Hoang Do
Napat Triroj
Scribe Report
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Carbon Nanotubes

Discussion Leader: Dimitrios Kazazis

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- CNT electronic properties.
- Overview of interesting CNT based FET.
- Multiple valued logic design using ballistic CNT FETs.

I. The end of CMOS:

+ By 2015 the size of traditional transistor will reach the limit of about 16nm.
+ The need for new materials and devices arises.
+ Improve CMOS with high k-dielectrics, new gate electrode, new S/D contacts, strained Si.

II. CNT:

+ A promising substitute for CMOS is CNT with many of its extraordinary properties.
+ First discovered in 1991 by Sumio Iijima at NEC, Japan.
+ CNT is one among many carbon structures (graphite, diamond, C60, etc.) It looks like a graphite sheet rolled into a seamless cylinder, with C atoms arrange themselves into hexagonal rings like chicken wire.

In diamond the carbon atoms link into four-side tetrahedra, but in nanotubes the atoms arrange themselves in hexagonal rings. Usually, tetrahedra structure is stronger than the hexagonal structure. But, when roll hexagonal sheet into a tube and pull the tube along the axis, the tube can be as strong as diamond.

+ Can be considered as one dimensional object (exceedingly narrow and long).
+ Can be single (SW) or multi-walled (MW) tubes (each contained a number of hollow cylinder of carbon atoms nested inside one another like Russian dolls).
+ High axial mechanical strength.
+ Superlative resilience
+ Thermal stability.
+ It could have different structures: zigzag, armchair (roll along one of symmetry axis's) or chiral tube (differs from symmetry axis).

III. Fabrication:

+ Arc Discharge:
First published in 1992 from NEC lab.
Frankensteinian method: Wire two millimeter-parted graphite rods to a power supply, throw the switch. Yield: 30% by weight.
Advantages: SW/MW tubes with few defects.

Disadvantages: Short tubes (<50 micrometers), randomly deposited and sized.
+ Chemical Vapor Deposition (CVD) or Hot gas:
Place a substrate in the oven, heat to 600C, add carbon-bearing gas, it will decompose and free C atoms to form CNT. Yield: 20-100%.
Ad: easiest way.
Limit: MW tubes with defects/small strength.

+ Laser Ablation:
Blasting graphite rods with intense laser pulses.
Yield: 70%
Ad: SW tubes with controlled diameters.
Disadvantages: Expensive.

IV. Electrical properties:
Graphite is known as semimetal, half metal half semiconductor.
Barely conducts, only a few electrons can access through a narrow path to a conduction state without external energy boost.
Straight CNT: 2/3 metallic, 1/3 semiconducting.
Twisted CNT: 1/3 metallic, 2/3 semiconducting.
The electrical conductivity of single-walled and multi-walled CNTs are similar. Single-walled CNTs has better field emitting properties because it has higher field enhancement factors.

VI. Nano-devices based on CNTs:
Spintronic: based on preserved ‘spin’ state of electrons of CNTs.
Single electron transistor: based on phenomenon: only one electron inserted into a cross section of CNT at a time.
CNTs as ultra-thin wires. Metallic CNTs can be used as interconnection. Expected to dissipate less heat (?).

VII. CNFET (TUBEFET):
1.4 nm wide. I-V curves are different from CMOS characteristic I-Vs.
CNT FET- A better approach:
Improved contacts (Ti/Co carbide)
10 nm deposited SiO2: reduces interface traps.
Tube length 1030nm. (Why long tubes?)
CNT FETS to logic:
Bottom gate design.
Logic1: -1.5V, logic 0: 0V (inverter, NOR, SRAM, Ring Oscillator)
Pros: - Bottom gate better than back gate (gate different devices separately).
- Low operating voltage.
- Logic devices work in promising ways.
Cons: - CNT exposed to air:
+ leads to p-type characteristics.
+ gate dielectric capacitance is diluted.
- Large overlap capacitance between Gate and S/D

=> not suitable for high frequency operation.

Comparison of characteristics of CNFETS and Si MOSFETs:

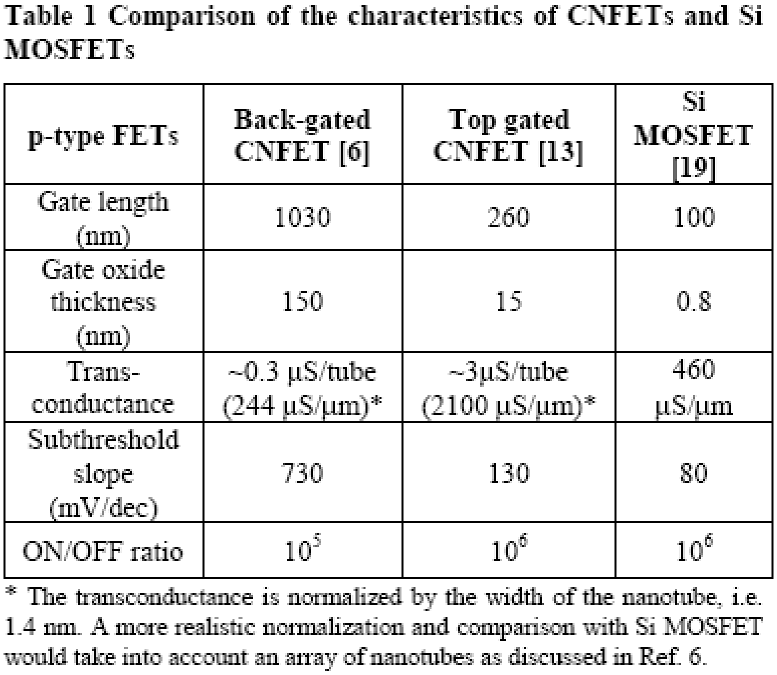

Table 1 Comparison of the characteristics of CNFETs and Si MOSFETs

p-type FETs	**Back-gated CNFET [6]**	**Top gated CNFET [13]**	**Si MOSFET [19]**
Gate length (nm)	1030	260	100
Gate oxide thickness (nm)	150	15	0.8
Trans-conductance	~0.3 µS/tube (244 µS/µm)*	~3µS/tube (2100 µS/µm)*	460 µS/µm
Subthreshold slope (mV/dec)	730	130	80
ON/OFF ratio	10^5	10^6	10^6

* The transconductance is normalized by the width of the nanotube, i.e. 1.4 nm. A more realistic normalization and comparison with Si MOSFET would take into account an array of nanotubes as discussed in Ref. 6.

Annealing (change the Fermi energy):
in vacuum: removes the absorbed oxygen and yields and reversible transformation of a CNFET from p- to n-type.
in air: inverse result.
Intermediate stage: ambipolar (the tubes can conduct both electrons and holes).
Change in energy.
Effect of doping Potassium:
-No change in the Fermi energy
-No ambipolar state.
-Change thickness D of barrier. The tunneling barrier decreases as the doping increases.

A simple Inverter using 2 ambipolar connected together: gain small (~0.3)
A sophisticated (intra-nanotube) inverter: Control Vthreshold with amount of doping. Gain is bigger (1.6)

Multiple Valued Logic using CNFETs (MVL):
MVL circuits allow more than 2 levels of logic, i.e. 3 for ternary, 4 for quaternary.
CNT FET's band gap is inversely proportional to the diameter of the tubes:

$$E_G = \frac{0.84}{d(nm)} eV$$

Vthreshold depends on the diameter of the tubes:

$$V_{TH} = \frac{0.42}{d(nm)} eV$$

Is MVL going to work? In reality, CNT FETs are not that ideal and real I-Vs are different.

VIII. Conclusion:
Pros: extraordinary properties as mentioned above.
Cons: No CNT FETs can beat the standard Si MOSFET.
Dimitrios said "Not EVER beat!"
There's no successful way to fabricate many CNT's.

Discussion:

There was a short discussion regarding CNT fabrication. A question was raised "Is there a way to grow CNT on a substrate?" No answers were compromised.

Napat has done some research to answer this question:

Now there are generally 2 ways to grow CNTs to be perpendicular to the substrate:

1) Use the electric field to induce the growth direction. An applied electric field of 0.1V/um between the substrate and an electrode during CVD growth has proven to be sufficient to direct the growth of the nanotube. Electrons in the CNTs will want to move along the electric field, and will direct the growth.

2) Use dense catalyst particles. A very thin layer of catalyst (Ni, Fe, Mo) is deposited, so in the CVD chamber at high temperature, the metal layer will break into small and dense particles, and these particles will catalyze the growth of CNT in the upward direction, where nanotubes hold themselves together with Van der Waals interactions. The diameter of the CNTs depends on the size of the catalyst particles. The metal film thickness is critical. If it is too thick, it will break into big chuck. The metal film thickness shouldn't be too small either because the particles will not be dense enough.

In both techniques, temperature in the CVD system is set to 600-900 C for growing MWNTs and 900-1100 C for growing SWNTs. The feed stock gases can be methane, ethylene, carbon dioxide, etc.

Regarding CNT electrical properties, there was an interesting question "What makes it semiconducting or metallic CNT?" I guess we need deeper understanding of CNT physics in order to answer this.

Napat's answer:

Whether a tube is a metal or semiconductor depends on the properties of the electrons in the tubes. In metallic conductors, electrons flow freely and there is no energy gap between the valence and the conduction bands. In a semiconductor, there will be a band gap, which is determined by the diameter of the nanotubes.

What makes CNT metallic or semiconduction is related to the Brillouin zone of the nanotubes that is adapt from the BZ of the 2-dimensional graphite plane. (The BZ is the set of point in k-space that represents different elementary state of the system, for instance electron states or vibrational modes.)

Graphite is a (semi-) metal with zero gap for electron excitations at wave vectors corresponding to the six corners of the hexagon. Nanotubes may inherit the metallic behavior. However, due to the closing condition for the cylindrical tubes, not all the wave

vector states of graphite are allowed any more. The 2-dimensional BZ of graphite is reduced to the 1-dimensional BZ for nanotubes.
If a tube is wraped around the corners of the hexagon, the tube will be metallic (inherit the metallic behavior from graphite). If not, the tube will behave as semiconductor

Also, is there a way to control the rolling direction of graphite sheets to make CNTs? Hmm.
Not yet. The researchers have been trying, though…
However, it has been shown that pulsed-laser-vaporization method makes mostly (10,10) → "armchair" → metallic.
CVD method makes most random structures of CNTs.

How does the CNT interconnector bend?
For the interconnectior, nanotube is attached between the electrode pads. So, the CNT get deformed since the pad clamps the nanotubes down. If this CNT interconnector is grown by CVD, it's very possible that the tubes deformed when they reach different height of the substrate via defect formations.

So it all comes to a point, is it worth-it to pursue CNT FETs? Dimitrios thought we would not be able to make it any more alive before hitting the 2015 apocalypse.
Why are the nanotubes long comparing to their diameters? In my opinion, its exceeding length comparing to its width makes it a relatively one-dimensional object, which makes ballistic conduction of electron—the ultimate of electronics.
Is there a way to fabricate CNTs for mass production? This is the question that will remain unanswered for a while, since all the work done on CNTs is still with a single CNT, in a lab, with a prototype model, and in concept-proof stage.
Dimitrios concluded that MOS FET will get ballistic by 2015, so why we bother making CNT FET with the same characteristic? In my opinion, it's always good to experiment new approach and new method, especially with promising subject like CNT with all its extraordinary characteristics and properties. We never know how beneficial CNT FET will be if it is not carefully researched and put into implementation.
In conclusion, CNT is no doubt a great substitute for traditional Silicon based approach, however we need deeper understanding of its physics in such a small scale, in order to bring it into practical use. Maybe CNT FET is not a good model to substitute MOS FET, but there should be other better or totally new approach to take advantage of CNT into electronic design. Nanocell approach is one of them, which will be discussed in the next few lectures.