CNTFET

CARBON NANOTUBE FIELD EFFECT TRANSISTOR

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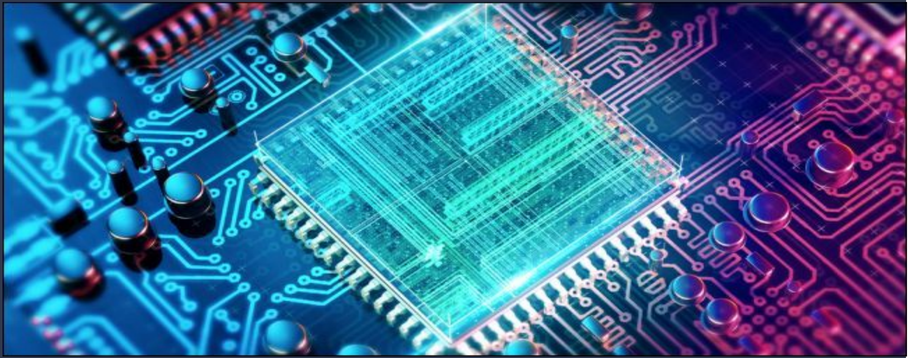
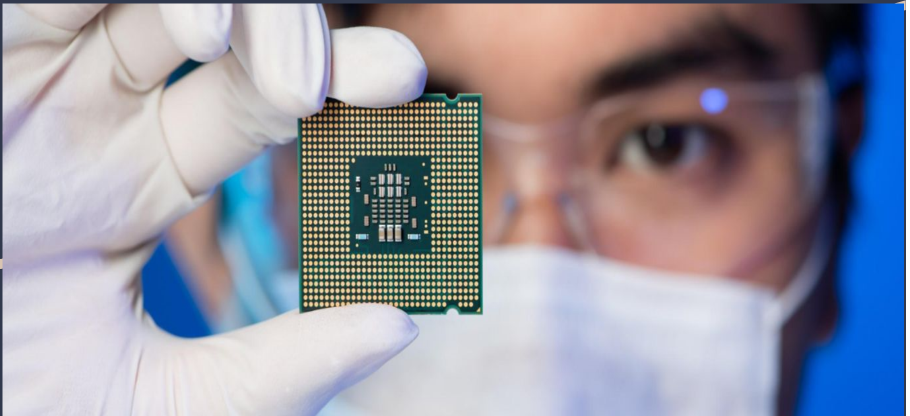
Why CNTFET ?

(Motivation)

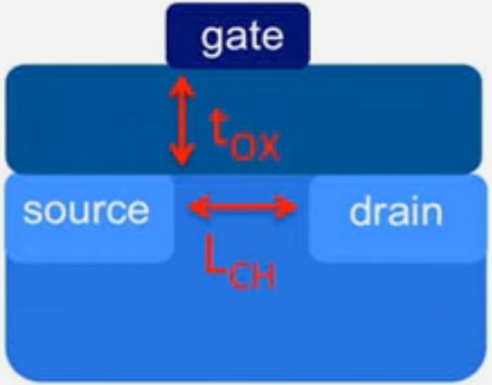




- As the size becomes smaller, scaling the silicon MOSFET becomes harder.
- Requirement of high performance channel material.
- High mobility requirement.
- High leakage Currents. (in MOSFETS)
- Extreme Short Channel Effects.
- High Field Effect.
- High charge mobility in Carbon Nanotubes(CNTs).
- CNTFETs can be scaled to much smaller sizes.

Key Problem:

If t_{ox} gets small (nm), device leaks
But t_{ox} must shrink with device
if not, then gate looses control of channel



two choices:

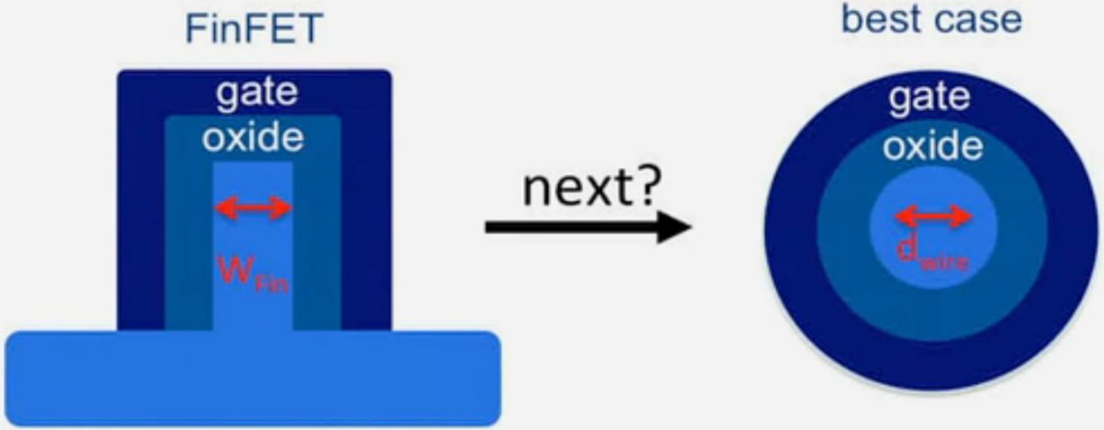
1. change materials
2. change geometry

solution 1: change materials (~ 2006)

$$C_{ox} = \epsilon_0 \kappa \frac{A}{t_{ox}}$$

increase K by changing the materials: SiO2 (3.9) to HfO2 (16)

solution 2: change geometry (~ 2013)

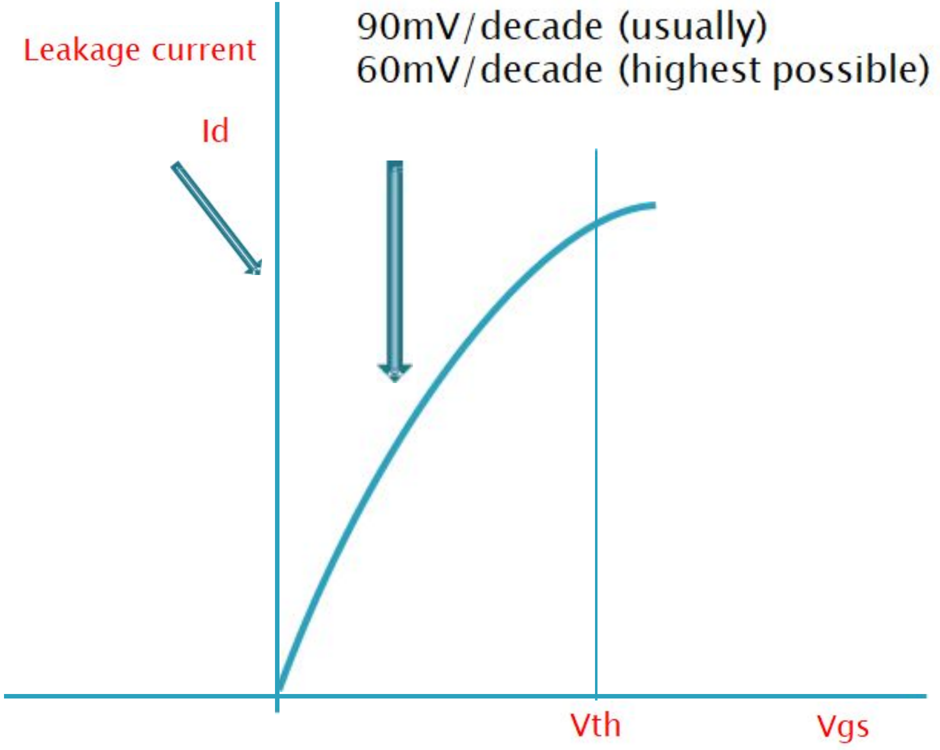


wrapping gate around channel allows better gate control
the thinner the body (W_{Fin}), the smaller the device can be

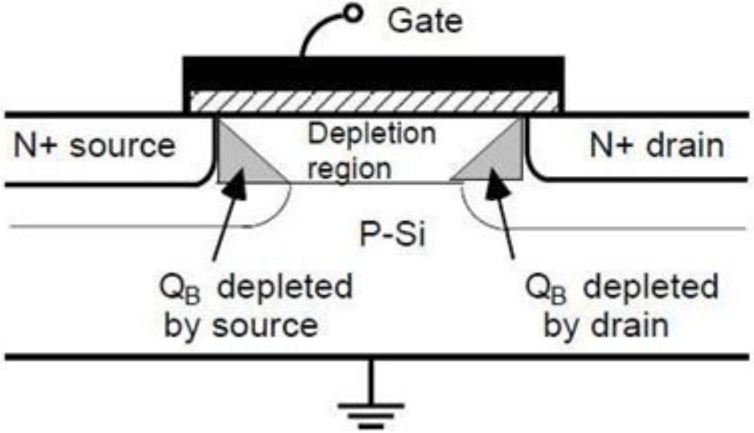
Problems in shrinking the conventional MOSFET

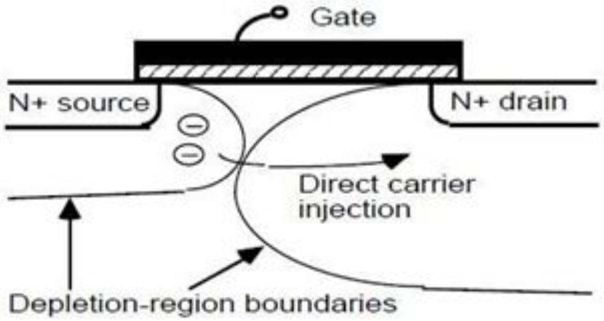
High leakage current

Due to leakage, static power is substantially increased.



Extreme Short Channel Effects



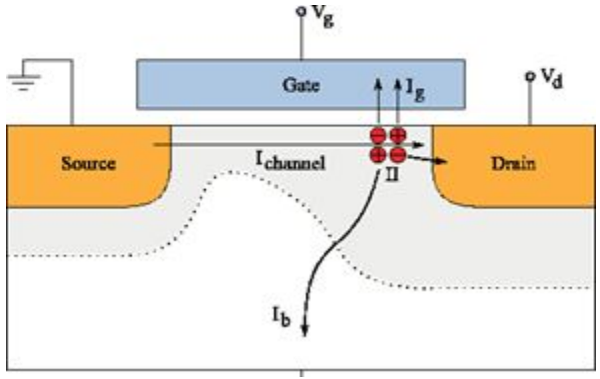


DIBL–Drain Induced Barrier Lowering & Punch through

- Extreme Short Channel Effects

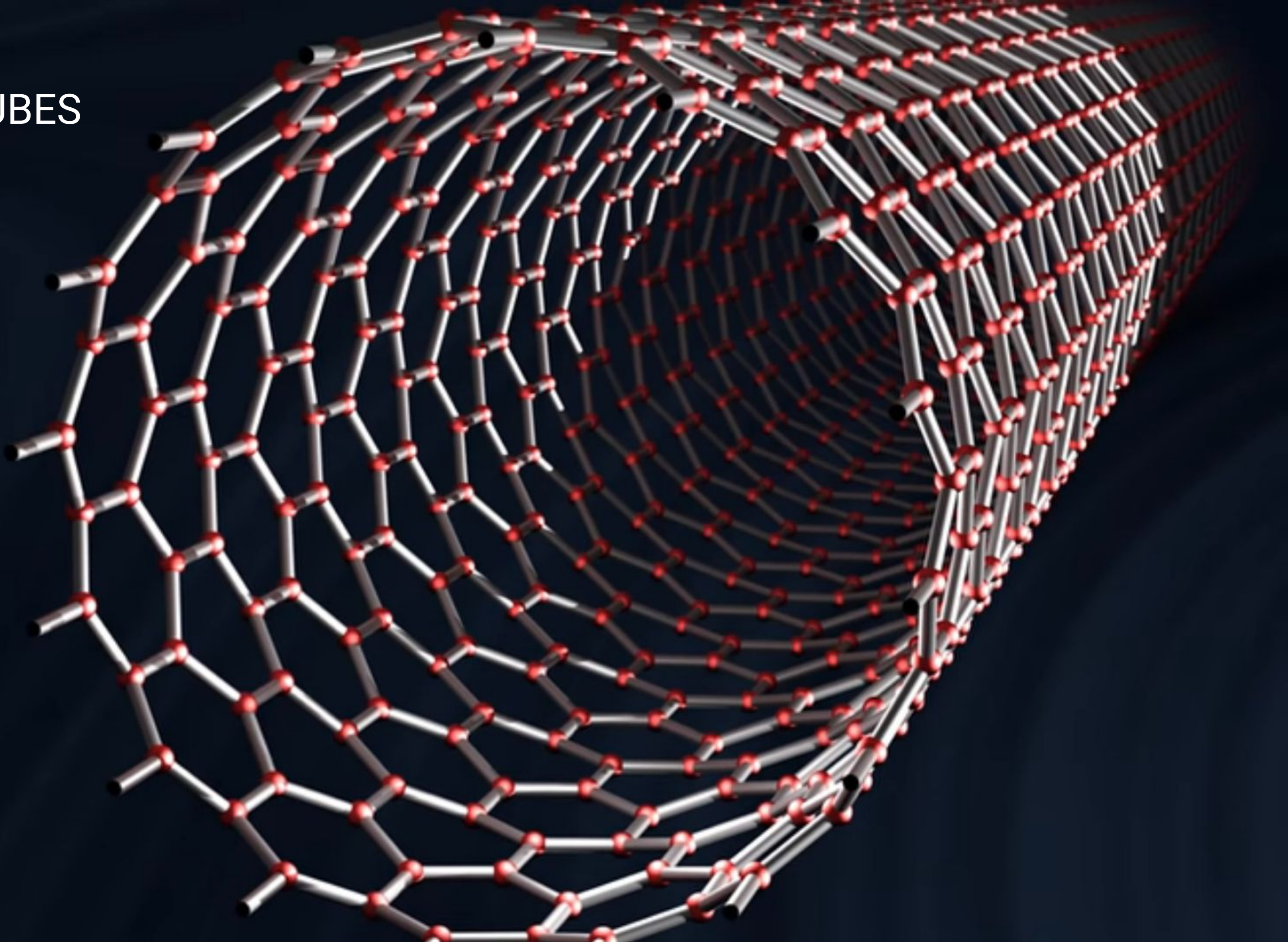
High Field Effects

As size decreases, electric field in channel increases which leads to high kinetic energy of electrons and holes (hot carriers) which penetrate into the gate oxide and temper the threshold voltage.



- High Field Effects

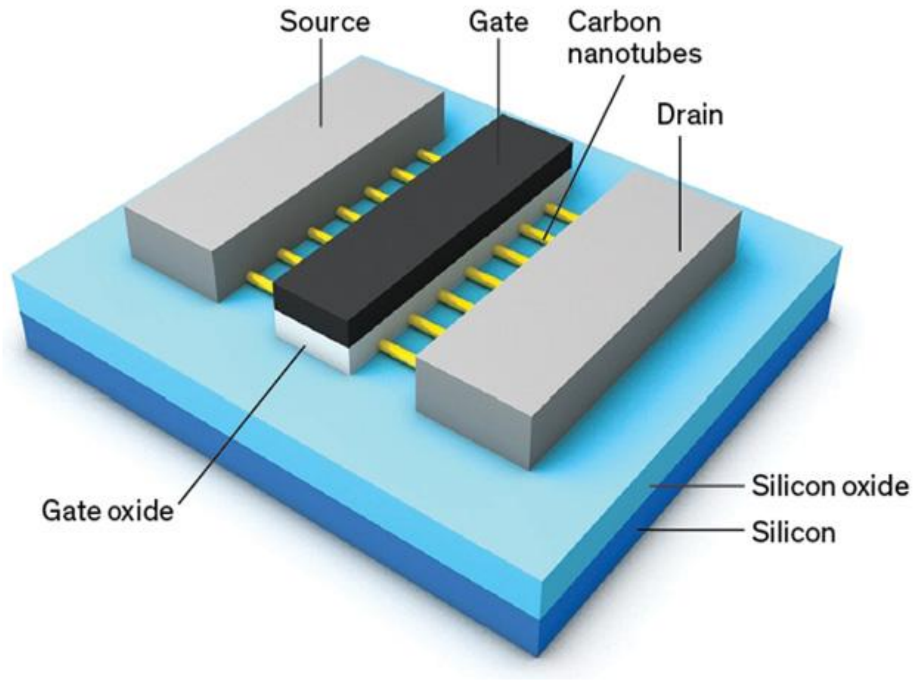
CARBON NANOTUBES
(CNTs)



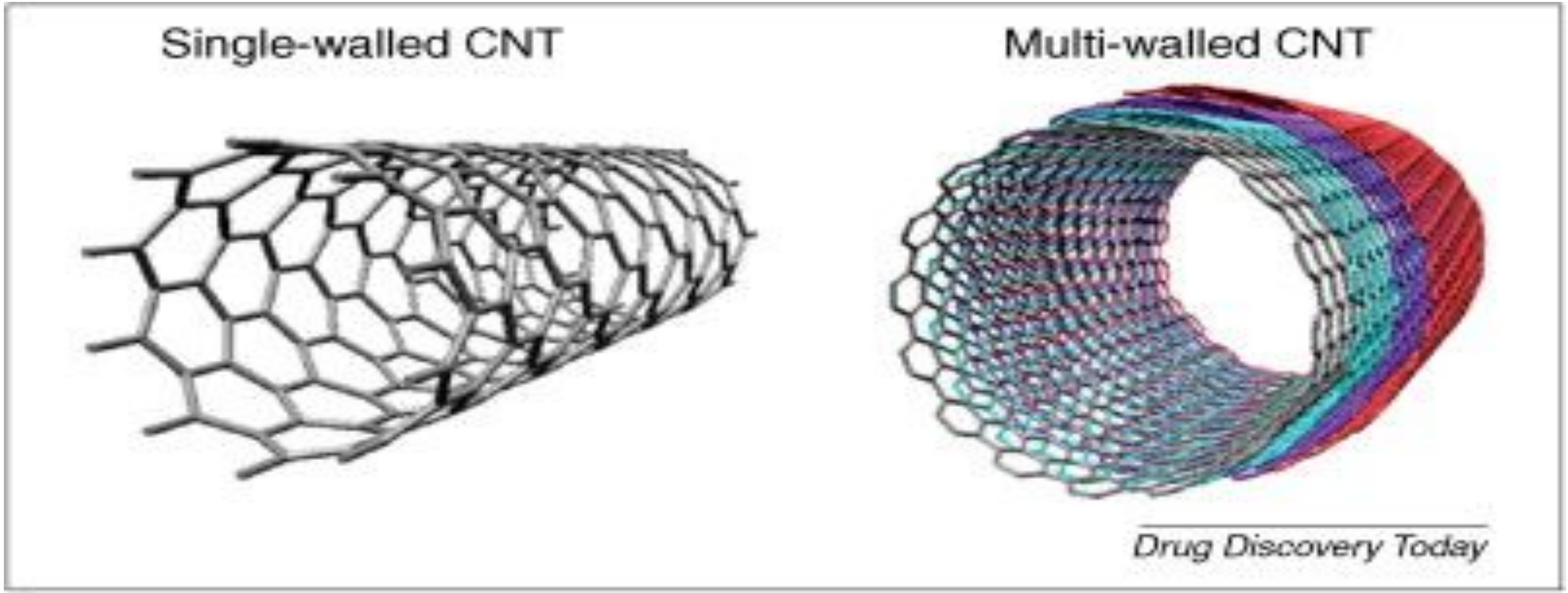
Introduction

- Carbon Nanotube Field Effect Transistors (**CNTFET**) are promising nano-scaled devices for implementing high performance very dense and low power circuits.

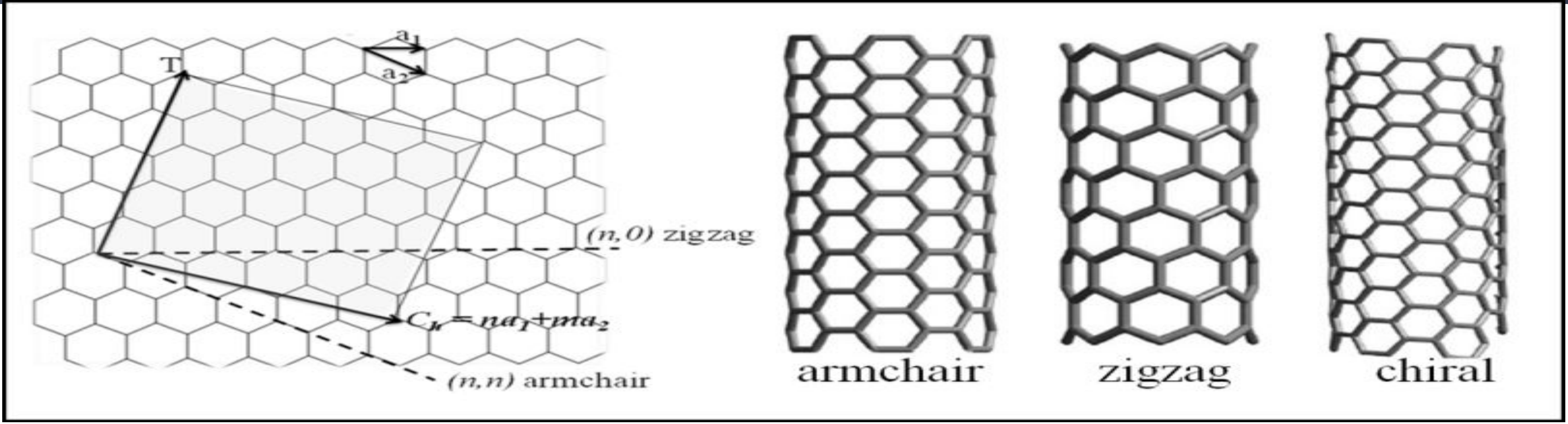
- A Carbon Nanotube Field Effect Transistor refers to a FET that utilizes a single CNT or an array of CNTs as the channel material instead of bulk silicon in the traditional MOSFET structure.The core of a CNTFET is a carbon nanotube.



Carbon nanotubes can be arranged as:



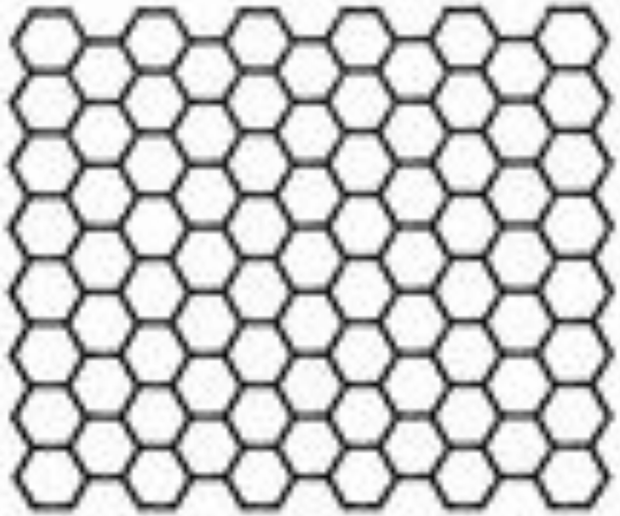
Carbon Nanotubes



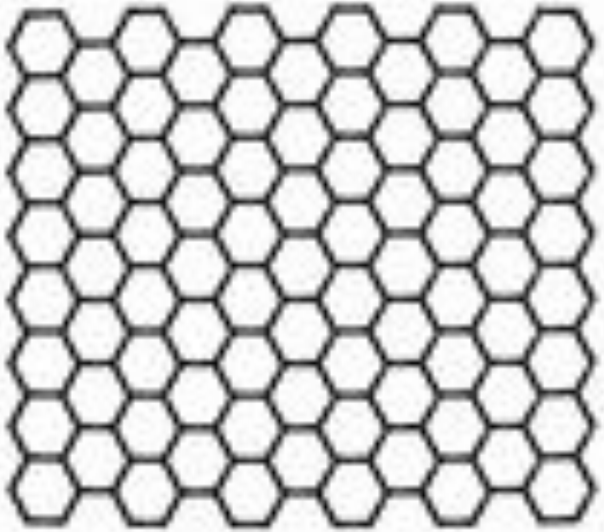
The indices (n1, n2) give different properties to the CNT. Accordingly, three types of CNTs can be identified based on way of folding the graphene sheet:

1. Armchair (n1 = n2)
2. Zig-Zag (n1 = 0 or n2 = 0)
3. Chiral (otherwise).

$$C_h = na_1 + ma_2$$



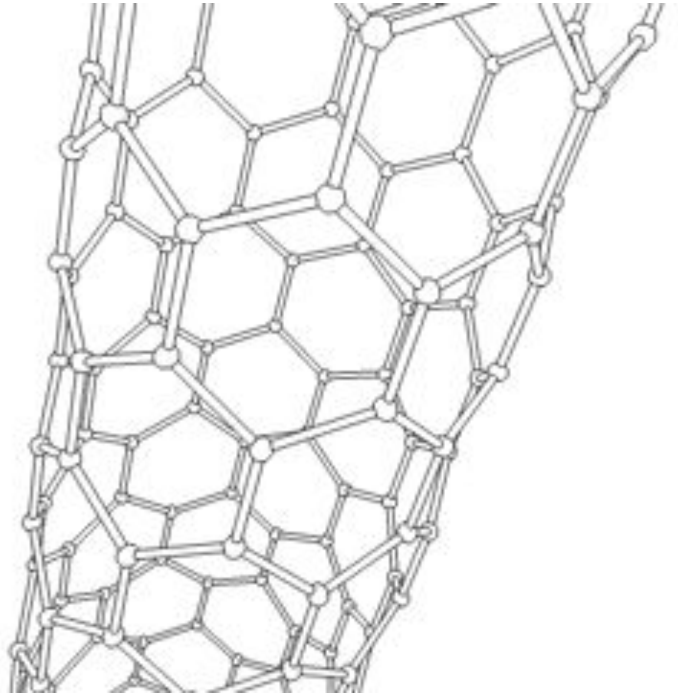
Zigzag SWNT (horizontal roll)

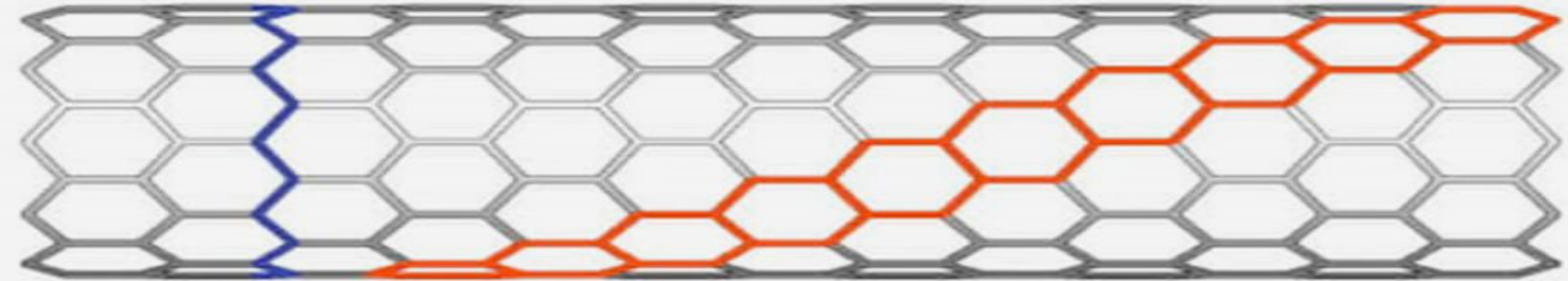


Armchair SWNT (vertical roll)

Rotating single-walled zigzag carbon nanotube

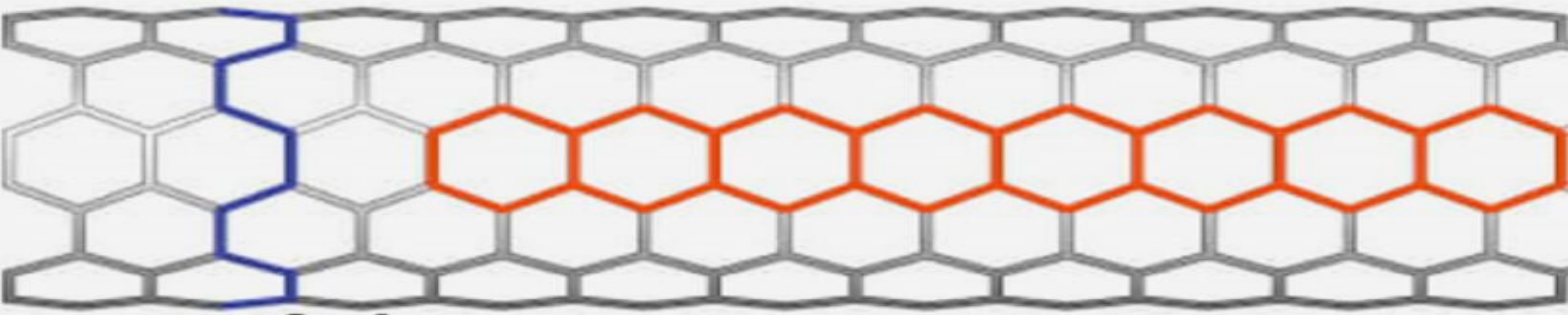
One defines a "zigzag" path on a graphene-like lattice as a path that turns 60 degrees, alternating left and right, after stepping through each bond.





Armchair Configuration

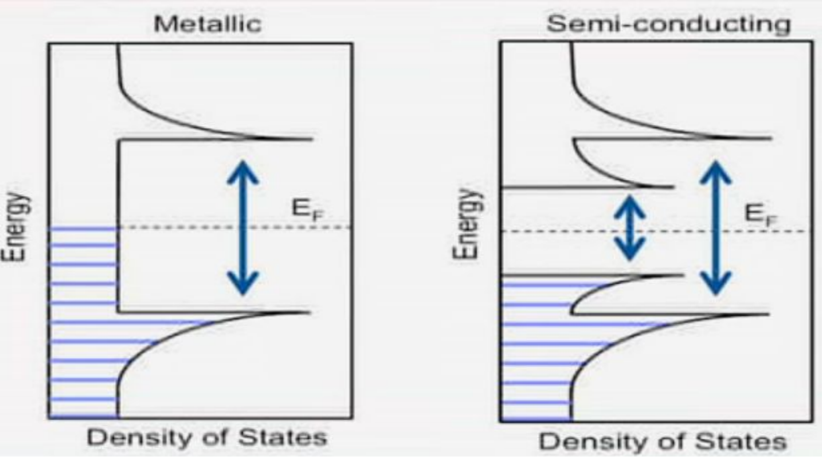
It is also conventional to define an "armchair" path as one that makes two left turns of 60 degrees followed by two right turns every four steps

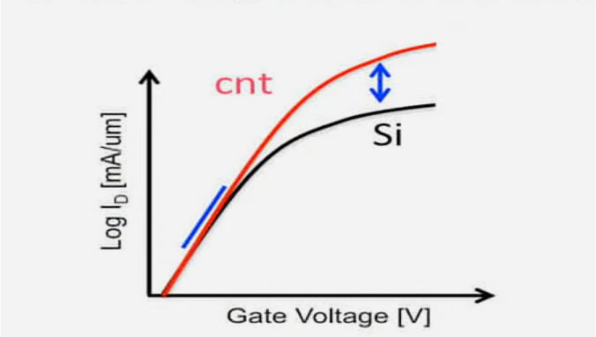


Theoretical Analysis & Working Principle

Why Carbon Nanotubes?

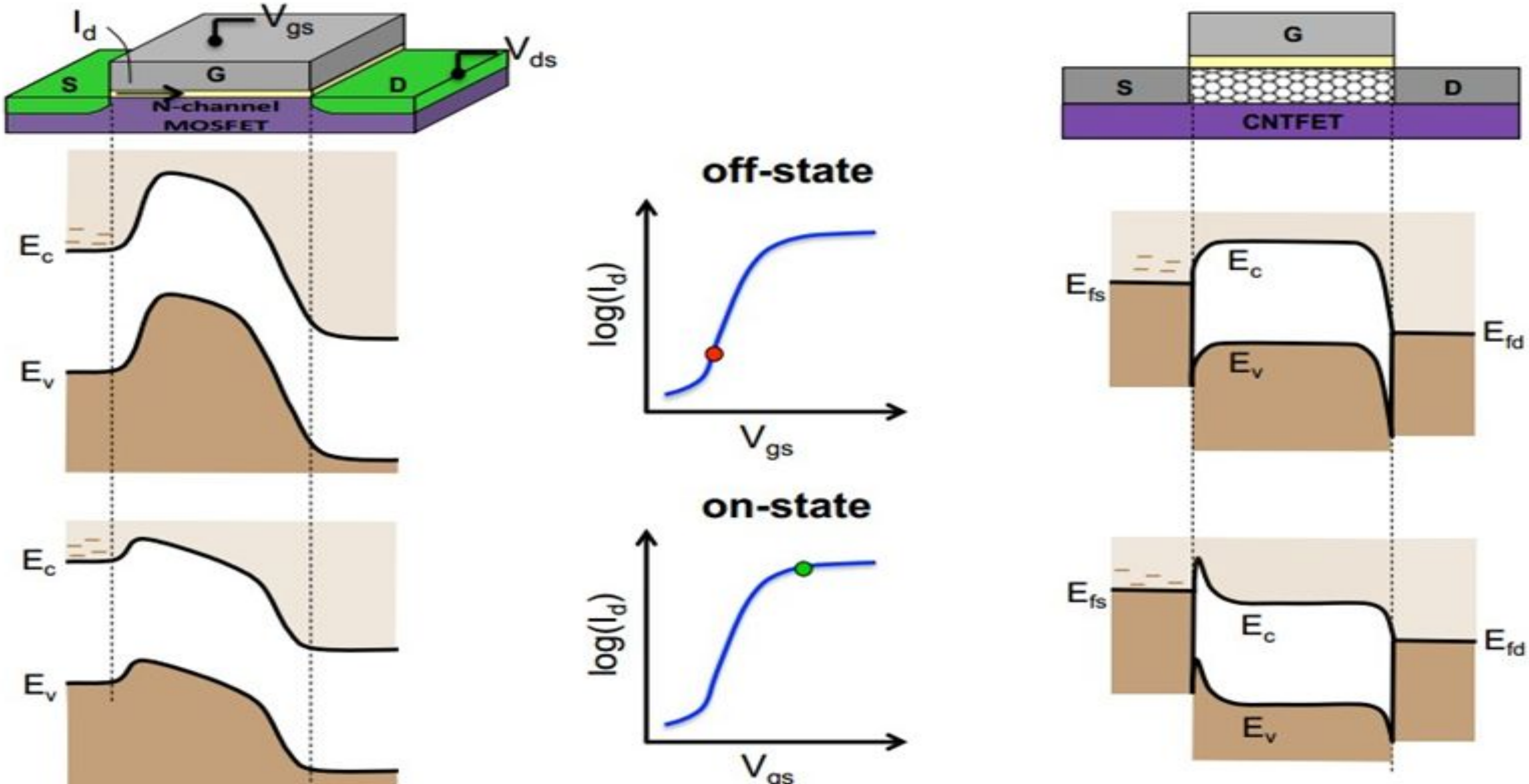
- A carbon nanotube band gap is directly affected by its way of folding and diameter. If these properties are controlled, CNTs become a promising candidate for nano-scale FETs.
- Moreover, because of the lack of boundaries in the hollow cylinder structure of CNTs, there is no boundary scattering.





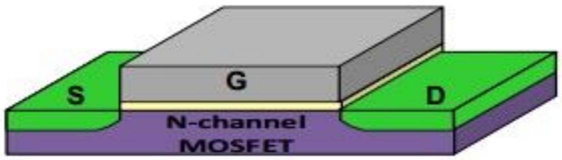
ON and OFF state of CNTFET and MOSFET

- The Gate voltage electrostatically turns the carrier flow in the CNT channel ON or OFF.



Drain Current parameters in CNTFET and MOSFET

Standard MOSFET



$$I_d = \mu_{eff}\,\frac{W}{L}\,\underbrace{C_{ox}\left(V_g - V_t\right)}_{\text{charge in channel}}\,V_{ds}$$

bias dependence

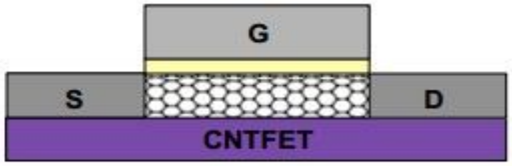
spatial dependence

carrier mobility

→ no DOS consideration

→ no consideration of contacts

CNTFET



$$I_d = q\int_{E_{fs}}^{E_{fd}} f(E,T)\cdot v(E)\cdot T(E)\cdot \underbrace{D(E)\cdot dE}_{\text{charge in channel}}$$

bias dependence (carrier injection determined by states between source/drain Fermi levels)

transmission at contacts

carrier (Fermi) velocity

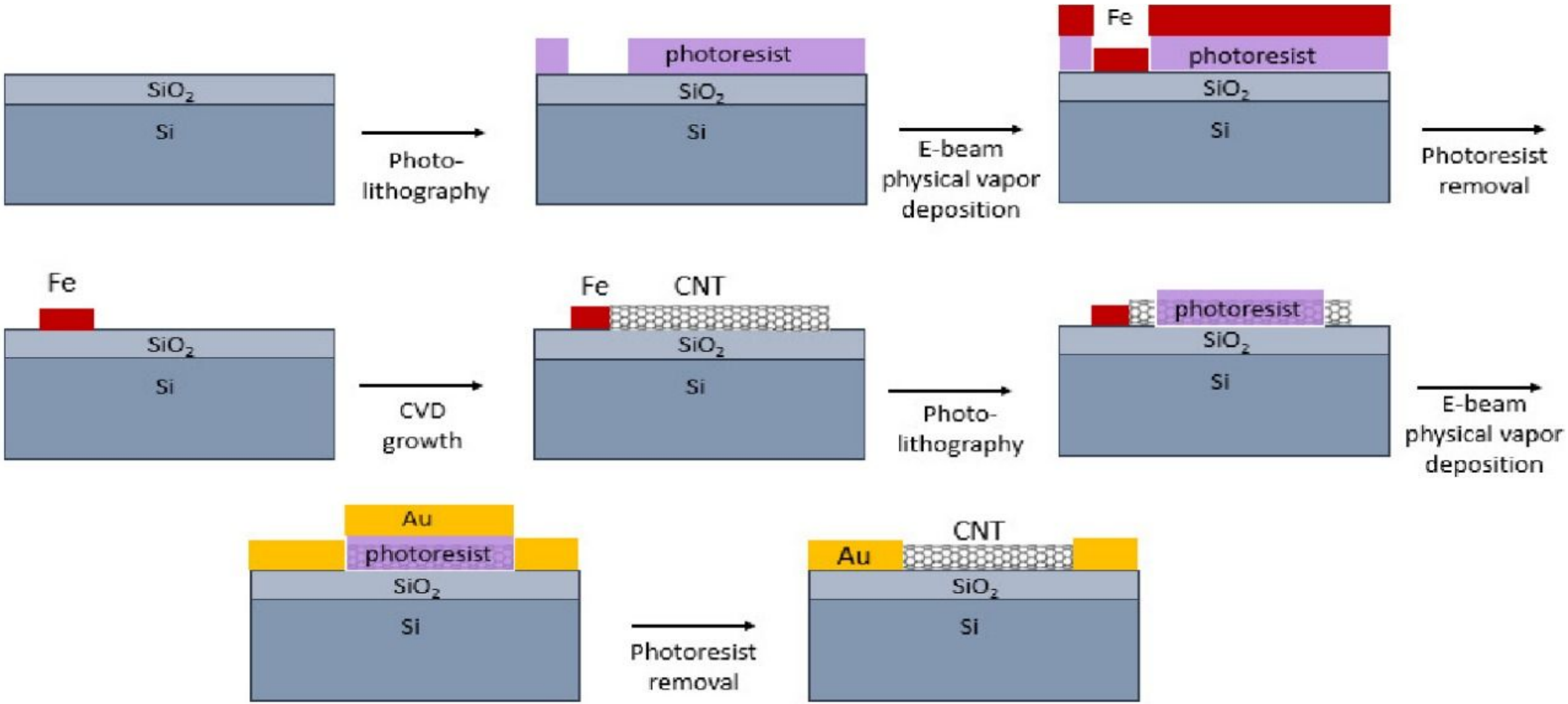
→ no spatial dependence

→ no mobility dependence

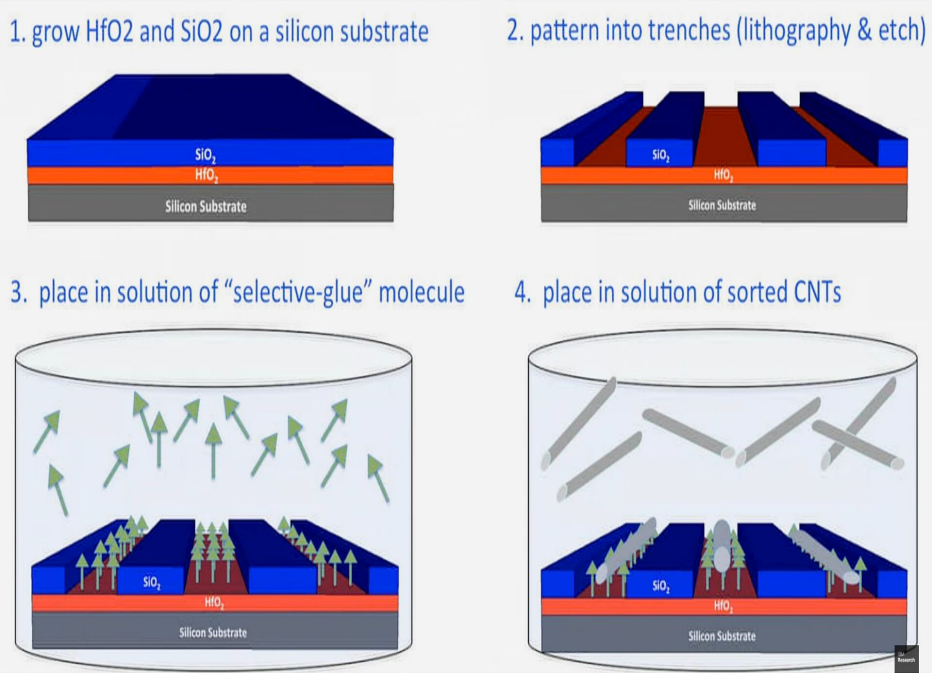
Fabrication

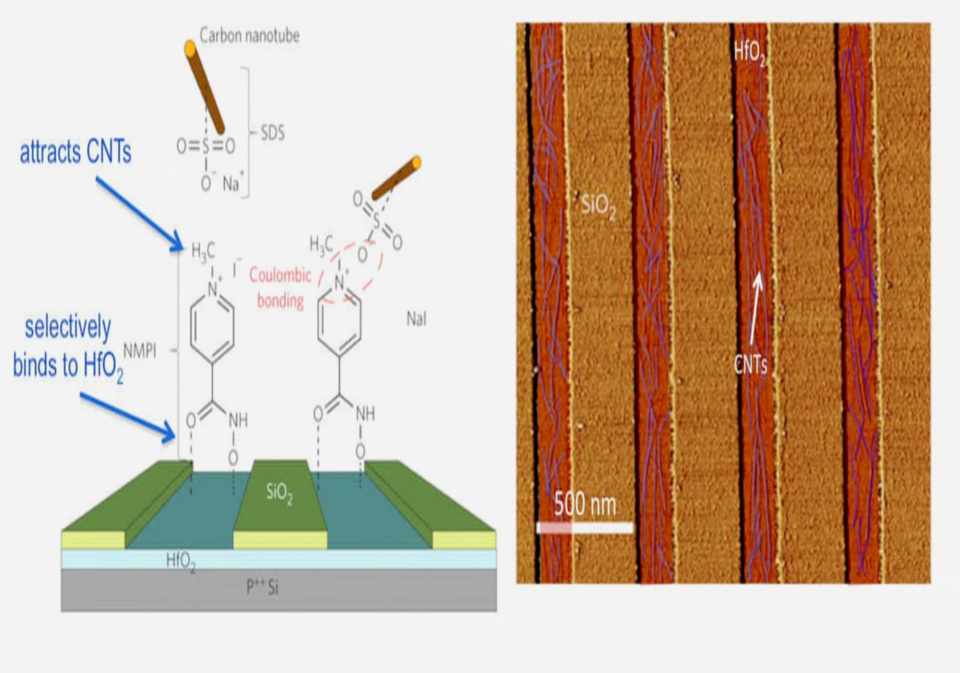
- CNTFETs are of many types, based on the mere placement of the CNTs in several orientations and different designs.
- Many difficult challenges have to be overcome in the fabrication process of CNTFETs, most of which include dealing with CNTs, which, as we know, are extremely small.
- Some of these challenges are discussed later in detail.

Fabrication of Top-Gated CNTFET



Placement of CNTs during the fabrication process





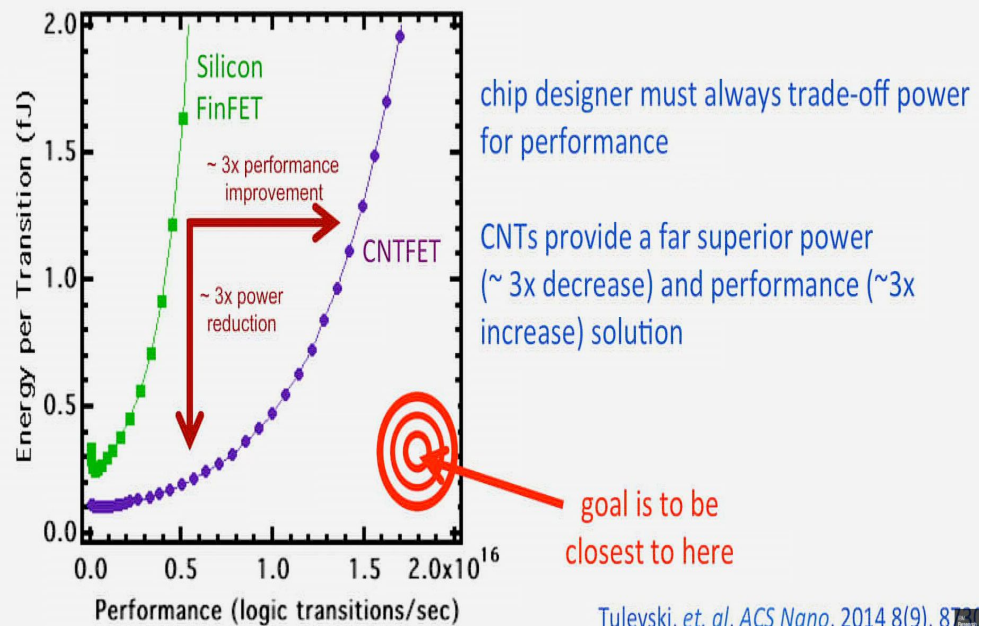
Some "Selective-glues"

Figure of Merits

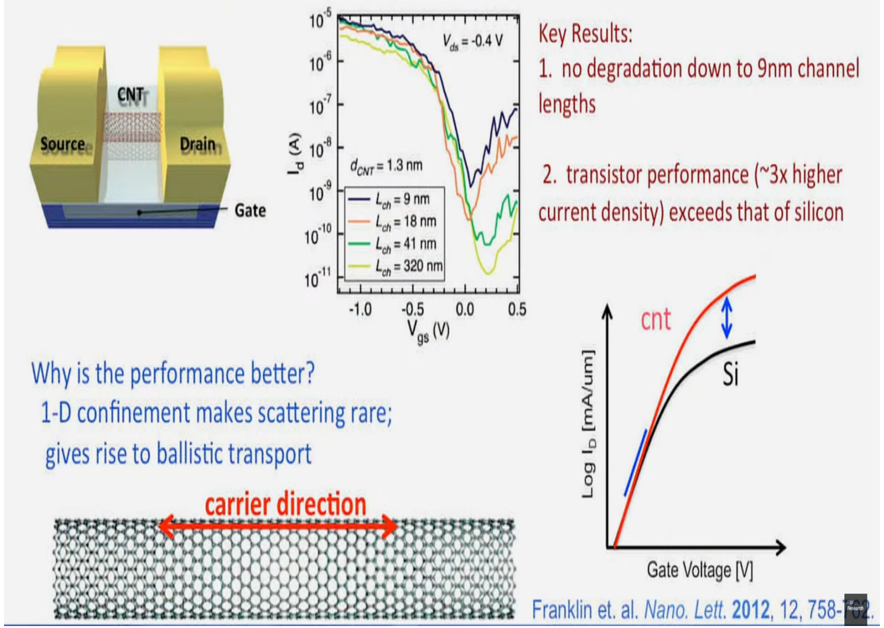
1. **CARRIER TRANSPORT**
   1-D ballistic transport of carriers leading to high carrier velocities.
2. **DEVICE CURRENT**
   High drive current and large transconductance.
3. **STRENGTH**
   High Temperature Resilience and strong covalent bonds in CNTs.
4. **DEVICE SCALING**
   Scaling to very small channel lengths(~9nm) has been possible till now.
5. **PERFORMANCE**
   High **Performance-to-Power** ratio compared to that of MOSFETs.

Figure of Merits

Performance comparison FinFET vs CNTFET



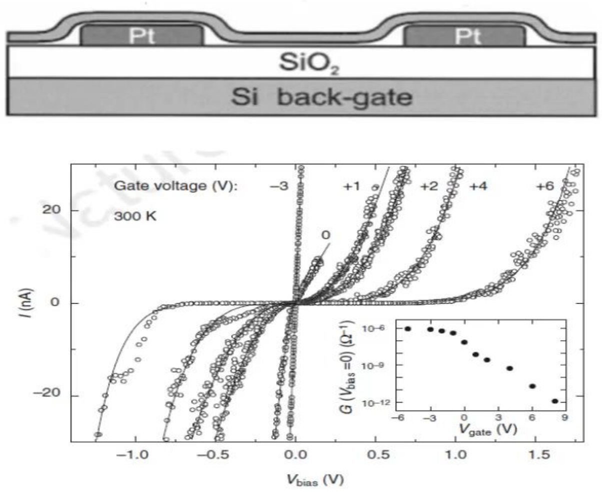
Scaling CNTFET



Relevant activities over recent years
(Device Realisation)

Carbon Nanotube Transistors

- First ever FET based on CNTs
  - Sander J. Tans, Alwin R. M. Verschueren & Cees Dekker (1998)
    - Two metal Electrodes
    - Single Wall CNT (SWCNT)
    - Room temperature operation
    - I-V data in accordance with the available semiconductor models of that time

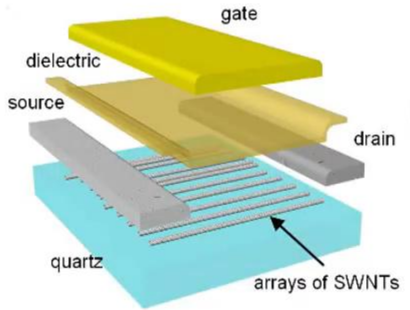


Schematic and I-V curves of first CNTFET [2]

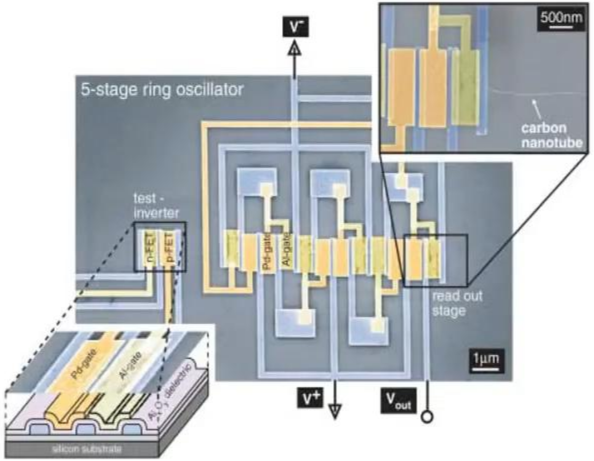
[2] Tans, S. J., Verschueren, A. R., & Dekker, C. (1998). Room-temperature transistor based on a single carbon nanotube. Nature,393(6680), 49-52. doi:10.1038/29954

Carbon Nanotube Transistors

- 2001, Single CNTs based FETs logic circuits [3]
  - Gain > 10 dB
  - On-off ratio >105
  - Different logic operations
- 2006, Five stage ring oscillator on a single CNT [4]
  - 12 FETs
  - Resonances at 13 MHz @ 0.5 V and 52 MHz @ 0.92 V
  - Delay of 1.9 ns per stage
- 2008, Nanotube transistor radios [5]
  - SWCNT Audio amplifiers, RF mixers, fixed RF amplifiers and resonant antennas



Schematic of transistor showing SWCNT aligned arrays [5]

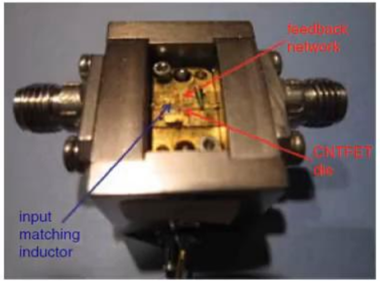


Five stage ring oscillator based on a single CNT [4]

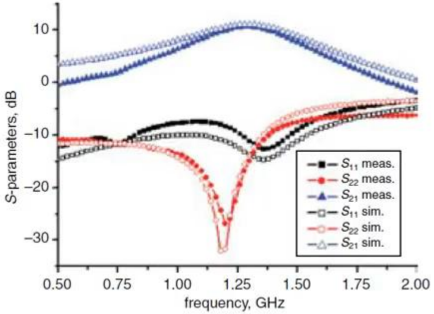
[3] Bachtold, A. (2001). Logic Circuits with Carbon Nanotube Transistors. Science,294(5545), 1317-1320. doi:10.1126/science.1065824
[4] Chen, Z. (2006). An Integrated Logic Circuit Assembled on a Single Carbon Nanotube. Science,311(5768), 1735-1735. doi:10.1126/science.1122797
[5] Kocabas, C., Kim, H., Banks, T., Rogers, J. A., Pesetski, A. A., Baumgardner, J. E., . . . Zhang, H. (2008). Radio frequency analog electronics based on carbon nanotube transistors. Proceedings of the National Academy of Sciences,105(5), 1405-1409. doi:10.1073/pnas.0709734105

Carbon Nanotube Transistors

- 2011, First CNT based L-band RF amplifier [6]
  - Gain > 11 dB @ 1.3 GHz
  - Input/Output return loss < 10 dB



- 2013, CNT transistor based computer [7]
  - Integer sorting and counting at the same time
  - Realization of future electronic systems with high energy efficiency

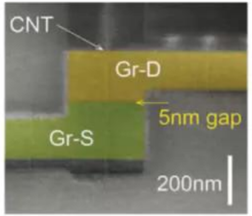


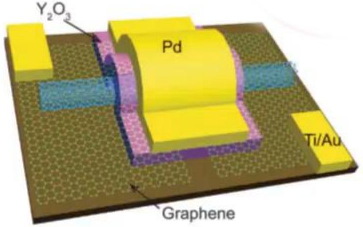
L band amplifier with S-parameters [6]

[6] Eron, M., Lin, S., Wang, D., Schroter, M., & Kempf, P. (2011). L-band carbon nanotube transistor amplifier. Electronics Letters,47(4), 265. doi:10.1049/el.2011.0018
[7] Shulaker, M. M., Hills, G., Patil, N., Wei, H., Chen, H., Wong, H. P., & Mitra, S. (2013). Carbon nanotube computer. Nature,501(7468), 526-530. doi:10.1038/nature12502

Carbon Nanotube Transistors (Recent achievements)

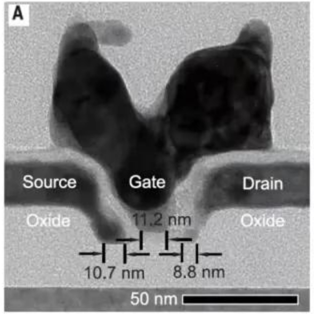
- 2017, realization of nanotube transistors with 5 nm gate length [8]
  - High on-state current
  - Large conductance at room temp.
  - CNTFET used with graphene contacts
    - Reduction of Drain/Source parasitic capacitances
    - Reduction of short channel effect





CNTFET with graphene contacts [8]

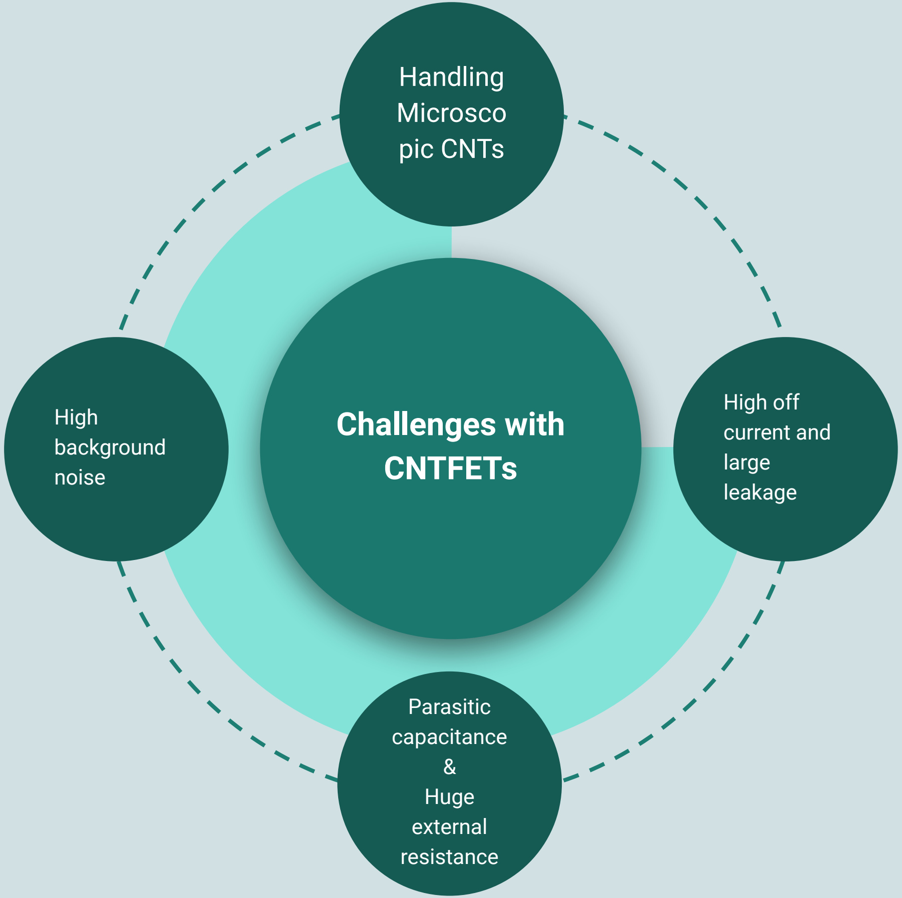
- 2017, CNT based transistor with 40 nm foot print [9]



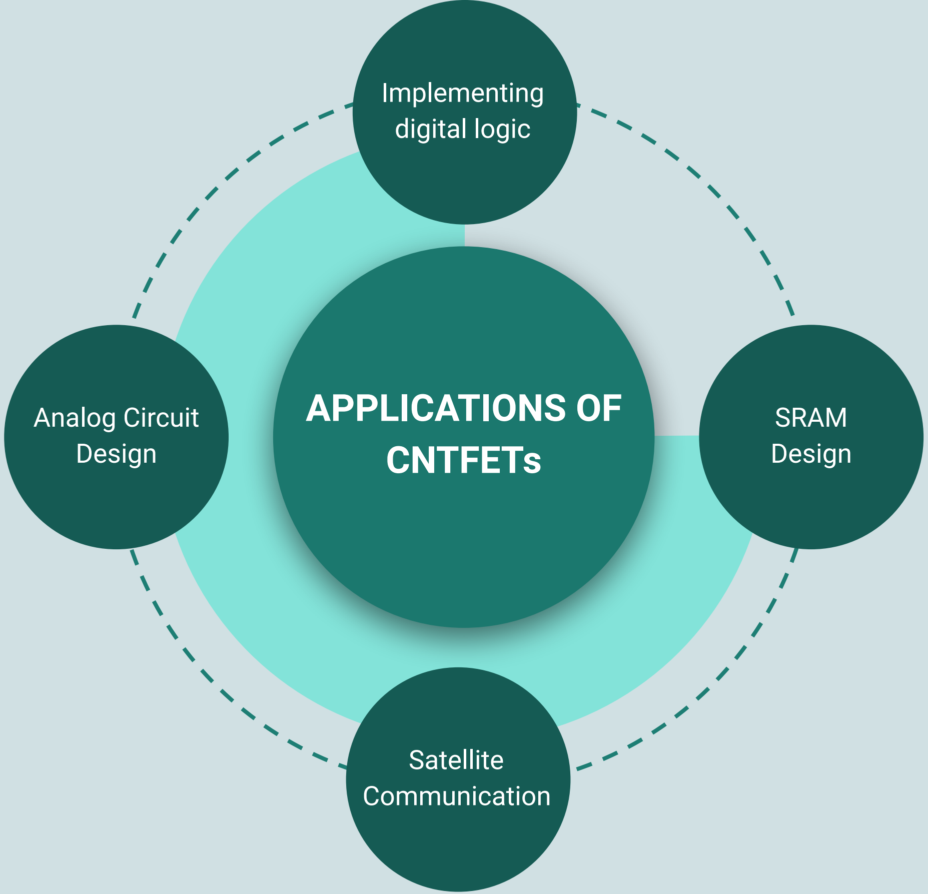
TEM image of single CNT based transistor with 40 nm foot print [9]

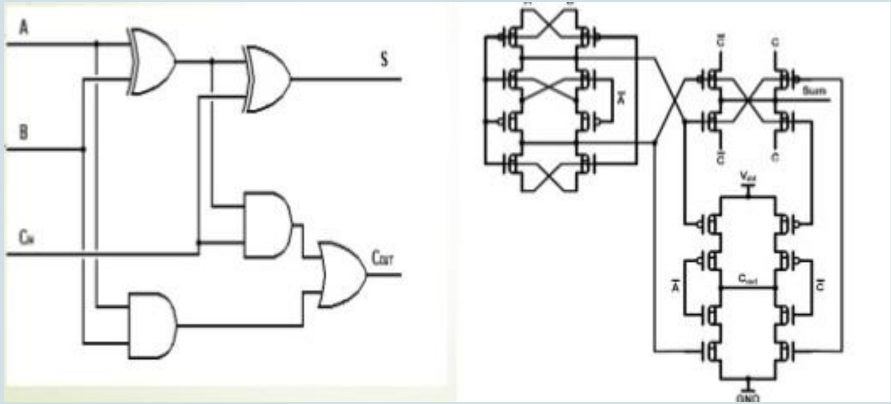
- 2017, Fabrication of five stage ring oscillator [10]
  - Complimentary carbon nanotubes
  - Switching frequency = 2.82 GHz

[8] Qiu, C., Zhang, Z., Xiao, M., Yang, Y., Zhong, D., & Peng, L. (2017). Scaling carbon nanotube complementary transistors to 5-nm gate lengths. Science,355(6322), 271-276. doi:10.1126/science.aaj1628
[9] Cao, Q., Tersoff, J., Farmer, D. B., Zhu, Y., & Han, S. (2017). Carbon nanotube transistors scaled to a 40-nanometer footprint. Science,356(6345), 1369-1372. doi:10.1126/science.aan2476
[10] Han, S., Tang, J., Kumar, B., Falk, A., Farmer, D., Tulevski, G., Haensch, W. (2017). High-speed logic integrated circuits with solution-processed self-assembled carbon nanotubes. Nature Nanotechnol
doi:10.1038/nnano.2017.115


Handling Microsco pic CNTs
High background noise
Challenges with CNTFETs
High off current and large leakage
Parasitic capacitance & Huge external resistance

CNTFETs can be used in high frequency applications, thanks to the high carrier mobility because of less carrier scattering, as mentioned earlier.





Implementation of Full adder circuit using CNTFETs

Future Work

The most desirable future work involved in **CNTFETs** will be the transistor with **higher reliability**, **cheap production cost**, or the one with **more enhanced performances**.

For example, such efforts could be made: adding effects external to the inner CNT transistor like -

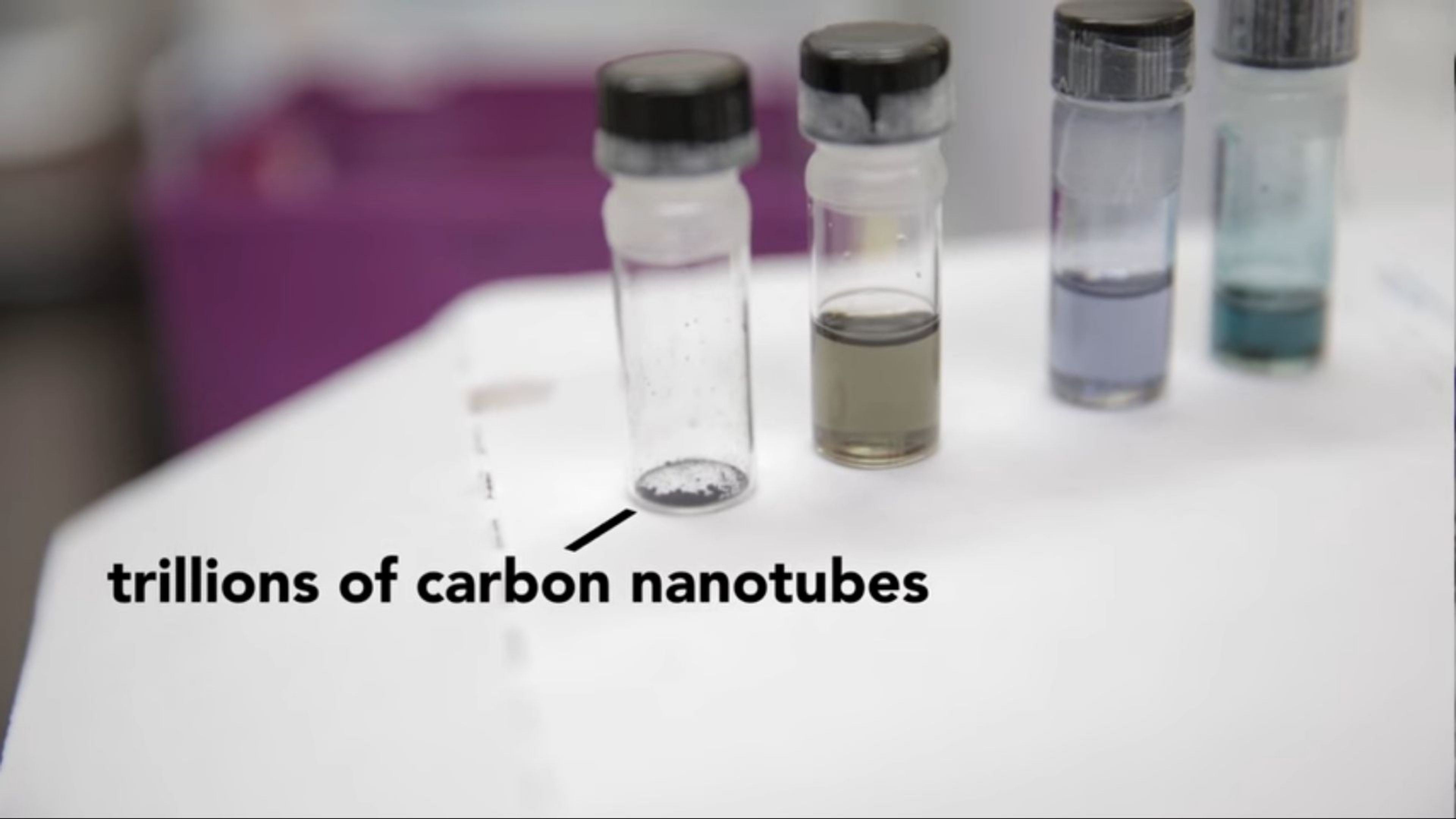
- Schottky barrier between the CNT and metal contacts
- multiple CNTs at a single gate
- channel fringe capacitances
- parasitic source/drain resistance
- series resistance due to the scattering effects.

CONCLUSION

- The evolution of carbon nanotube transistors over the last two decades has made CNTFET technology as potential candidate to replace silicon based CMOS technology

- CNTFET technology has the capability to go below 7nm node

- The high intrinsic carrier mobility and velocity of CNTFETs as well as the thermal ruggedness and their possible high linearity have made CNTFETs also attractive for high-frequency (HF) applications.


trillions of carbon nanotubes

References

[1] Rabaey, J.M., Chandrakasan, A. , Nikolic, B., Digital Integrated Circuits Second Edition, 2002, Prentice-Hall
[2] Ale, I., Hasan, M., Islam A. , Abbasi, S.A., “Optimized Design of a 32-nm CNFET-Based LowPower Ultra wideband CCII” IEEE Transactions On Nanotechnology, vol. 11, no. 6, pp. 1100-1108, Nov. 2012 [3] P. L. McEuen, M. S. Fuhrer, and P. Hongkun, “Single-walled carbon nanotube electronics” IEEE Transactions on Nanotechnology., vol. 1, no. 1, pp. 78–85, Mar. 2002 [4] Leonardo de Camargo e Castro, (2006) Modelling of Carbon Nanotube Field-Effect Transistor, (Doctoral Dissertation), University of British Columbia [5] Deng, J. (2007) Device Modelling And Circuit Performance Evaluation For Nanoscale Devices: Silicon Technology Beyond 45 Nm Node And Carbon Nanotube Field Effect Transistors (Doctoral Dissertation), Stanford University.
[6] Cho G, Kim Y-B, and Lombardi F: “Assessment of CNTFET based circuit performance and robustness to PVT variations”. In Proceedings of the MWSCAS '09 52nd IEEE International Midwest Symposium on Circuits and Systems: August 2–5: Cancun. New York: IEEE 2009, 2009:1106–1109. [7] Moradinasab, Mahdi. Fathipour, Morteza. “High Performance SRAM based on CNFET”, Ultimate Integration of Silicon, 2009. Pp.317-320, Mar. 2009[8] A. Javey, J. Guo, D. B. Farmer, Q. Wang, E. Yenilmez, R. G. Gordon, M. Lundstrom, and H. Dai, “Self-aligned ballistic molecular transistors and electrically parallel nanotube arrays,” Nano Lett., vol. 4, no. 7, pp. 1319–1322, 2004. [9] Murrae J. Bowden, “Moore’s Law and the Technology S-Curve” Current Issues in Technology Management, winter 2004 Issue 1 Volume 8. [10] Semiconductor Industry Association. (2005). International Technology Roadmap for Semiconductors-2005.


Q&A