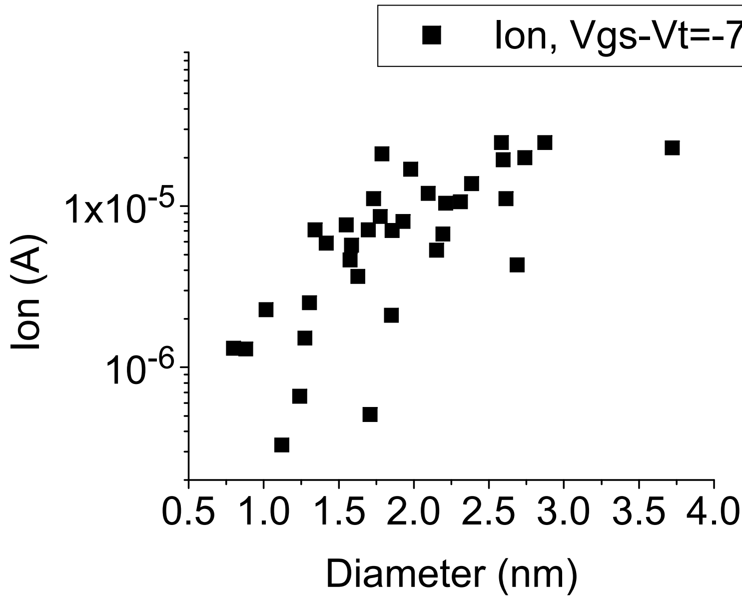




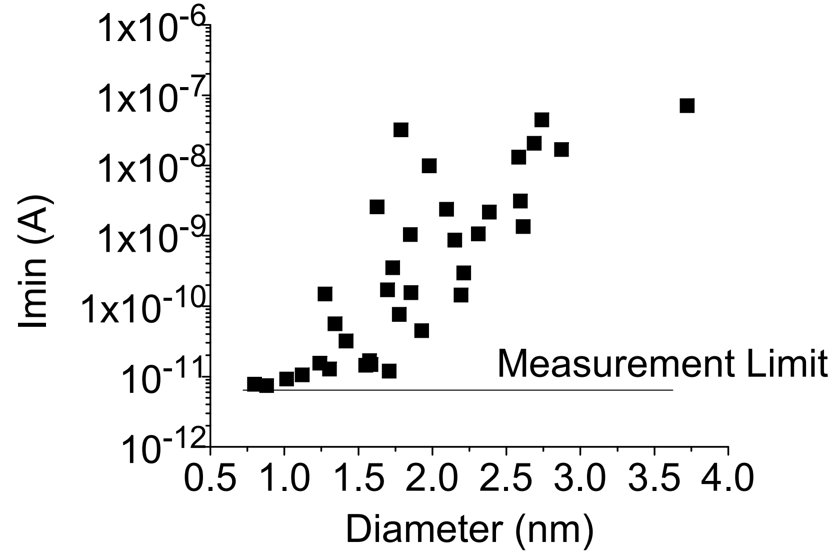


Tseng, et al, Nano Lett. (2004)
[UCB/Stanford, Bokor/Dai groups]

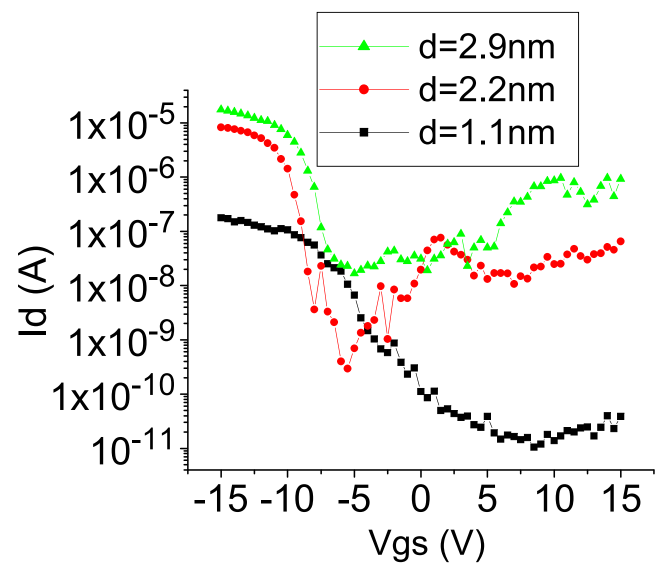
Direct correlation to diameter variation



1 tube per device

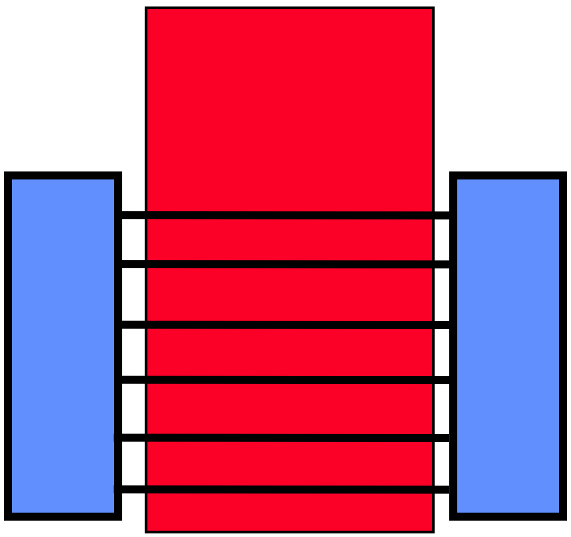


Tseng, et al, Nano Lett. (2006)
[UCB, Bokor group]



Parallel Tube CNTs

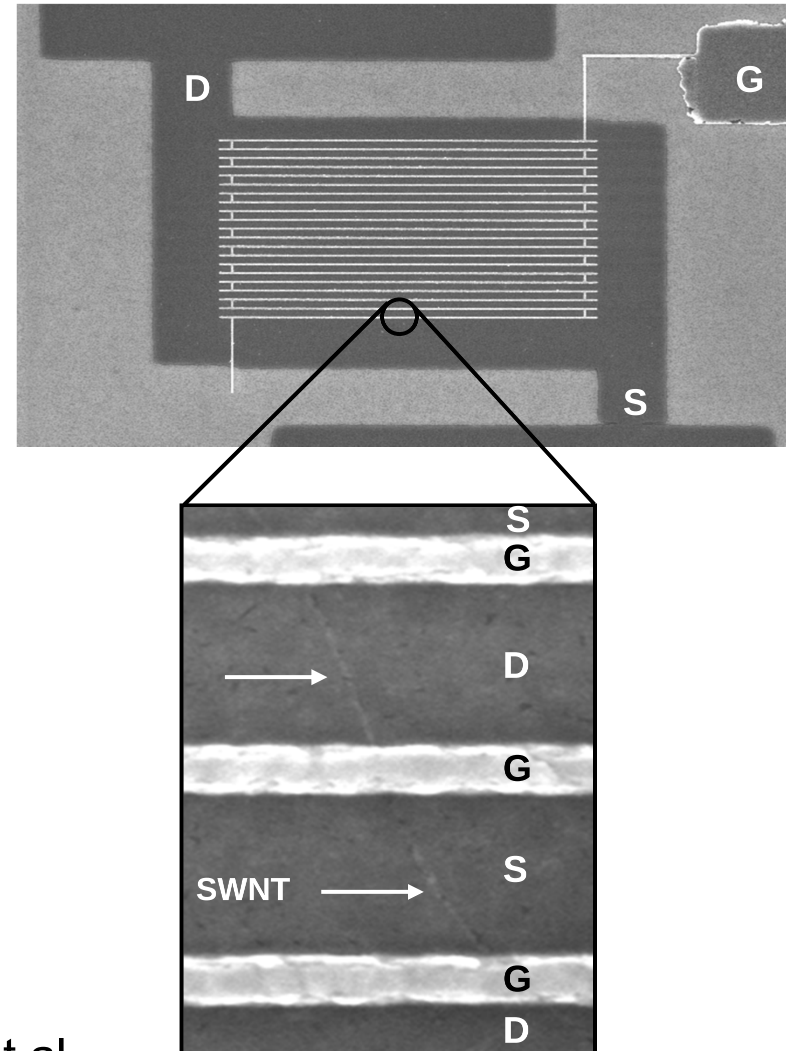
- To get large drive, need to stack multiple tubes in parallel with common contacts, gate

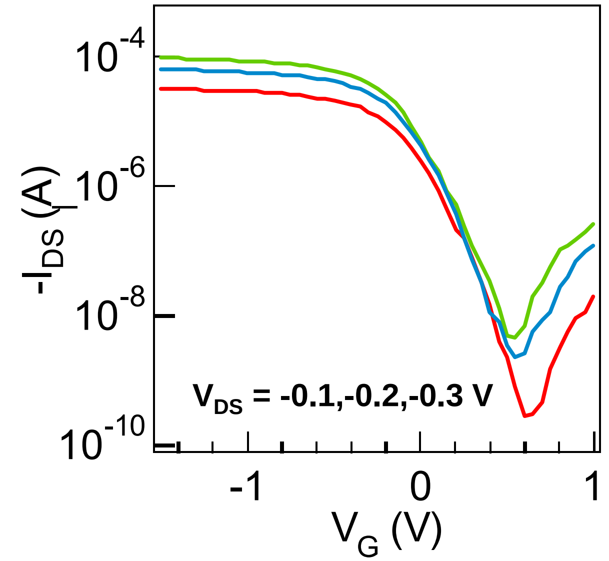


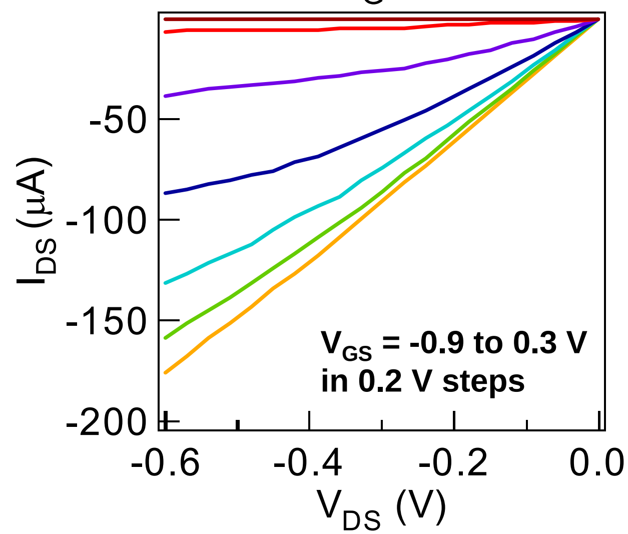
- Do parallel array currents add?
- How close can tubes be stacked?

- Important for ultimate circuit application

Parallel Array of Self-Aligned Ballistic FETs



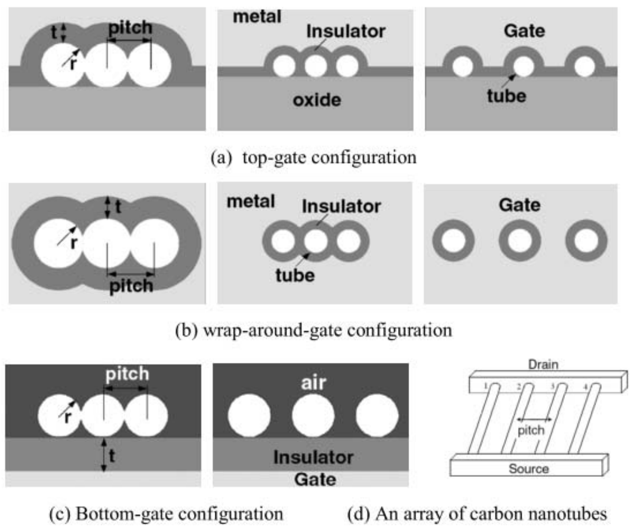


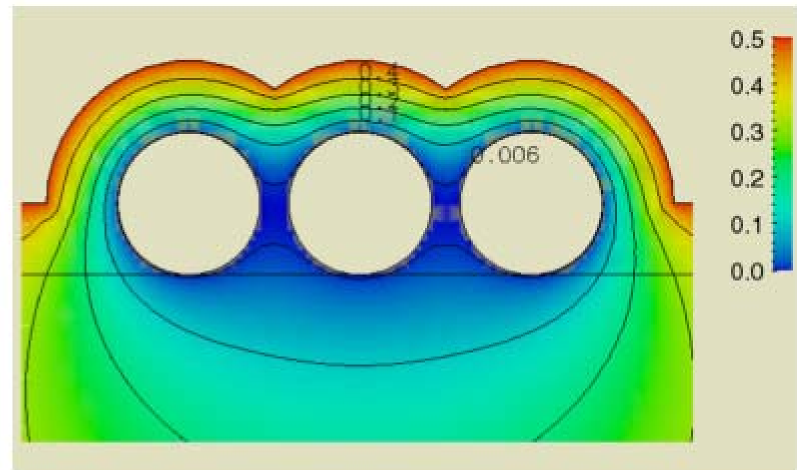


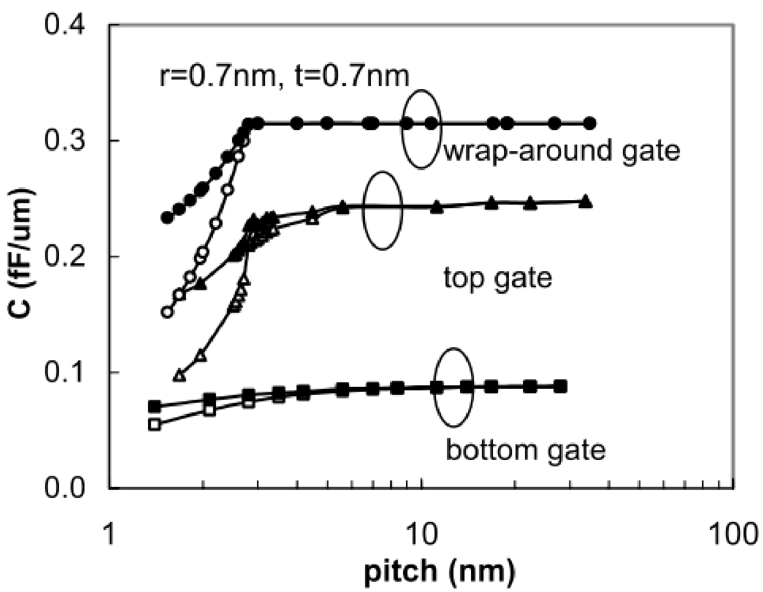
Javey, et al.,
Nano Lett. (2004)
[Stanford, Dai group]

- 1st demonstration of a parallel array
- ~200 uA of current for the array of 8 tubes.

CNT Array Density Limited by Screening

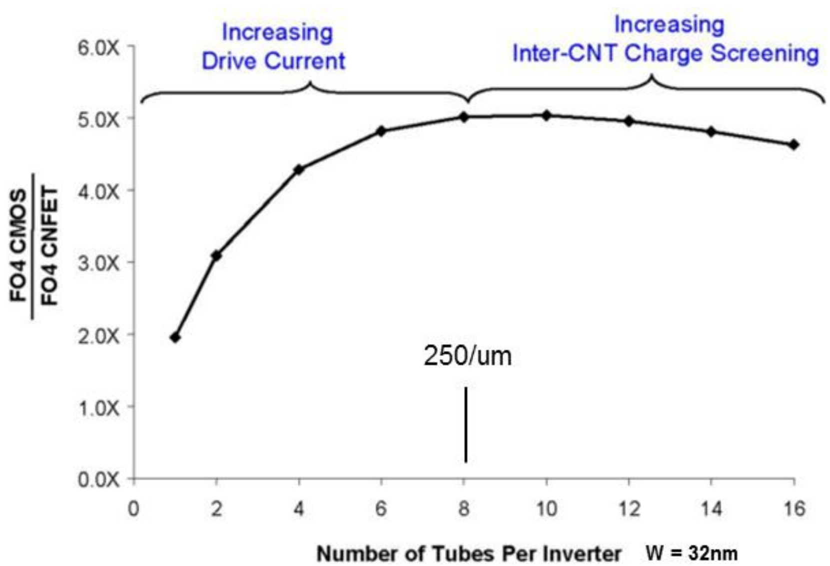


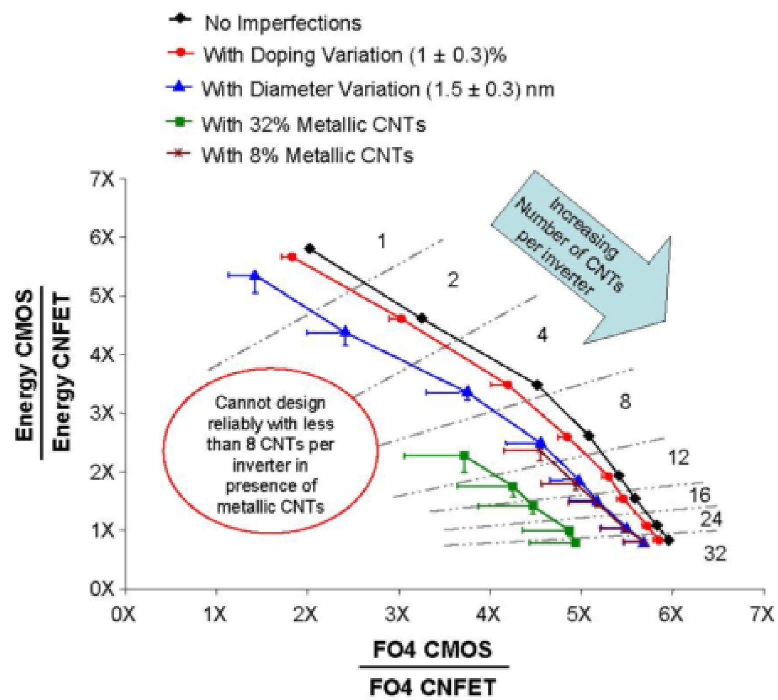




Wang, et al. SISPAD (2003) [IBM]

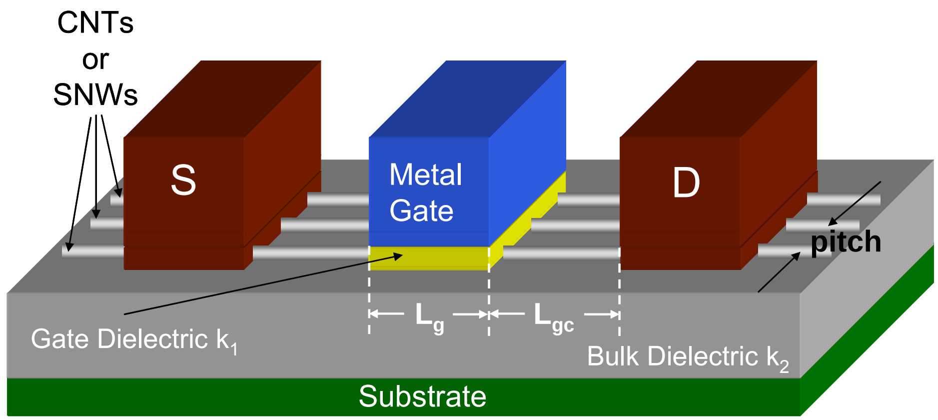
CNT Array Transistor Circuit Performance





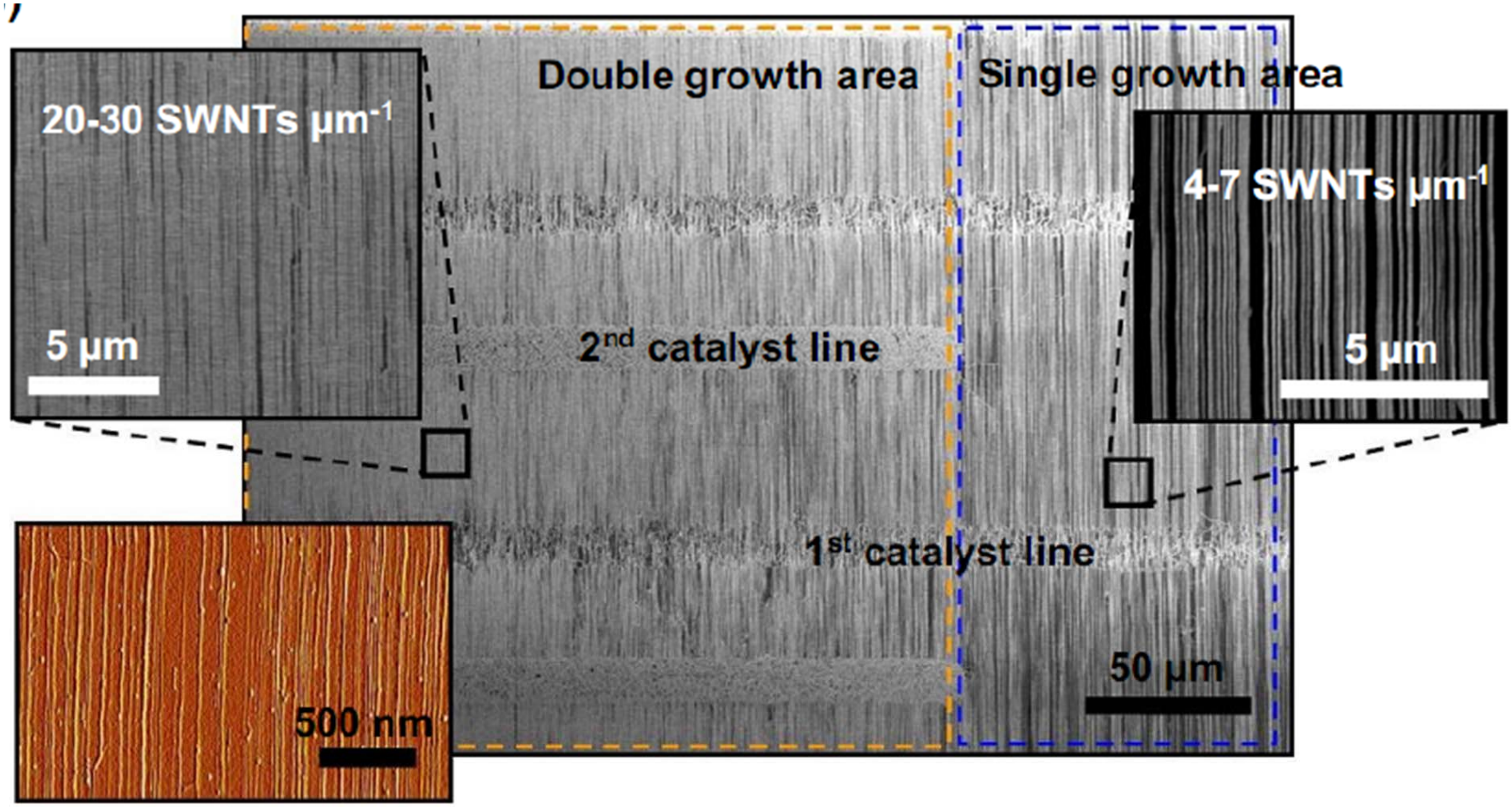
Jie, et al., ISSSC (2007)
[Stanford/USC, Wong/Mitra/Zhou groups]

Vision for CNT channel array MOSFETs



- Array of 1D channels, densely packed
- Density 200-250 per μm
- No metallic tubes
- Narrow diameter distribution

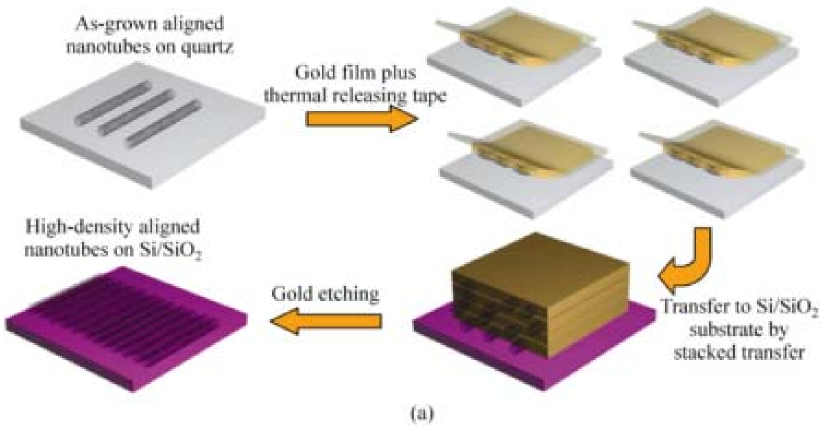
A Multiple Growth Strategy to High Densities

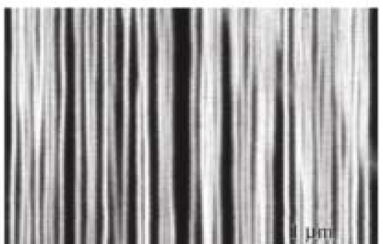


- Single-crystal quartz growth substrate
- “Epitaxial” CNT growth
- Layer transfer to Si wafer

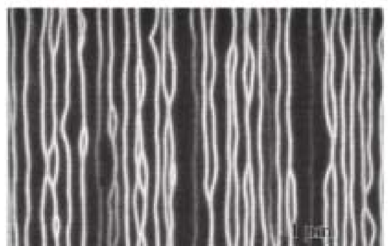
Hong, et al, Adv. Mat. (2010)
[UIUC, Rogers group]

Density Scaling by Multiple Transfers

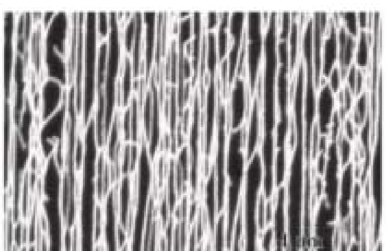




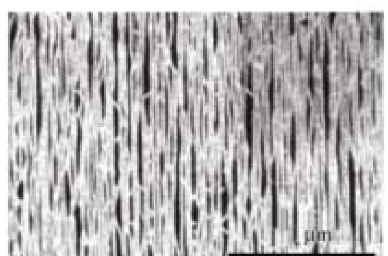
as grown: 15/um



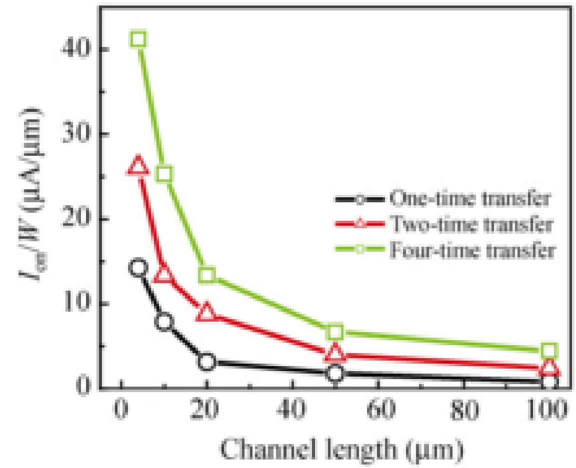
transferred: 15/um



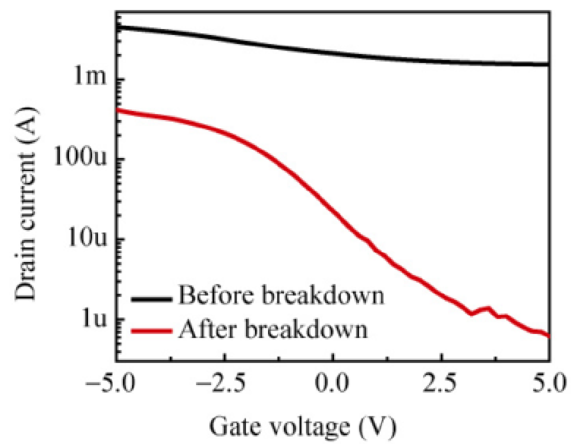
2X transfer: 29/um



4X transfer: 55/um

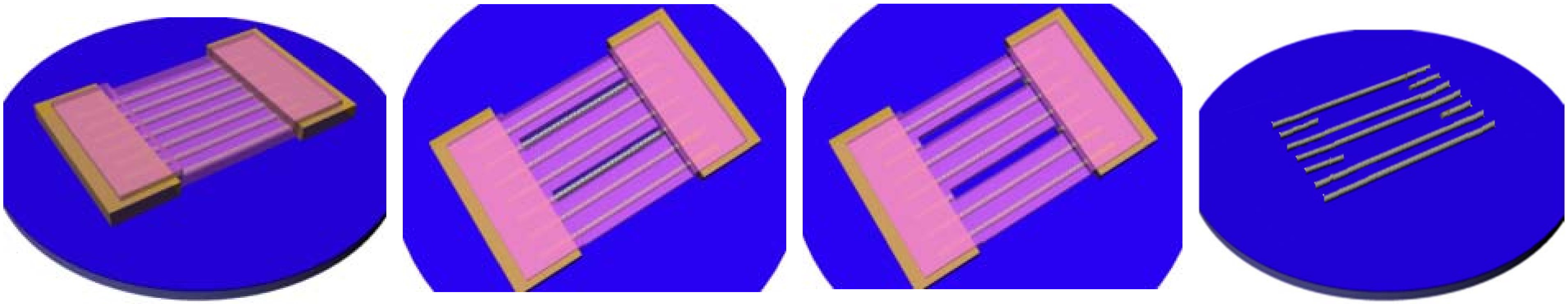


Removal of m-tubes by 'breakdown'

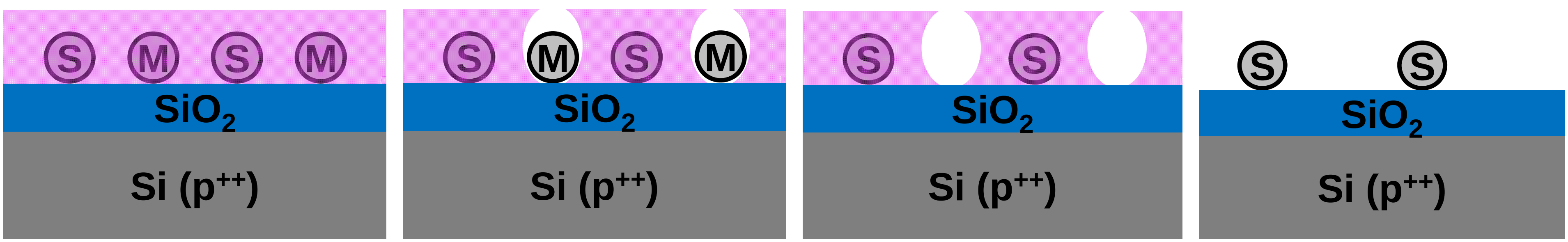


Wang, et al., Nano Res. (2010)
[USC, Chou group]

Selective Removal of m-tubess From Aligned Arrays



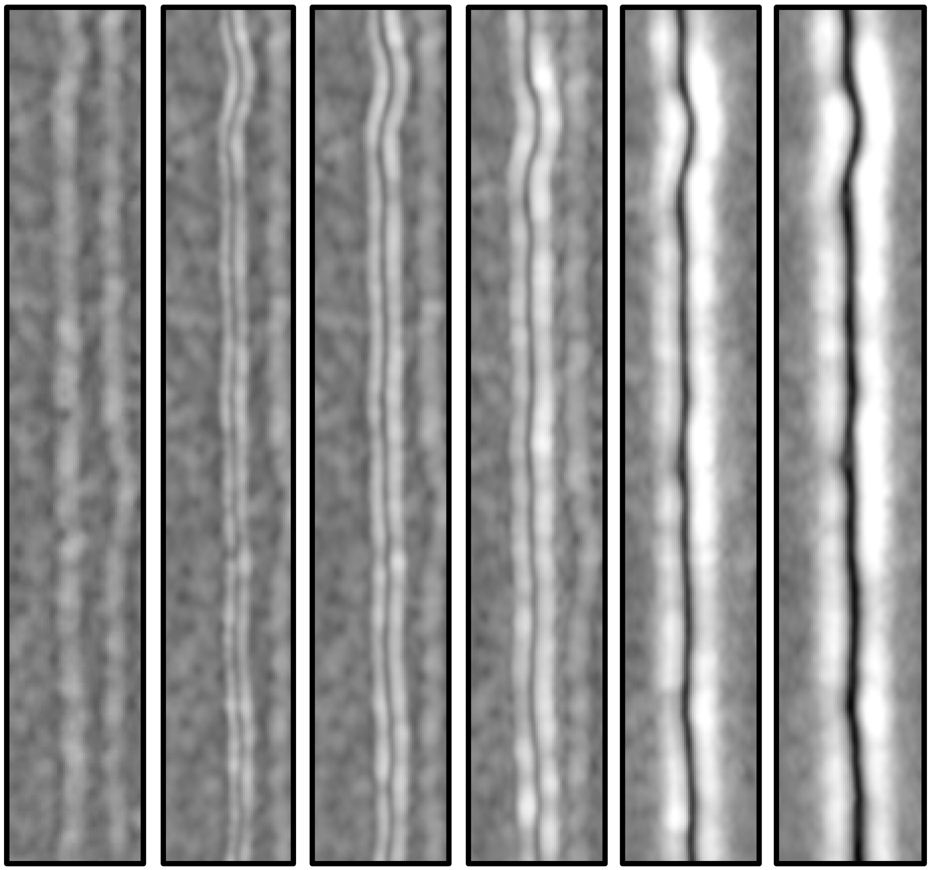
Coat with small molecule film	Induce Joule heating selectively in m-SWNTs to form trenches by thermocapillarity	O_2 plasma etch exposed m-SWNTs	Remove film and electrodes; build circuits on remaining s-SWNTs



J. Rogers group, UIUC

Dynamics of Thermocapillary Flow

Joule Heating by a SWNT (ΔT~5-15C)



t= 0 0.1 1 10 100 300 s

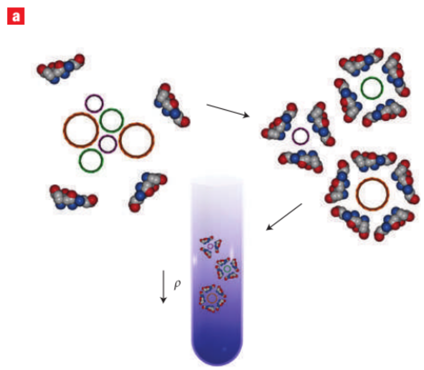
2 μm

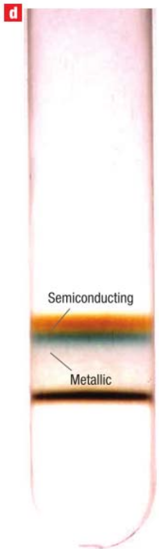
Heating options:

- Gated electrical Joule heating
- Selective laser absorption
- Selective microwave absorption

Jin, et al., Nat. Nano. (2013)
[UIUC, Rogers group]

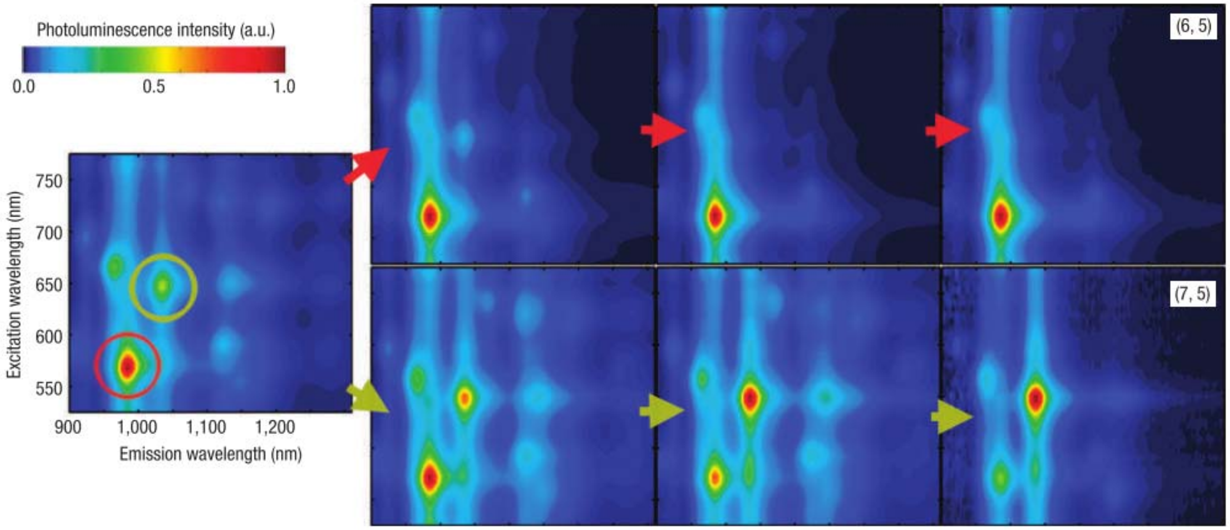
Solution phase nanotube 'sorting'/purification





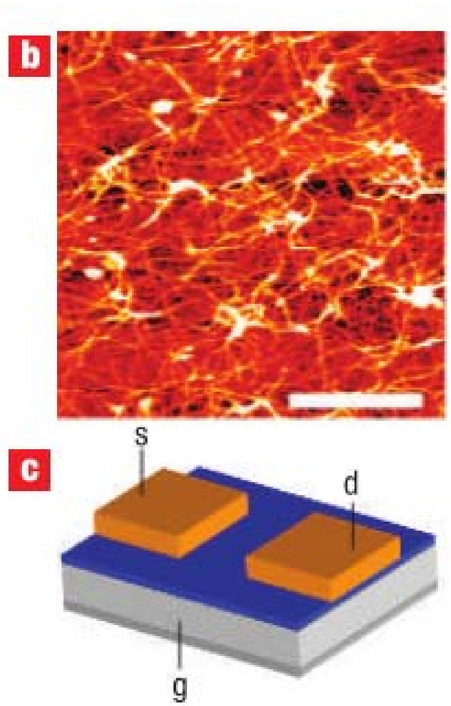
"Density gradient" centrifugation

Arnold, et al., Nat. Nano. (2006)
[Northwestern, Hersam group]

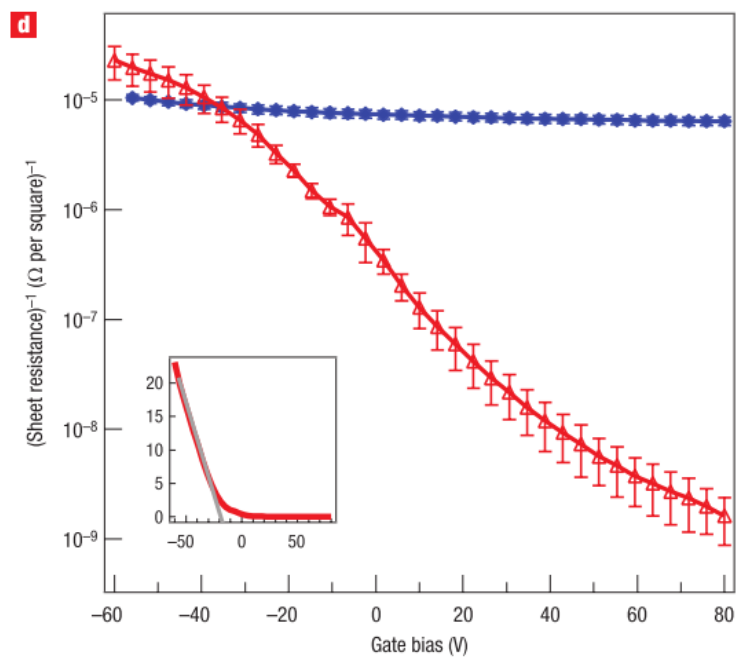


Electrical results on sorted CNTs

Percolating network transistor



Sorted tube transistor high on/off ratio



Arnold, et al., Nat. Nano. (2006)
[Northwestern, Hersam group]

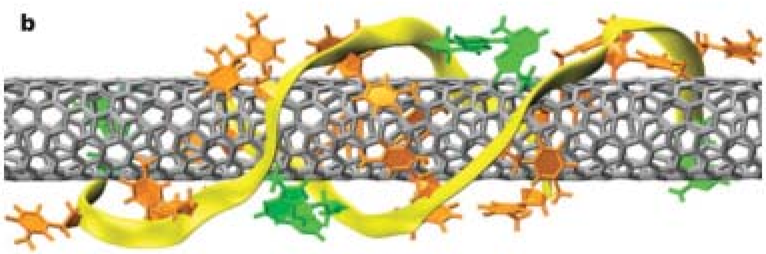
DNA sequence specific wrapping for sorting

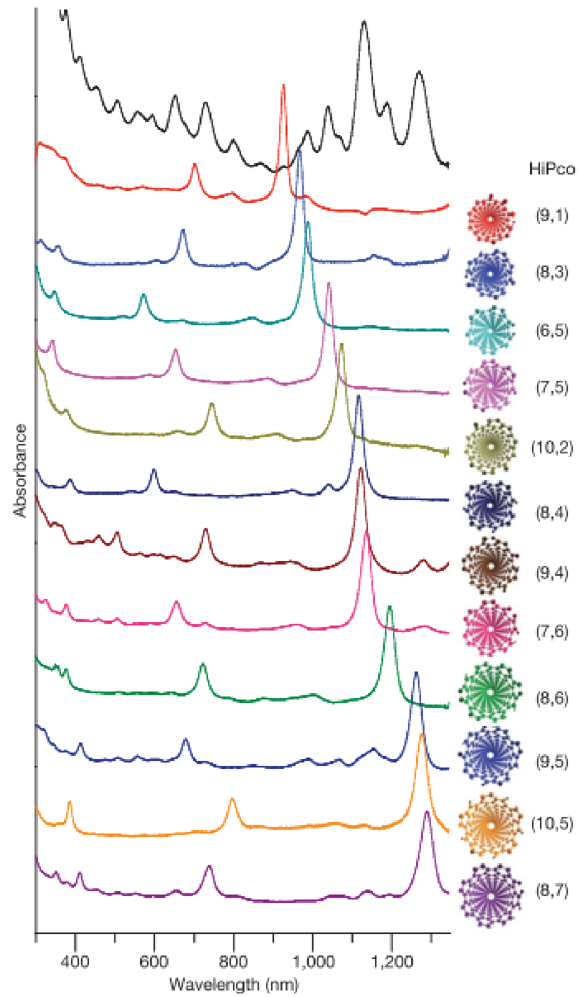
"size exclusion" chromatography

Table 1 | DNA sequence versus SWNT chirality

Chirality (*n*,*m*)	Sequences
(9,1)	$(TCC)_{10}$, $(TGA)_{10}$, $(CCA)_{10}$
(8,3)	$(TTA)_4TT$, $(TTA)_3TTGTT$, $(TTA)_5TT$
(6,5)	$(TAT)_4$, $(CGT)_3C$
(7,5)	$(ATT)_4$, $(ATT)_4AT$
(10,2)	$(TATT)_2TAT$
(8,4)	$(ATTT)_3$
(9,4)	$(GTC)_2GT$, $(CCG)_4$
(7,6)	$(GTT)_3G$, $(TGT)_4T$
(8,6)	$(GT)_6$, $(TATT)_3T$, $(TCG)_{10}$, $(GTC)_3$, $(TCG)_2TC$, $(TCG)_4TC$, $(GTC)_2$
(9,5)	$(TGTT)_2TGT$
(10,5)	$(TTTA)_3T$
(8,7)	$(CCG)_2CC$

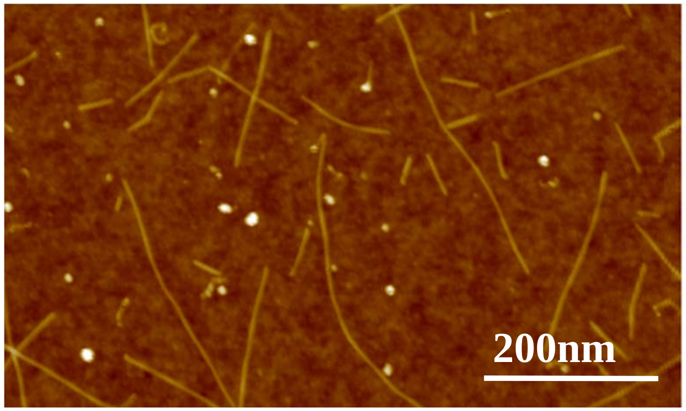
DNA sequences enabling chromatographic purification of single chirality semiconducting SWNTs.

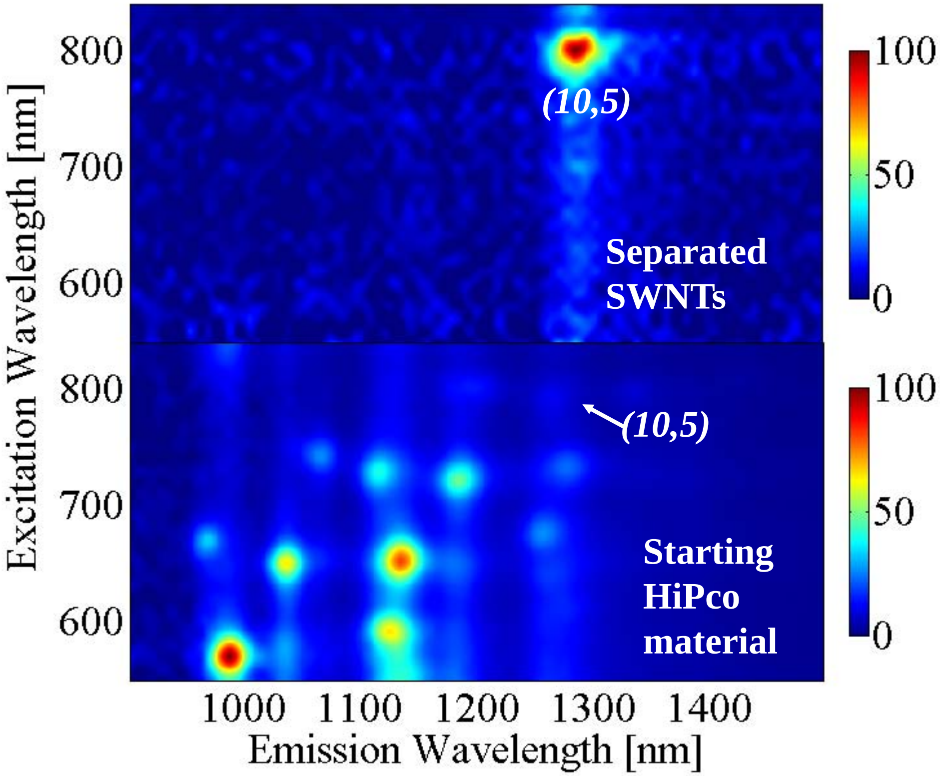




Tu, et al., Nature (2009)
[Dupont, Zheng group]

Purified Single Chirality (10,5) SWNTs

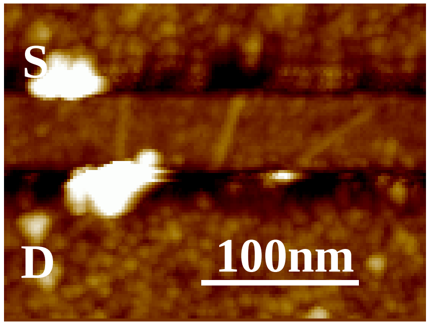




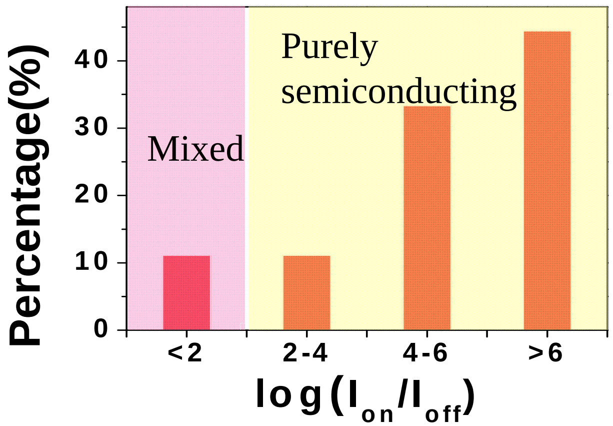
Zhang, et al, JACS (2009),
[Stanford/Dupont, Dai/Zheng groups]

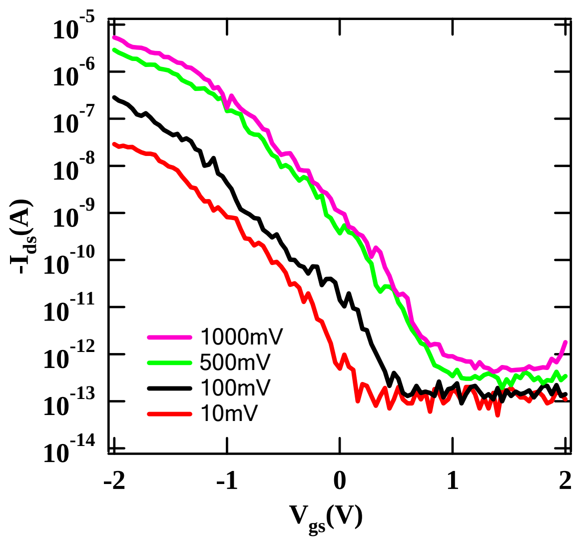
DNA used: (TTTA)3T

FETS with 99% Semiconducting Tubes



Mostly (10,5) SWNTs

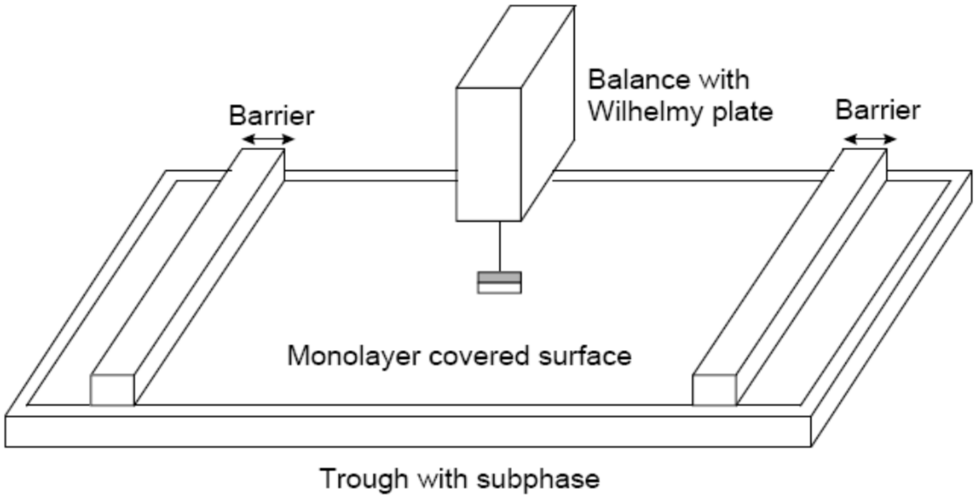




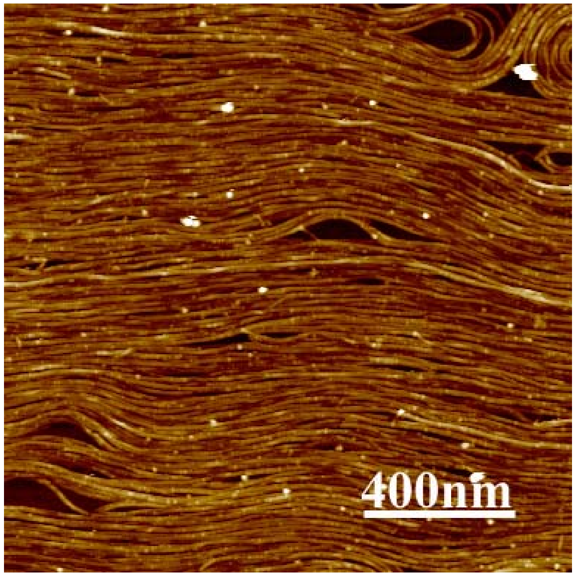
Average 15 tubes per device
Ion/Ioff >10^2 : 88% semiconducting tubes:
99% (0.99^{15} ~ 88%)

Zhang, et al, JACS (2009),
[Stanford/Dupont, Dai/Zheng groups]

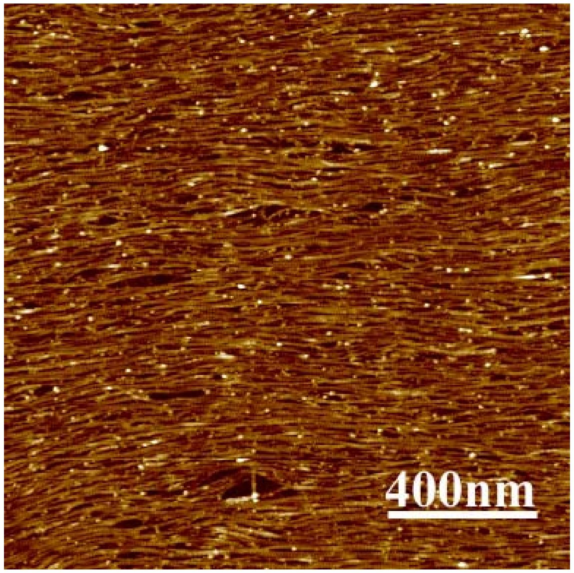
Solution phase array assembly by Langmuir-Blodgett technique



Li, et al. JACS (2007)
[Stanford, Dai group]

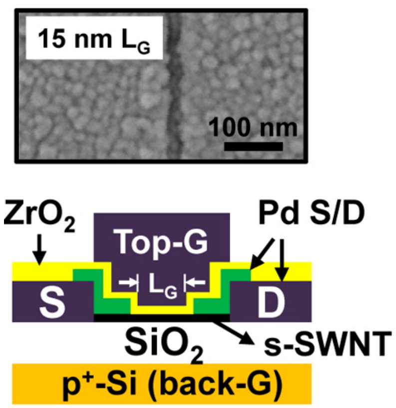


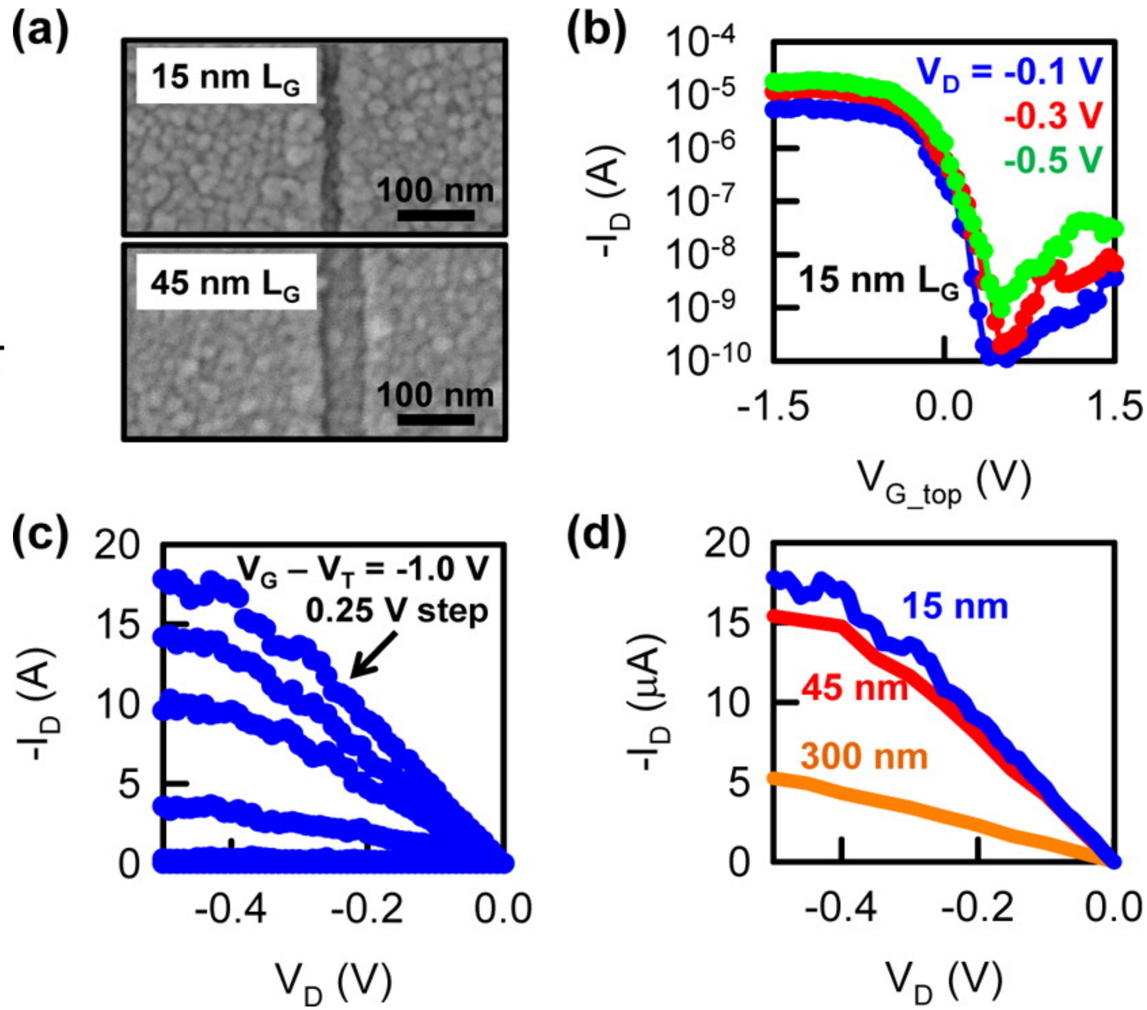
~70/um



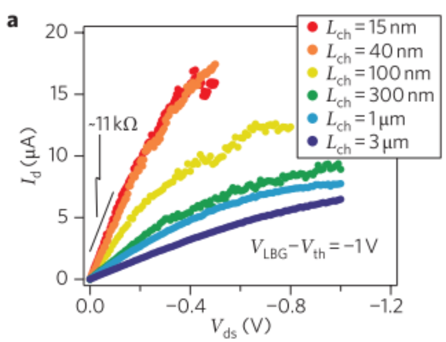
~80/um

Solution processed CNTs are as good as CVD tubes at nanoscale Lg





CVD tubes

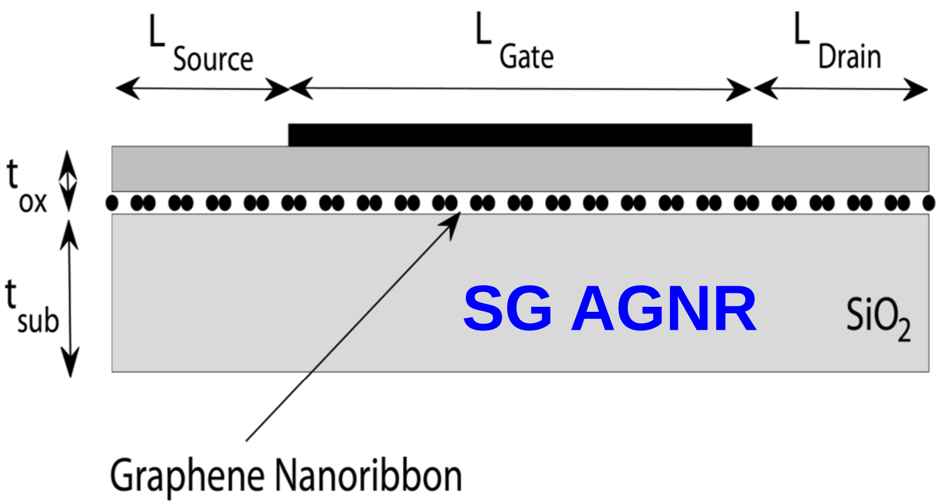


Franklin and Chen, Nat. Nano. (2010) [IBM

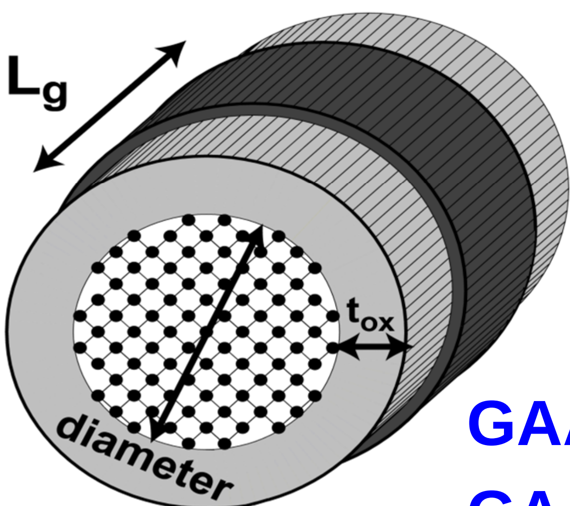
Choi, et al., ACS Nano (2013) [UCB, Bokor/Javey groups]

Ultimate scaling study

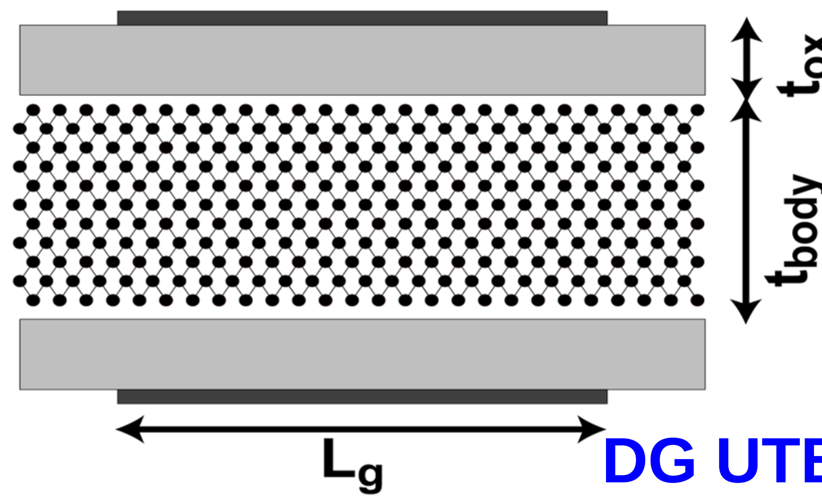
M. Luisier (Purdue)



Also
DG AGNR



GAA CNT
GAA NW



DG UTB

Simulation parameters and assumptions

Device Characteristics:

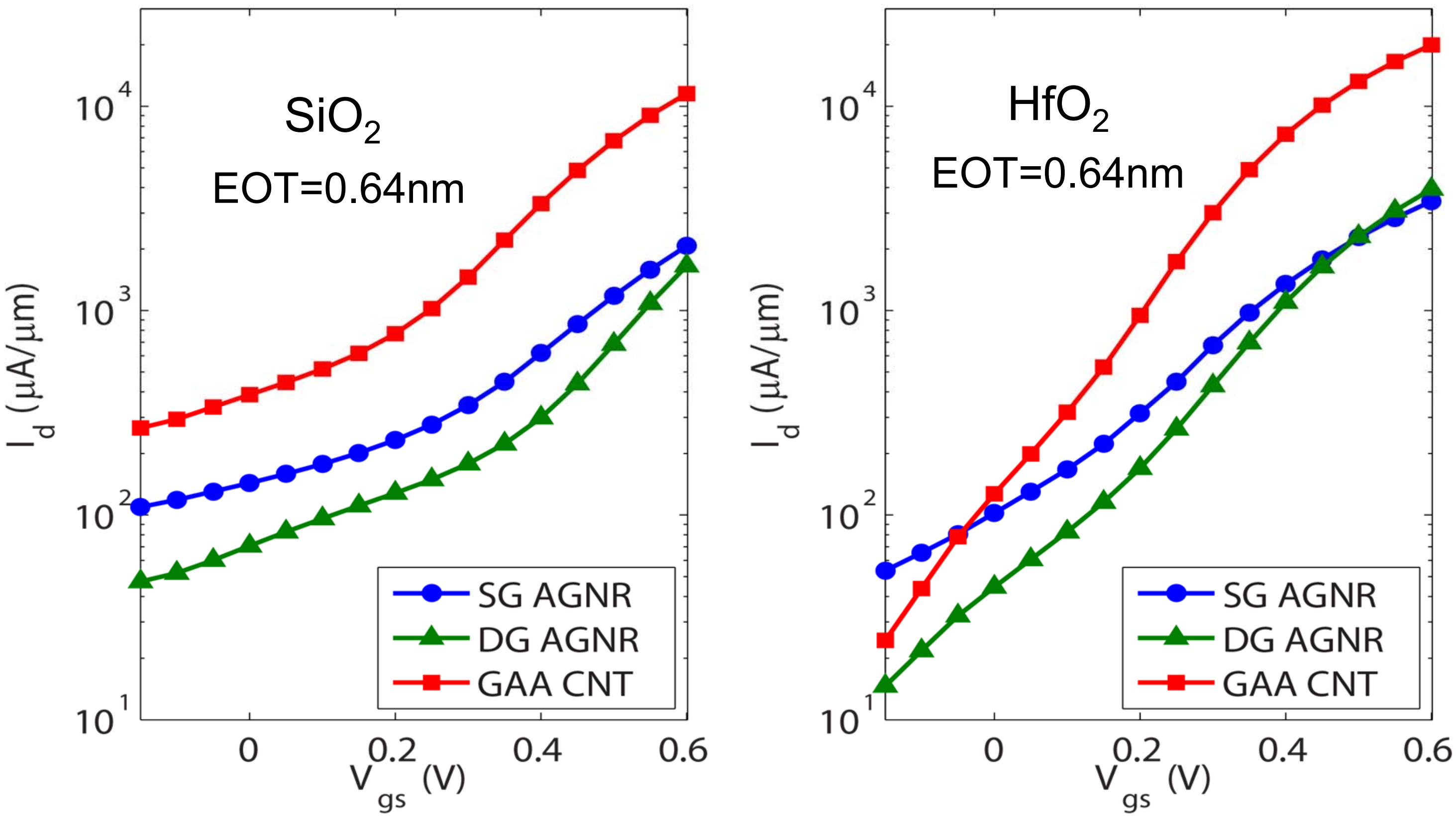
- **All:** L_g=5nm, V_{DD}=0.5 V, EOT=0.64nm (3.3nm of HfO_2 with ε_R=20)
- **SG and DG AGNR:** width=2.2nm, normalization by width
- **GAA CNT:** diameter=1.58, 1.0, and 0.6 nm, normalization by diameter
- **GAA and Ω-NW:** Si, diameter=3nm, transport=<110>, 1% uniaxial strain
- **DG UTB:** Si, body=3nm,, transport=<110>, 1% uniaxial strain

Simulation Approach:

- Same quantum transport simulator for all devices based on Non-equilibrium Green's Functions (NEGF) formalism with atomistic resolution of simulation domain and finite element method for Poisson equation
- Bandstructure model: single-p_z for carbon and $sp^3d^5s^*$ for silicon (tight-binding)
- Ballistic limit of transport (no electron-phonon scattering nor interface roughness taken into account)
- Intrinsic device performances (no contact series resistances included)
- No gate leakage currents included
- No structure optimization for any of the selected devices

I_d-V_{gs} at V_{ds}=0.5V in carbon-based Devices

AGNR width: 2.2nm / CNT diameter: 1.58nm / Band Gap E_g=0.56 eV



- Same EOT gives very different electrostatic gate-channel coupling

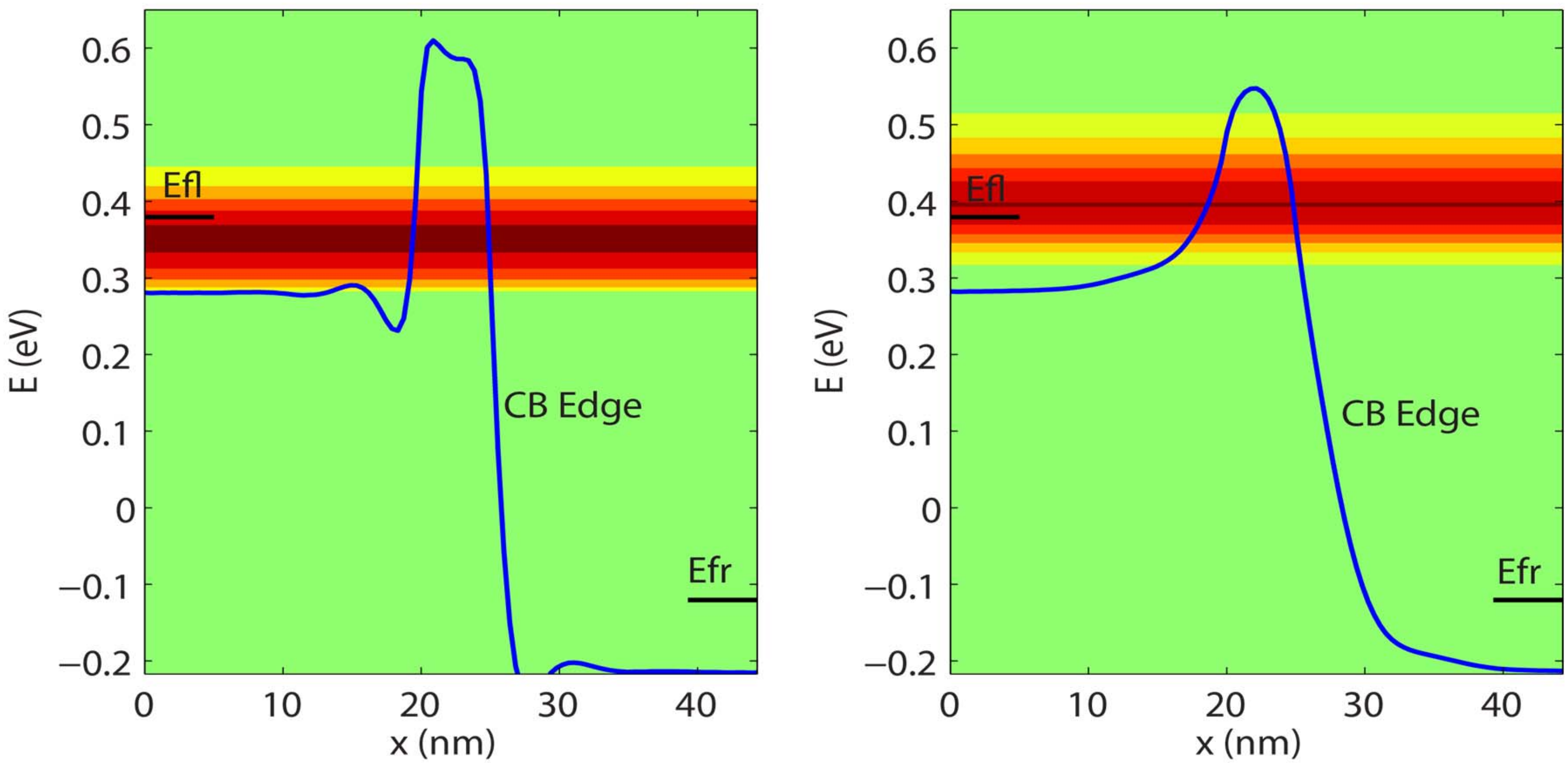
M. Luisier (Purdue)

Gate Dielectric Effect In Carbon-Based Devices

Comparison of Conduction Band Edge and Spectral Current in Single-Gate AGNR with **0.64nm SiO_2** (ε_R=3.9) and **3.3nm HfO_2** (ε_R=20) => same EOT=0.64nm

OFF- state

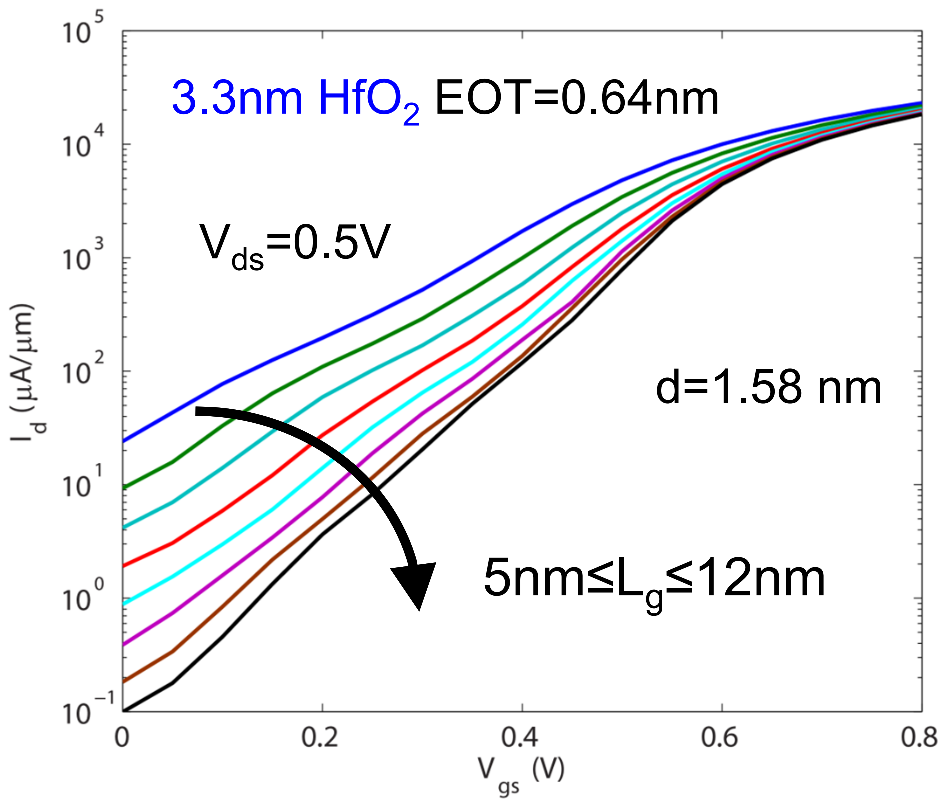
SiO_2 HfO_2



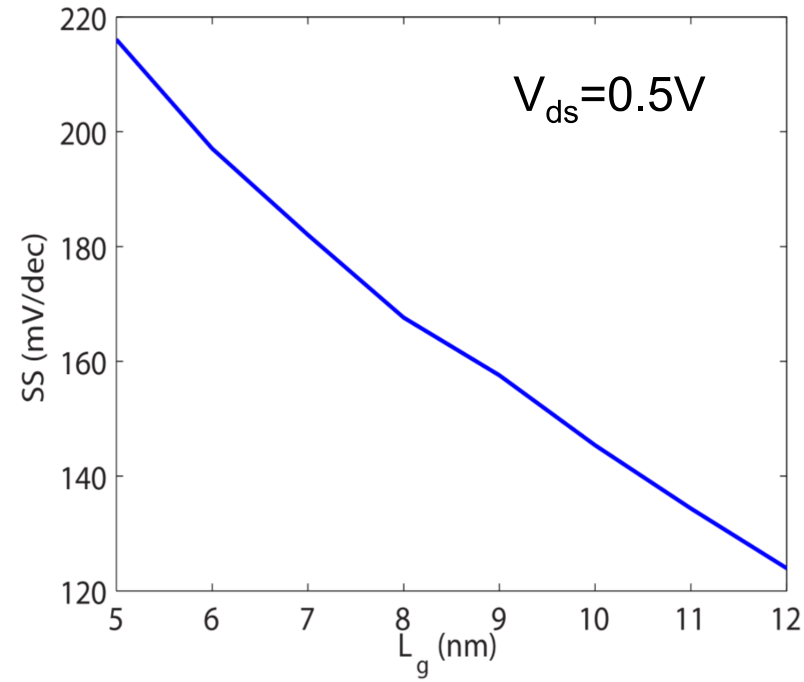
- Effective channel length is longer for the thicker HfO_2
- Barrier widens and tunneling current drops

Extreme (sub-10 nm S-D Tunneling regime)
d=1.58 nm CNT FETs

Transfer Characteristics



Sub-threshold swing

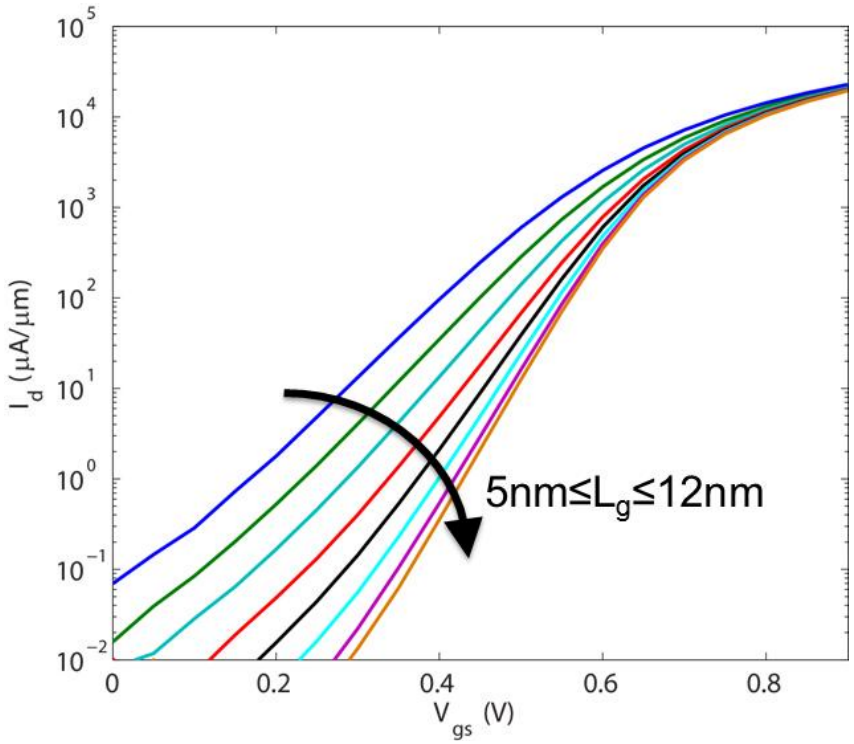


- Bandgap 0.56 eV GAA- CNT (d=1.58 nm) scales poorly

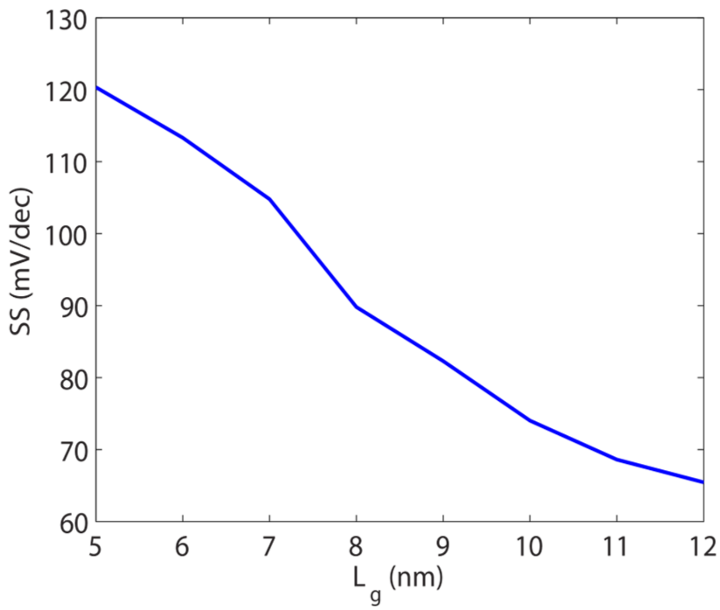
M. Luisier, et al., IEDM (2011)
[Purdue/MIT/UCB, Lundstrom/Antoniadis/Bokor groups]

Gate-length trend for 1 nm CNTs

Transfer Characteristics



Sub-threshold Slope



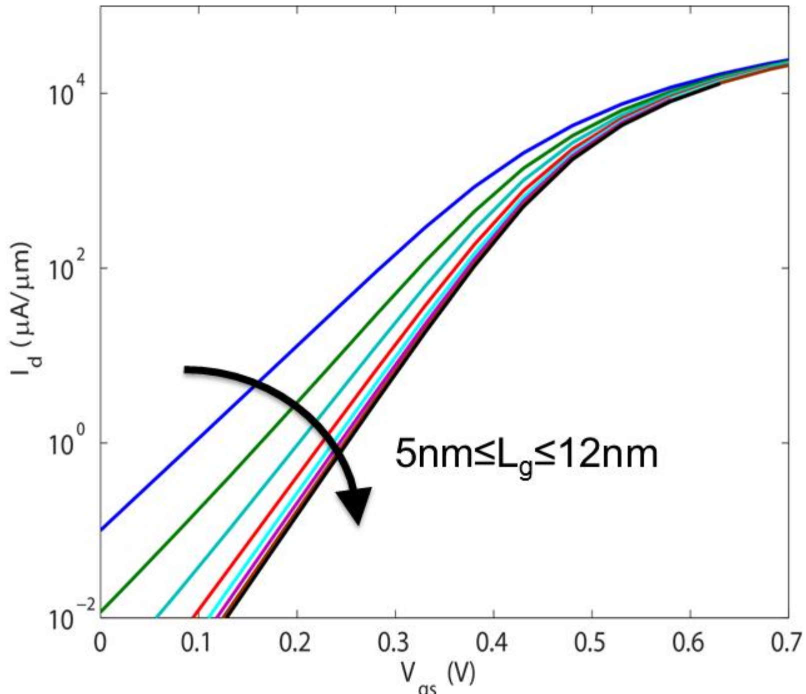
- Bandgap 0.8 eV GAA- CNT (d=1.0 nm) scales better

M. Luisier, et al., IEDM (2011)
[Purdue/MIT/UCB, Lundstrom/Antoniadis/Bokor groups]

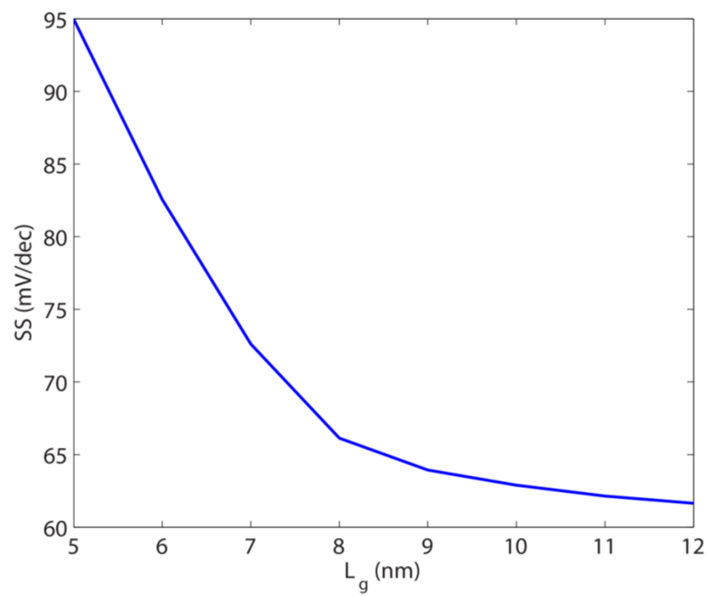
Gate-length trend for 0.6 nm CNTs

I_d-V_{gs} at V_{ds}=0.5V in CNT FETs with
d=0.6nm and 5≤L_g≤12 nm

Transfer Characteristics



Sub-threshold Slope

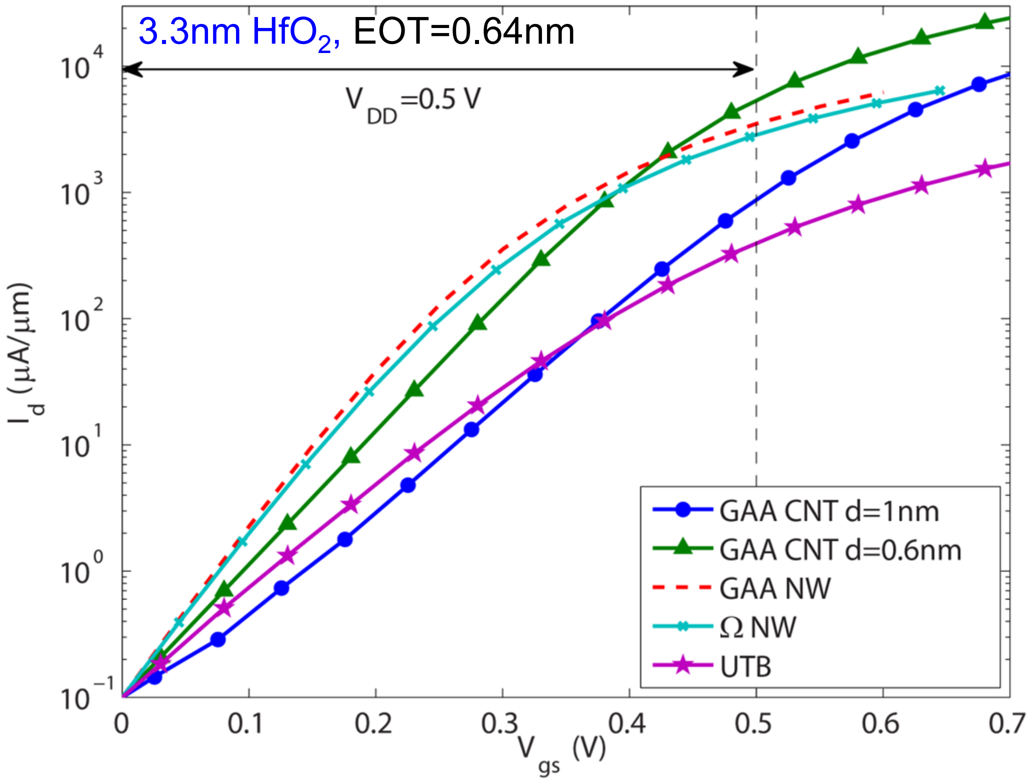


- Bandgap 1.4 eV GAA- CNT (d=0.6 nm) scales well

M. Luisier, et al., IEDM (2011)
[Purdue/MIT/UCB, Lundstrom/Antoniadis/Bokor groups]

Comparison of different channel materials

I_d-V_{gs} at V_{ds}=0.5V in CNT, NW, and UTB Devices



- CNT with d=0.6nm and NW with d=3nm have same band gap E_g=1.4eV
- CNT with d=1.0nm has band gap E_g=0.817eV

- Bandgap 0.8 eV GAA-CNT (d=1.0 nm) scales poorly
- Bandgap 1.4 eV GAA-CNT (d=0.6 nm) scales well
- Si NW (d=3 nm) scales very well due to high-mass and band-gap

9 nm CNT transistor

NANO LETTERS 2012 Letter
pubs.acs.org/NanoLett

Sub-10 nm Carbon Nanotube Transistor

Aaron D. Franklin,*[,†] Mathieu Luisier,[‡] Shu-Jen Han,[†] George Tulevski,[†] Chris M. Breslin,[†] Lynne Gignac,[†] Mark S. Lundstrom,[§] and Wilfried Haensch[†]

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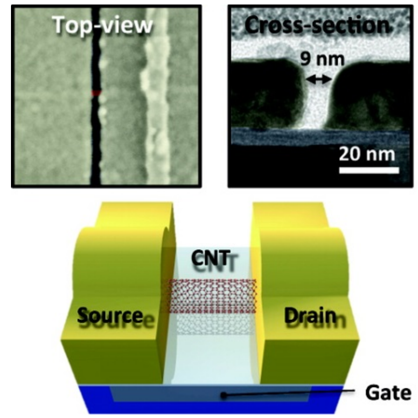
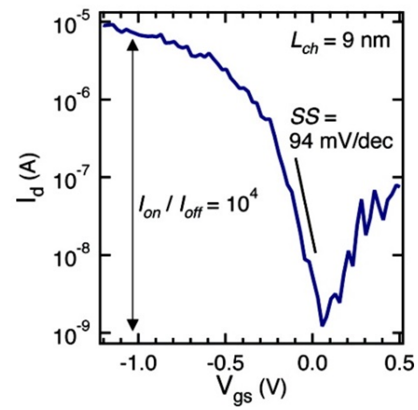
[‡]Integrated Systems Laboratory, ETH Zurich, 8092 Zurich, Switzerland
[§]School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907, United States





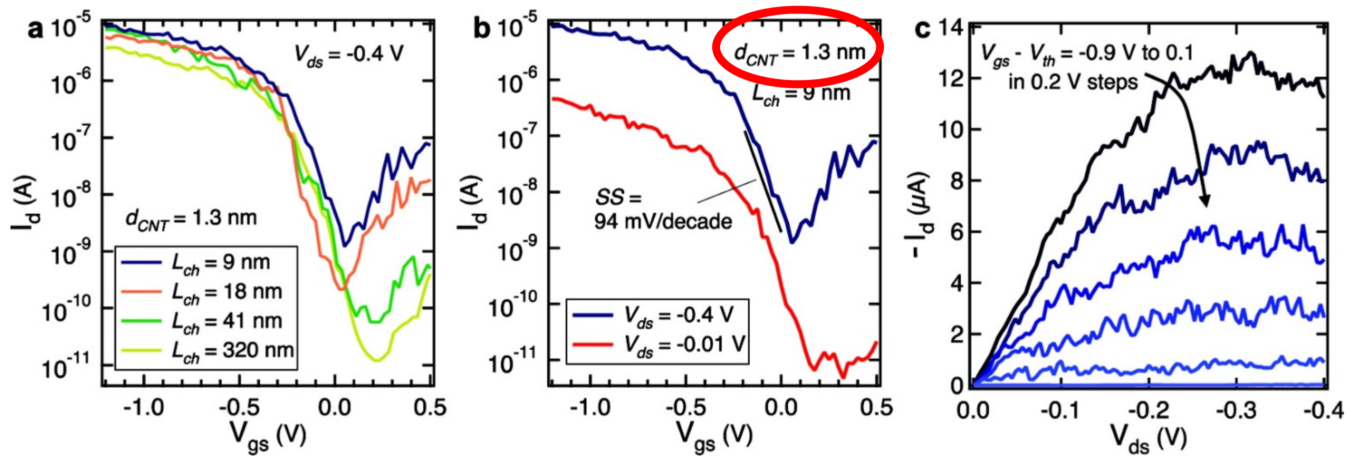
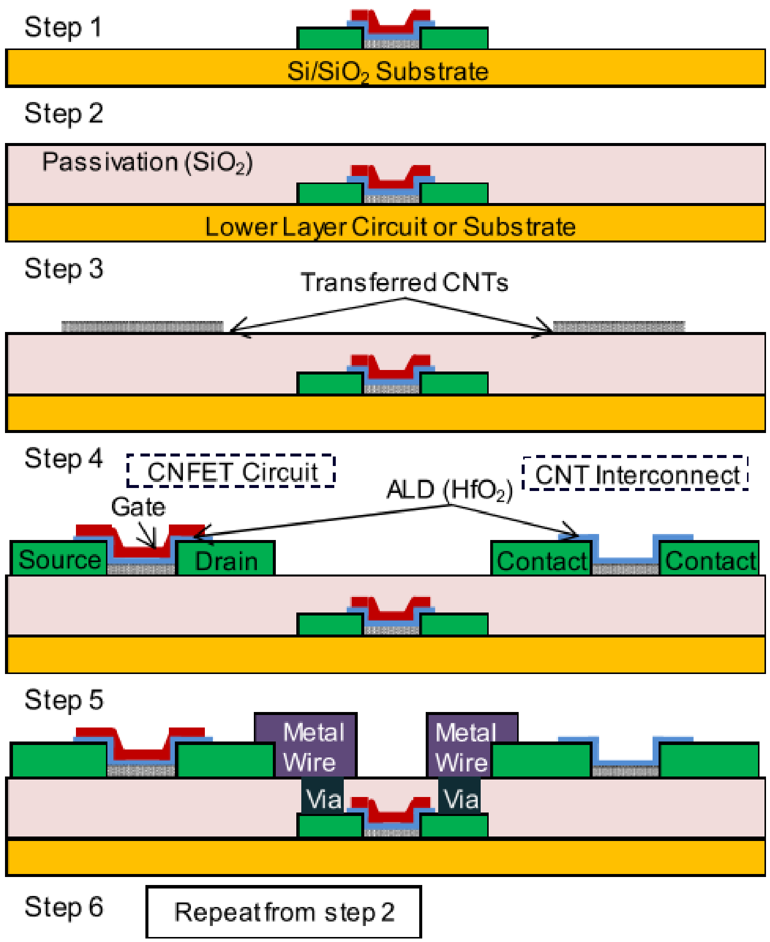
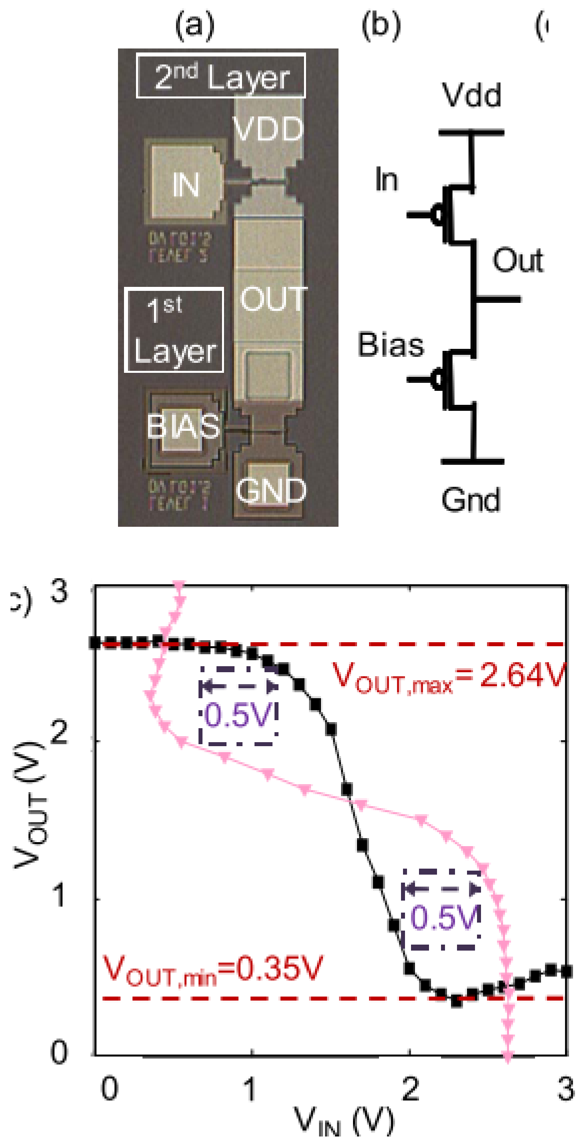


Table 1. Comparison of Performance Metrics between This Work and the Best-Reported Sub-10 nm Si-Based Transistors

ref	channel	L_{ch} (nm)	EOT (Å)	$\|V_{ds}\|$ (V)	$\|V_{gs}\|$ (V)	I_{on} (μA/μm)[a]	I_{on} (μA/μm) at V_{dd} = 0.5 V[c] diameter[a]	pitch[b]	
this work	CNT	9	6.5	0.4	0.5	1760	2410	630	(5 nm)
15	Si nanowire	10	25	0.5	0.6	469	469	300	(20 nm)
16	Si Fin	10	17	0.5			28	138	(20 nm)
17	ETSOI	8	15	0.5	0.6	55	41	41	(20 nm)

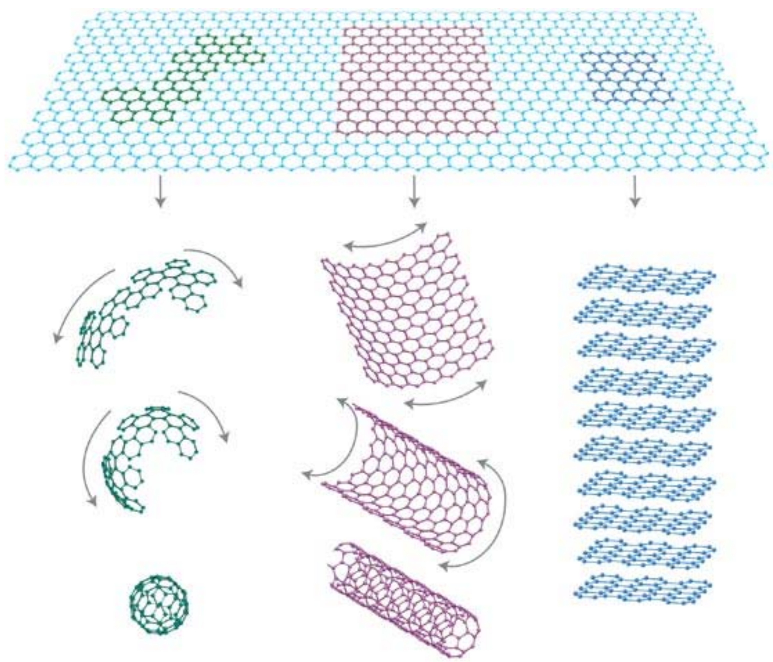
Monolithic 3D CNT Circuits!



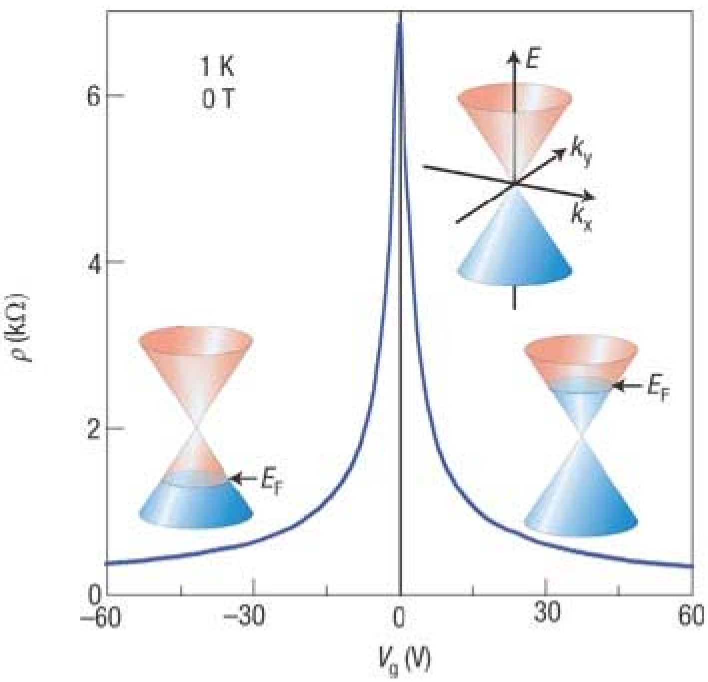


Hai, et al., IEDM (2010)
[Stanford, Mitra/Wong groups]

Graphene



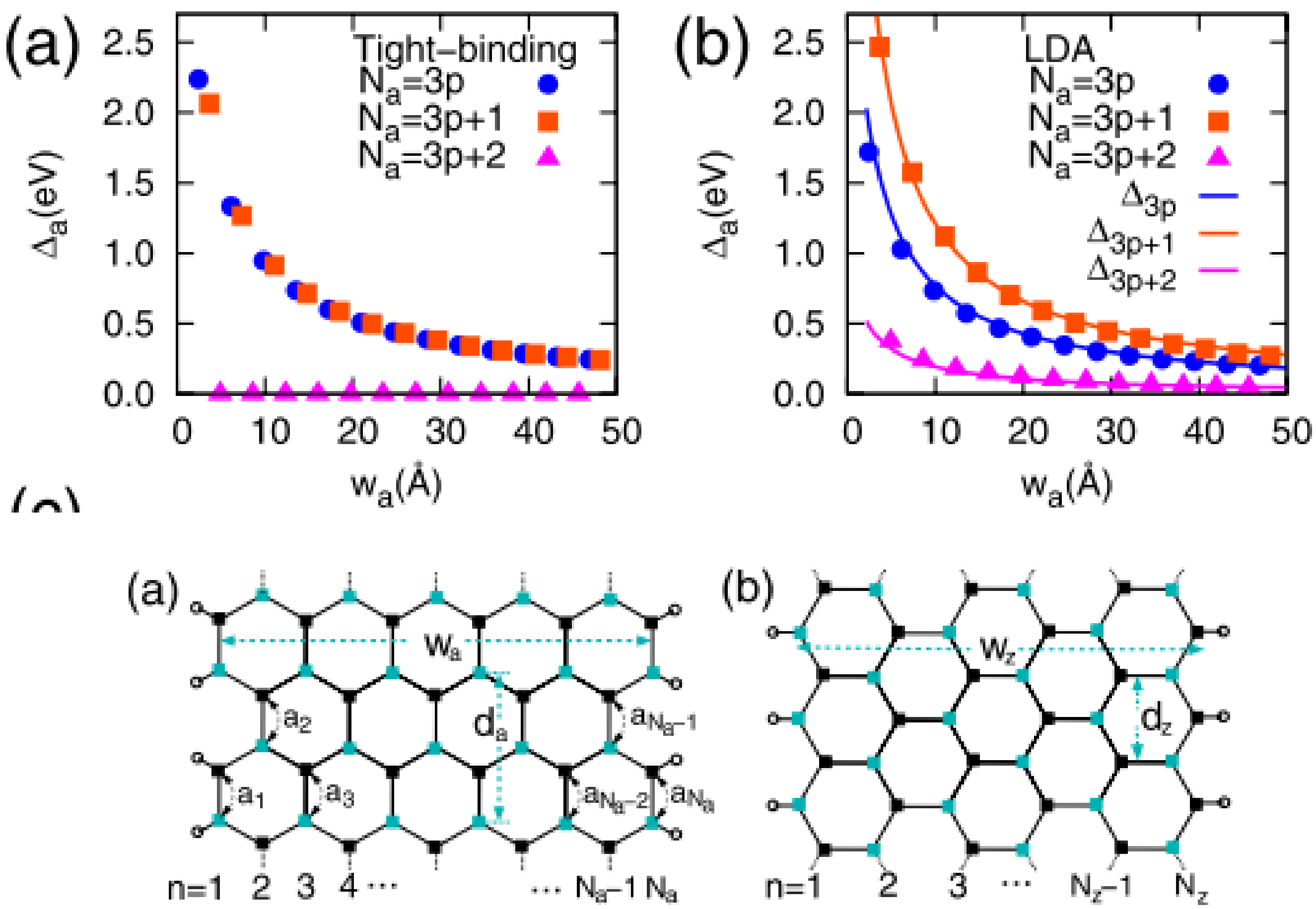
Forms of graphene



Graphene resistivity

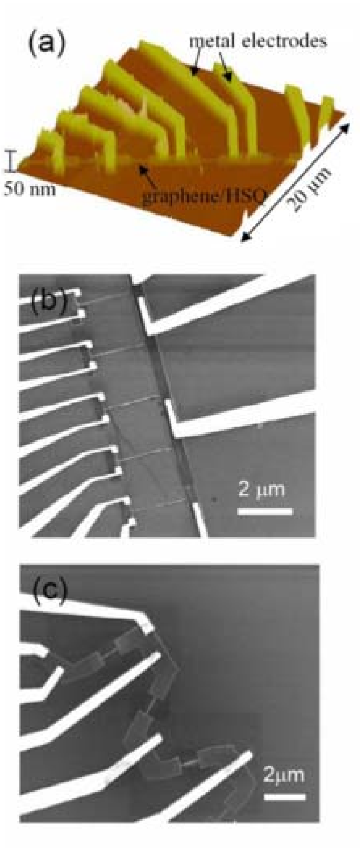
Geim and Novoselov, Nat. Mat. (2007) [Manchester]

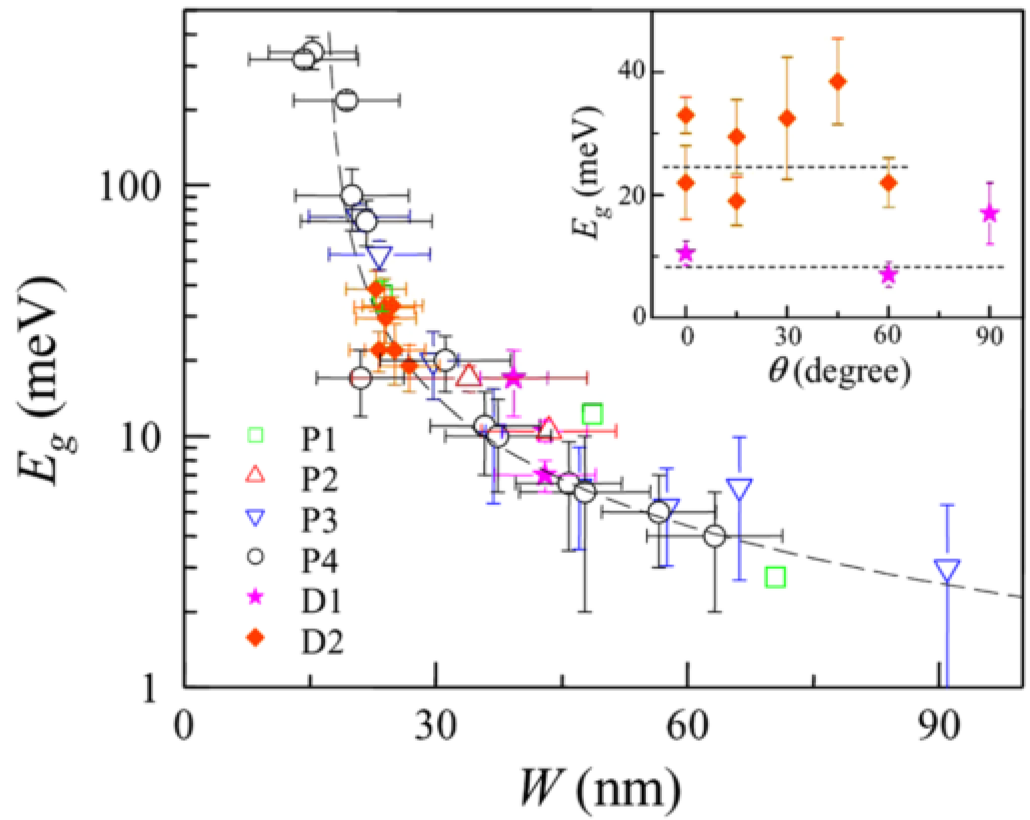
Bandgap Prediction for Graphene Nanoribbons



Son, et al., PRL (2006)
[UCB, Louie group]

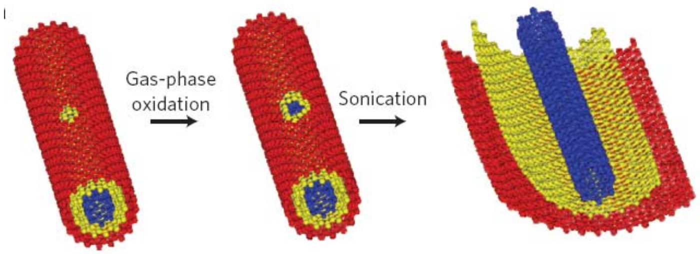
Bandgap Measurements of Etched GNRs

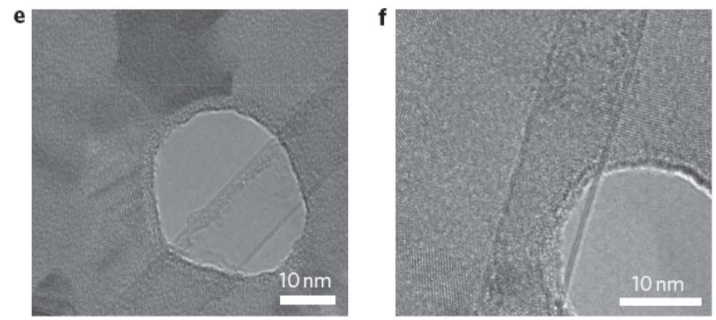


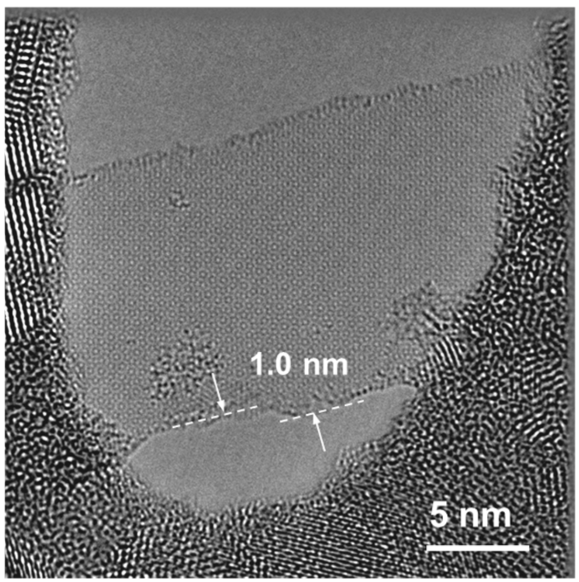


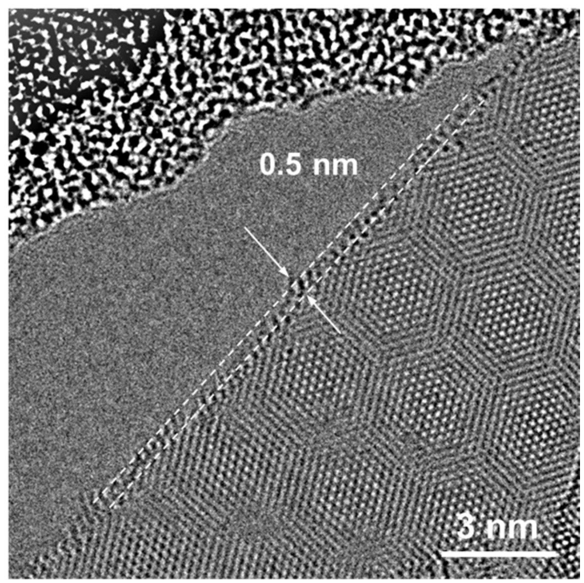
Han, et al., PRL (2007) [Columbia, Kim group]

GNR formation by unzipping CNTs



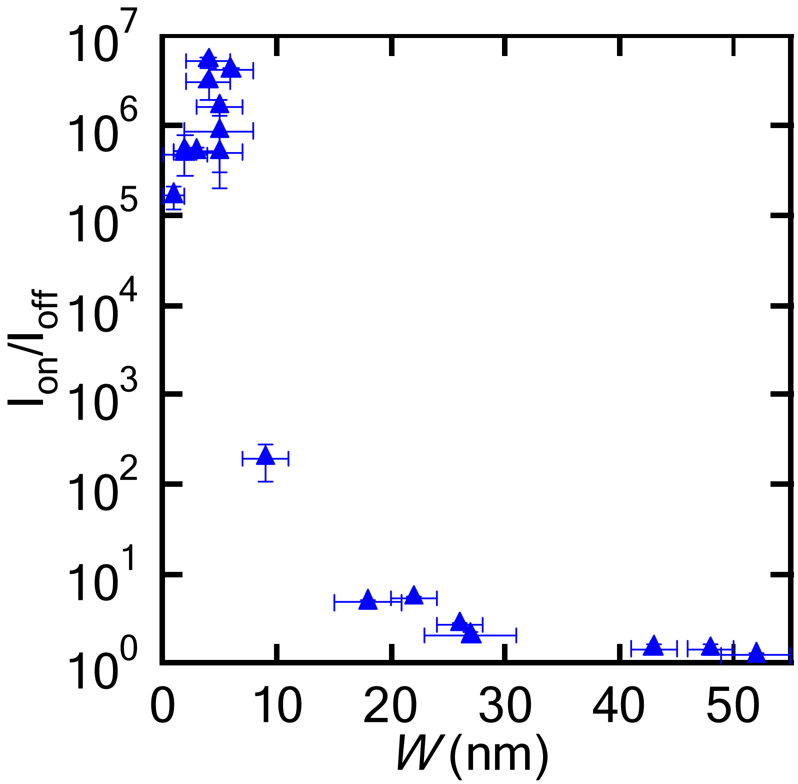


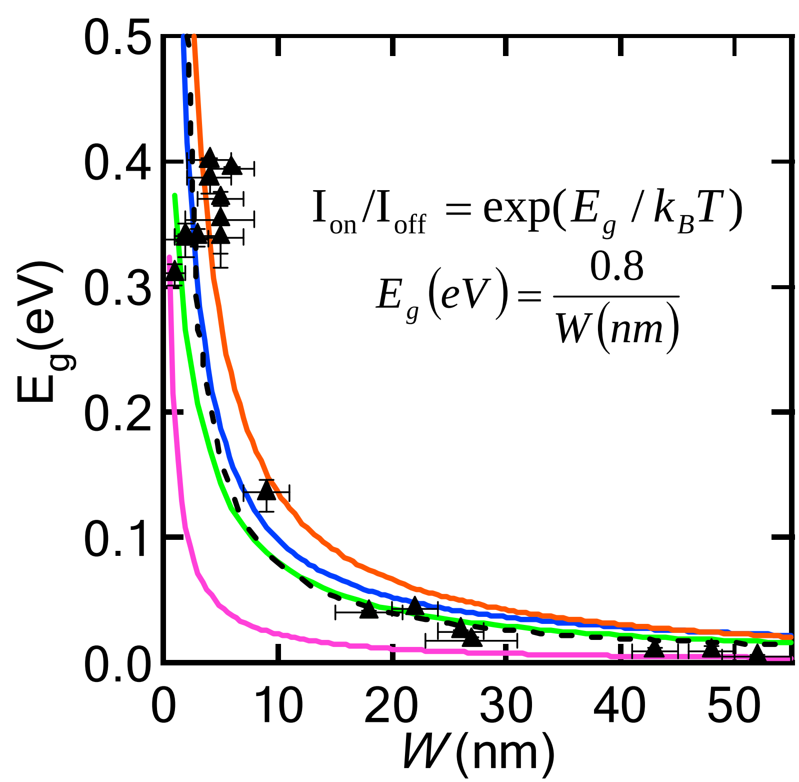




Jiao, Nat. Nano. (2010) [Stanford, Dai group]

GNR Bandgap vs. width

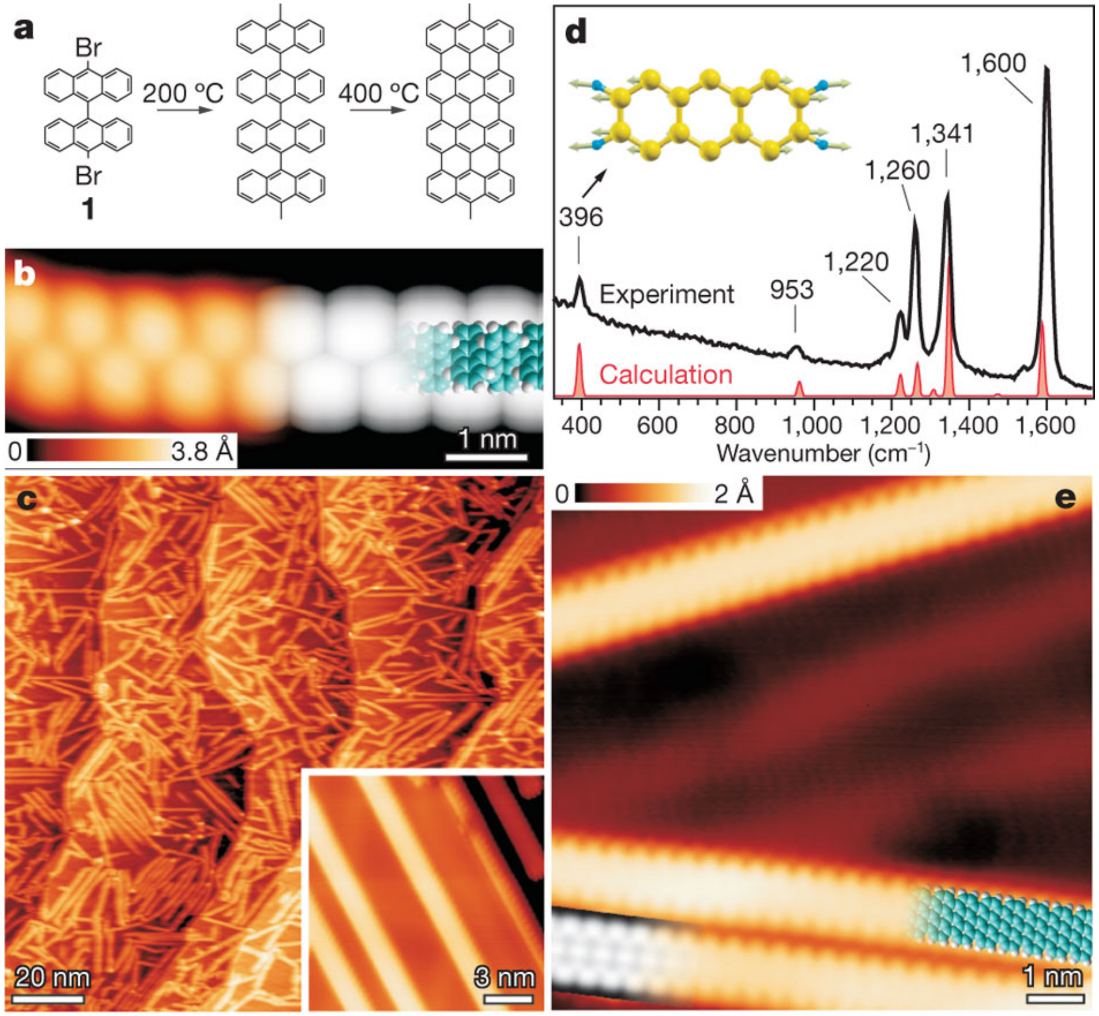




All sub-10nm GNRs are semiconducting
Ion currents few uA

Li, et al. Science (2008)
[Dai group]

Bottom-up Synthesized GNRs

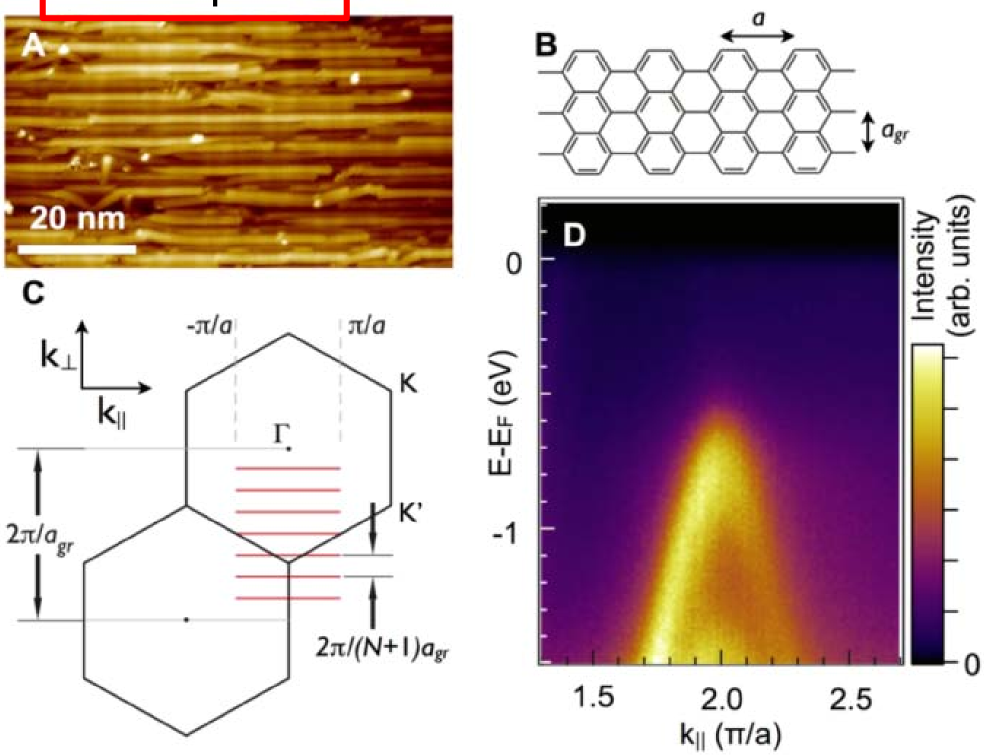


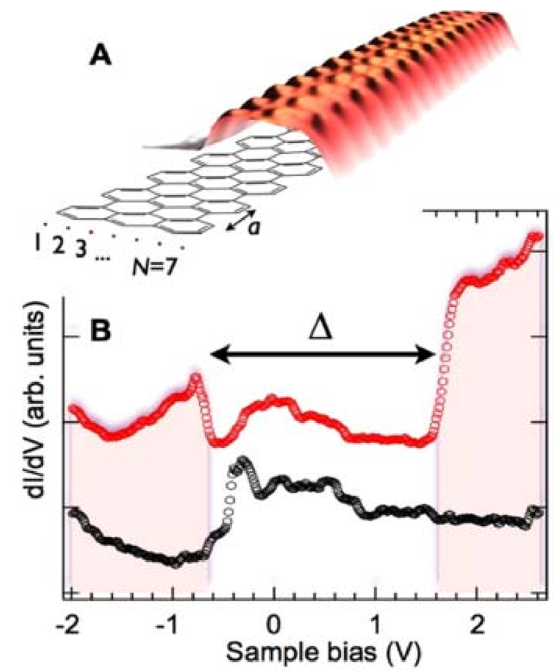
- **Atomically perfect edges!**
- **7 C atoms wide**
- **W = 0.74 nm!**

Cai *et al. Nature* (2010) [EMPA (Switzerland), Fasel group]

Aligned Growth – Bandstructure Measured

~2 nm pitch!



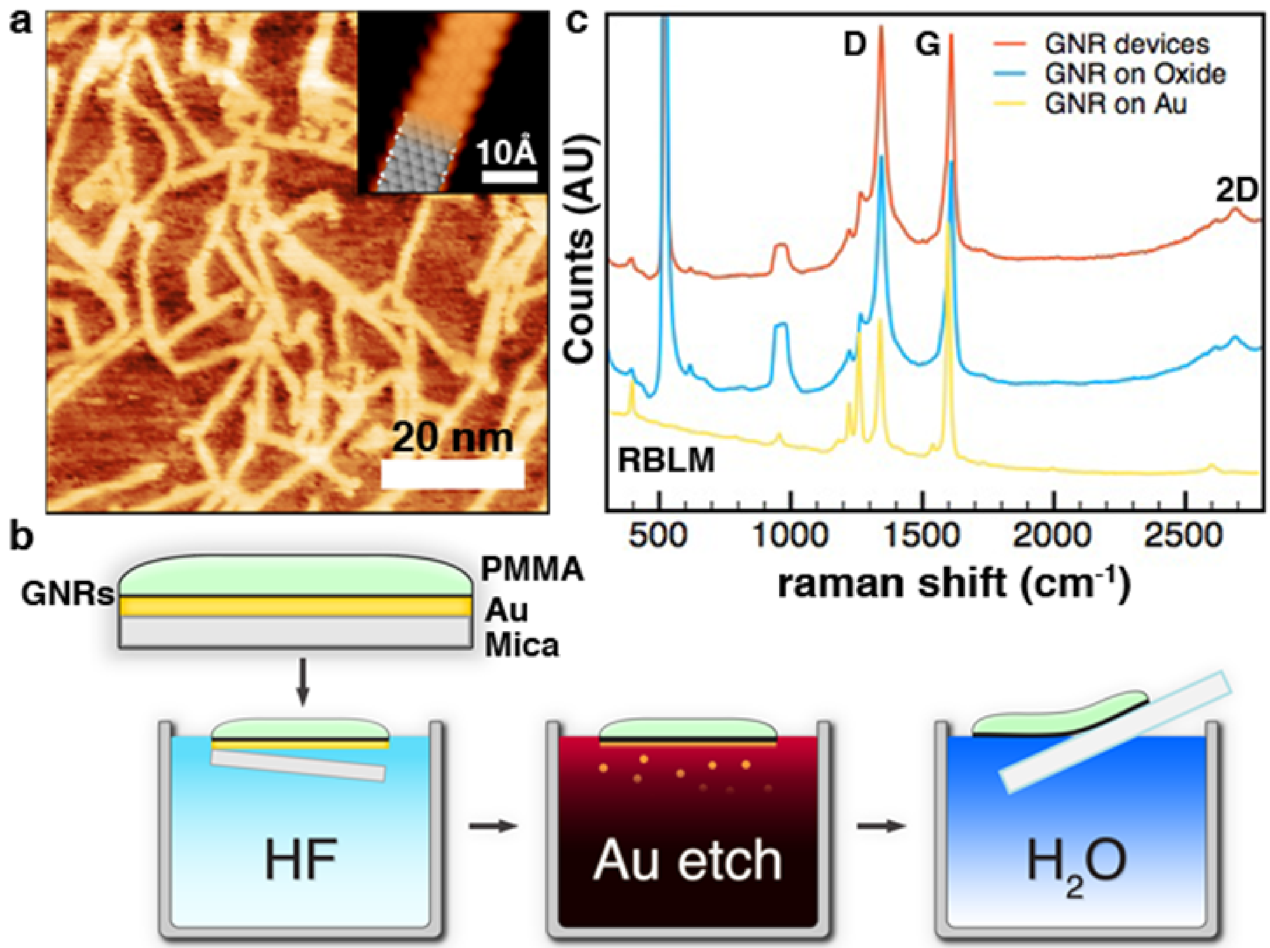


$m^* = 0.21\ m_e$

Eg = 2.3 eV

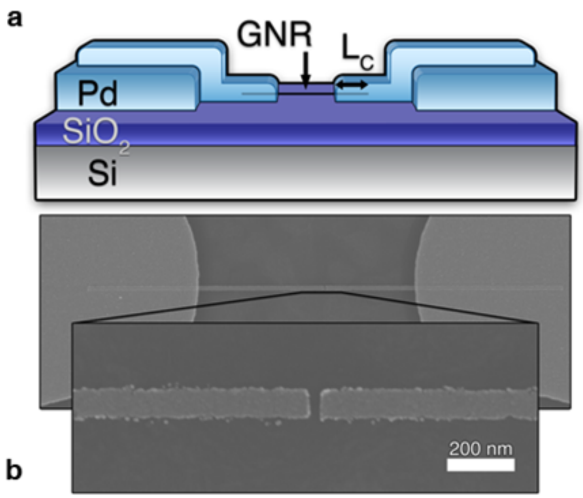
Ruffieux, et al. ACS Nano (2012) [Fasel group]

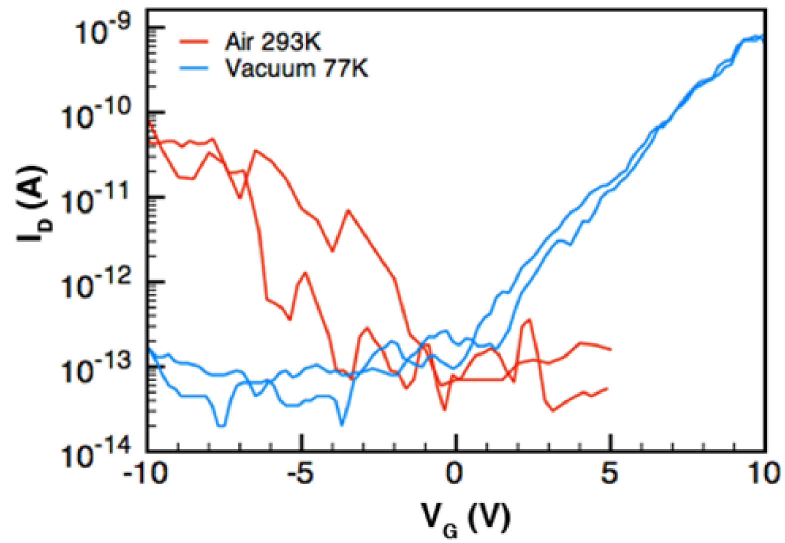
Synthesized GNR Transferred to SiO2



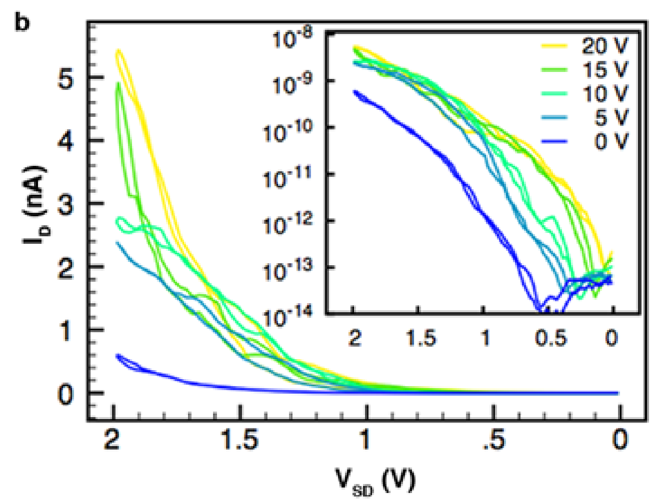
Bennett, et al., unpublished [UCB, Bokor/Crommie/Fischer groups]

Synthesized GNR Transistor Results

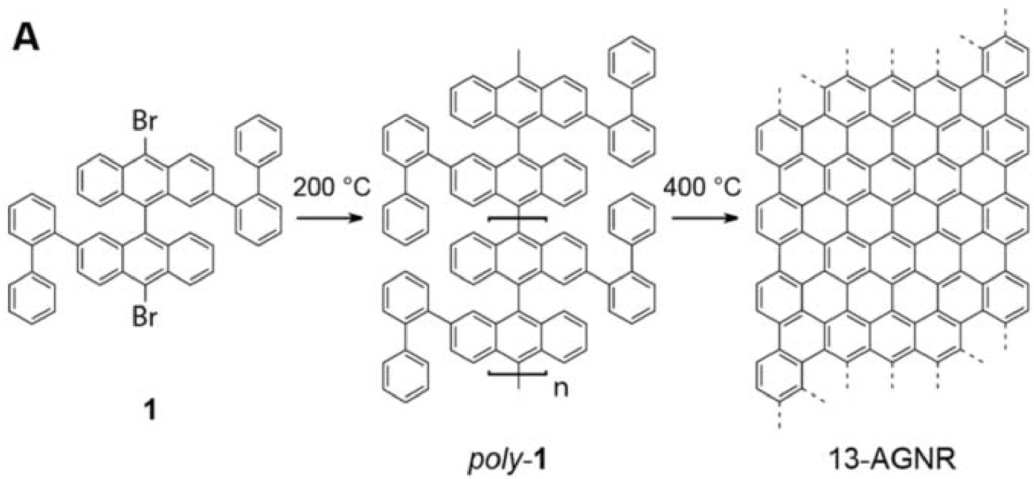


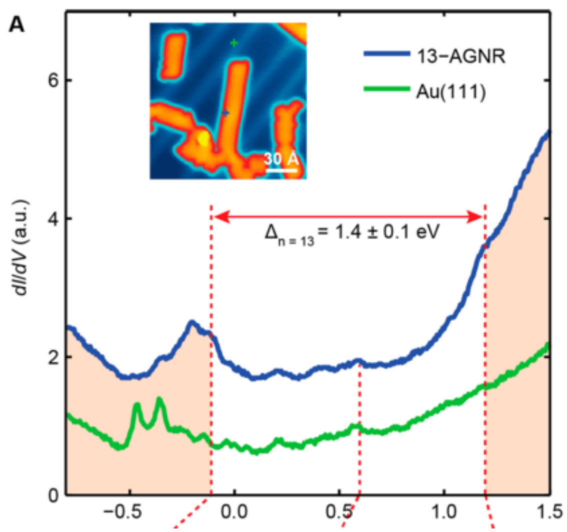


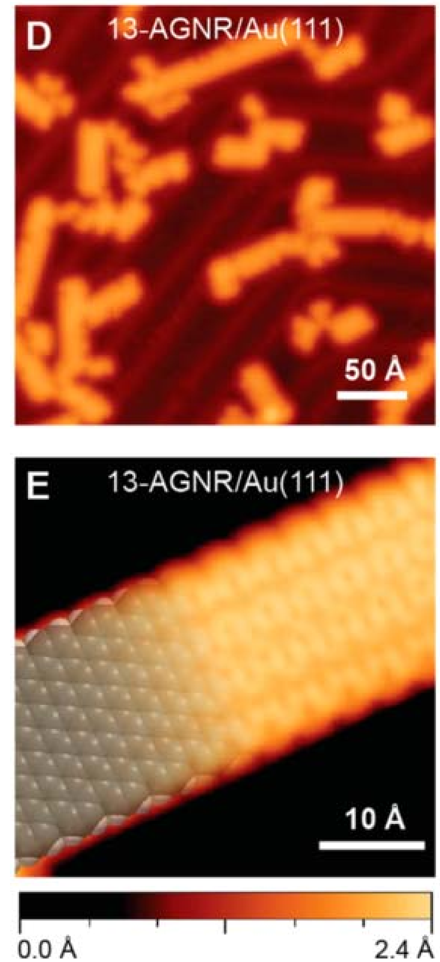
Bennett, et al., unpublished
[UCB, Bokor/Crommie/Fischer groups]



Wider GNRs Synthesized with 1.4 eV Gap

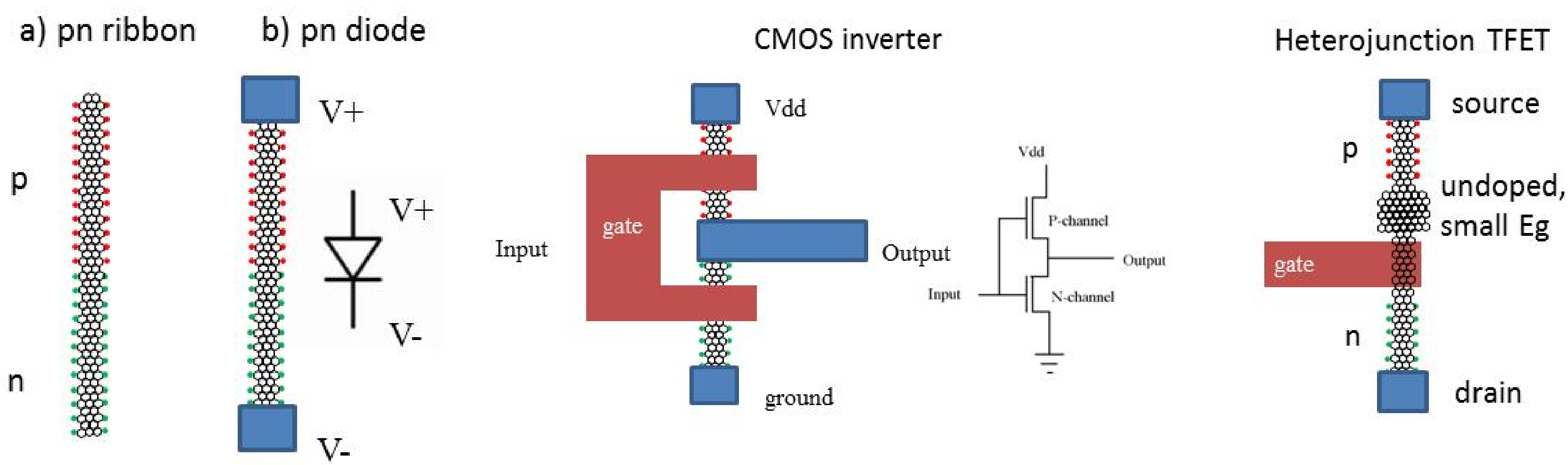






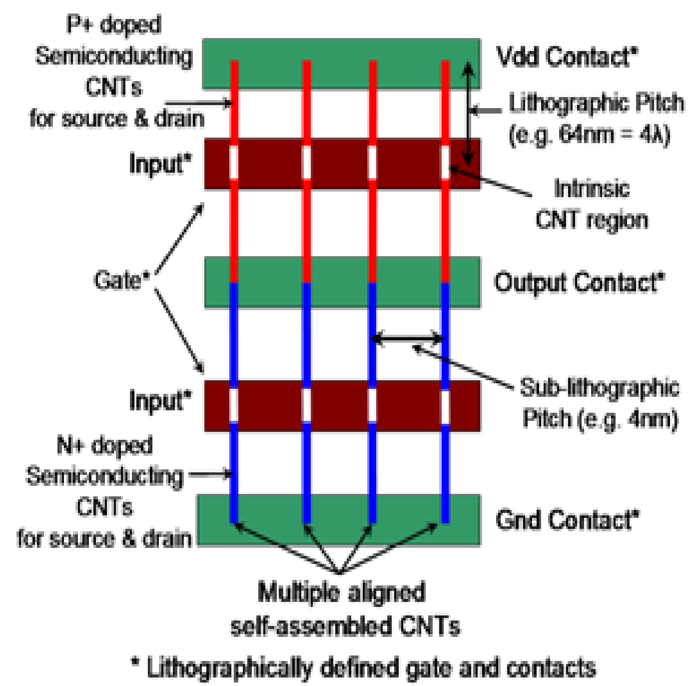
Chen, et al., ACS Nano (2013)
[UCB, Fischer/Crommie groups]

Single-Molecule Heterostructures



Summary/Outlook

- CNT and GNR both promising candidates for CMOS channel material for ≤ 8 nm gate length
- Why?
  - High drive at low V
  - Good scalability
  - 3D layer stacking:
    10 layers = 3 nodes on roadmap!



- More work needed:
  - Purified chirality for tubes
  - Longer, wider GNRs
  - Dense aligned arrays
  - **Low resistance contacts**
- **GSR opportunities in my group**