HW 8 SET and CNT fundamentals ECE/ENGR 4243-6243 F. Jain 110916

Q.1 Recently (Physics Today, October 2014 p. 14, copy attached) it was reported that some research groups have succeeded in making carbon nanotubes with n=m=6 using $c_{96}H_{54}$ precursor that attaches to Pt catalyst during the chemical vapor deposition.

(a) Are these tubes metallic or semiconducting?

The tubes with n,m = 6,6 are metallic nanotubes

(b) What is novel in this approach **(Grad Students?)**

All grown nanotubes by this precursor method have found to be identical

Q.2Why metallic tubes are not desirable in making CNT-FETs if they are mixed with semiconducting nanotubes.

Because metallic tubes cannot be inverted or depleted and hence gate voltage will not control the channel current.

Q.3(a) Schematically show an n-channel CNT-FET and a p-channel CNT FET using SiO2 as the gate insulator and nSi and p-Si being the gate material respectively.

n-Channel CNT-FET

Use p-type CNTs

Vacuum annealing or

Potassium Doping of CNTs

Makes them p-type nanotubes.

Resulting in n-channel CNT FET.

p-Channel CNT-FET

Use n-type CNTs

Oxygen exposure makes CNTs as n-type.

This results in a p-type FETs when n-doped tubes

PMMA is a coating that protects CNT from oxygen

(Polymer, Electron Beam resist): See Reference by V. Derycke, et al. see pages 8 and 9 (this set).

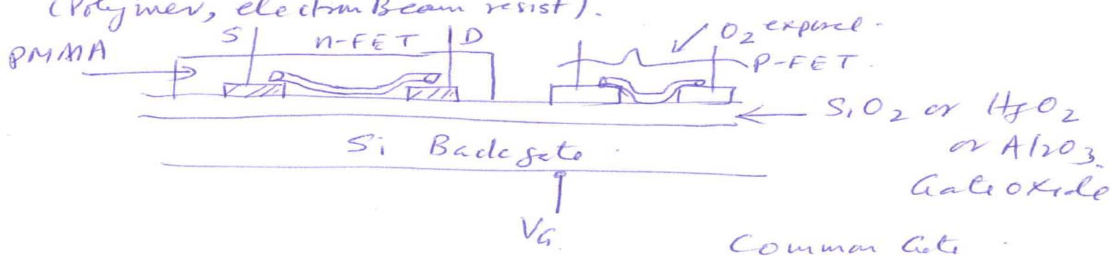
n-channel CNT-FET

Vacuum annealing or Potassium Doping of CNTs. Makes them p-type resulting in n-channel CNTFET.

P-channel CNT-FET

oxygen exposure makes CNTs as (n) type. This results in p-type FETs

PMMA is a coating that protects CNT from oxygen. (Polymer, electron Beam resist).



Q3(b). indenify n-FET and p-FET un figure below what are their threshold voltages in the n- and p-type CNT FETs shown below.

Threshold voltages can be obtained from the following figure.
Vacuum annealed and protected by PMMA results in n-FET on p-type CNTs, and the threshold is 5.0V from Fig. b below.
Oxygen exposed CNT are n-type and results in p-FET whose threshold is 0V (see Fig. b below left plot).

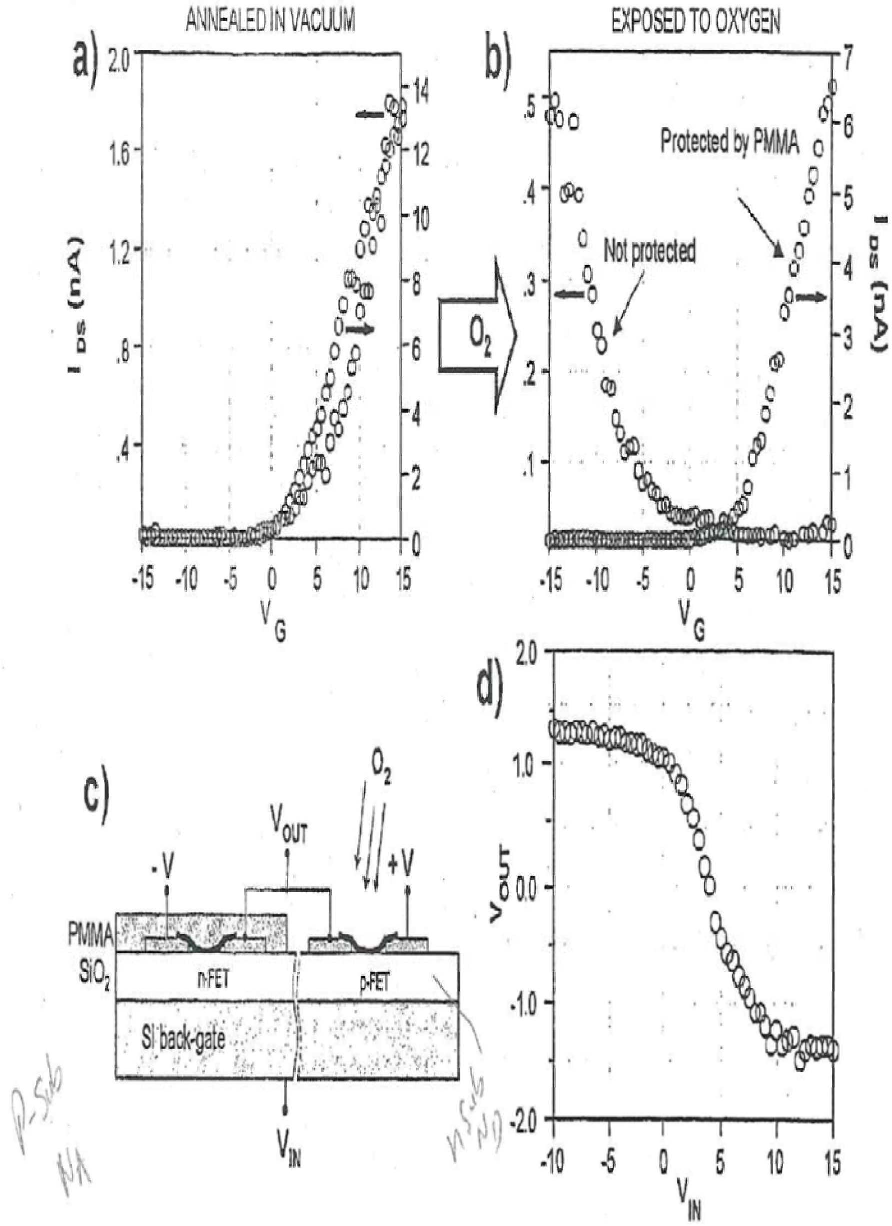


Figure 2. Fabrication of a voltage inverter ("NOT" logic gate) using two nanotube FETs. Initially the two CNTFETs are p-type. One of them is protected by PMMA, the other is not. (a) After vacuum annealing both CNTFETs are converted to n-type. (b) The two CNTFETs are exposed to oxygen (10^{-3} Torr of oxygen for 3 min). The unprotected n-CNTFET (black curve) converts back to the original p-type, while the protected CNTFET (red curve) remains n-type. (c) The two complementary CNTFETs are wired as shown in the schematic. (d) Characteristics of the resulting intermolecular inverter ($V = \pm 1.5$ V) are shown.

Q.3c how would you make an inverter gate out of n-FET and p-FET CNT-FET.

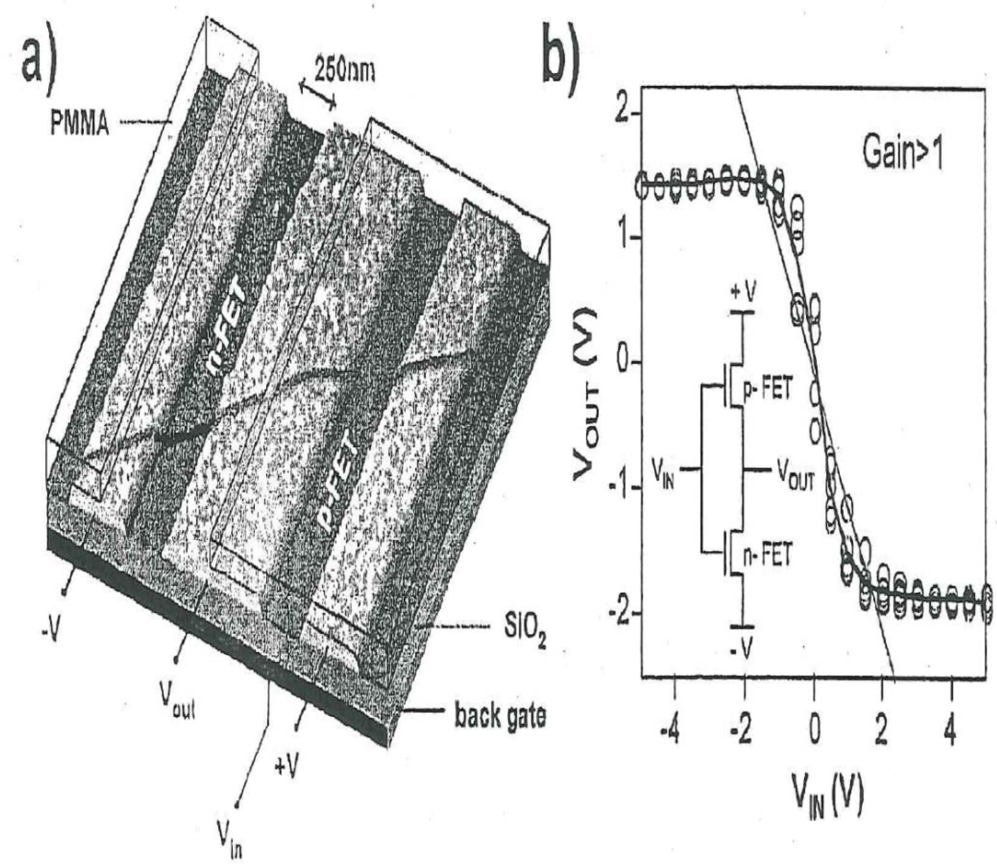


Figure 3. (a) AFM image showing the design of an intramolecular logic gate. A single nanotube bundle is positioned over the gold electrodes to produce two p-type CNTFETs in series. The device is covered by PMMA and a window is opened by e-beam lithography to expose part of the nanotube. Potassium is then evaporated through this window to produce an n-CNTFET, while the other CNTFET remains p-type. (b) Characteristics of the resulting intramolecular voltage inverter. Open red circles are raw data for five different measurements on the same device ($V = \pm 2$ V). The blue line is the average of these five measurements. The thin straight line corresponds to an output/input gain of one.

remains n-type. In the completed circuit, the input voltage is applied simultaneously to the gates of the two complementary CNTFETs. The p-CNTFET is polarized by a positive voltage, the n-FET by a negative voltage. A common contact is used as the intermolecular inverter's output. A positive input voltage turns the n-FET ON (the p-FET being OFF), resulting in the transmission of the negative polarization voltage to the output. A negative input, on the other

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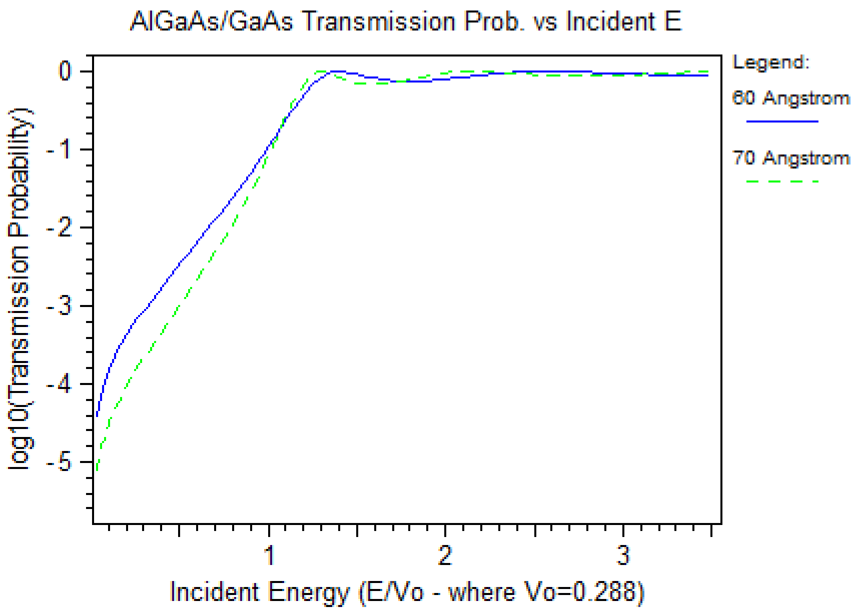
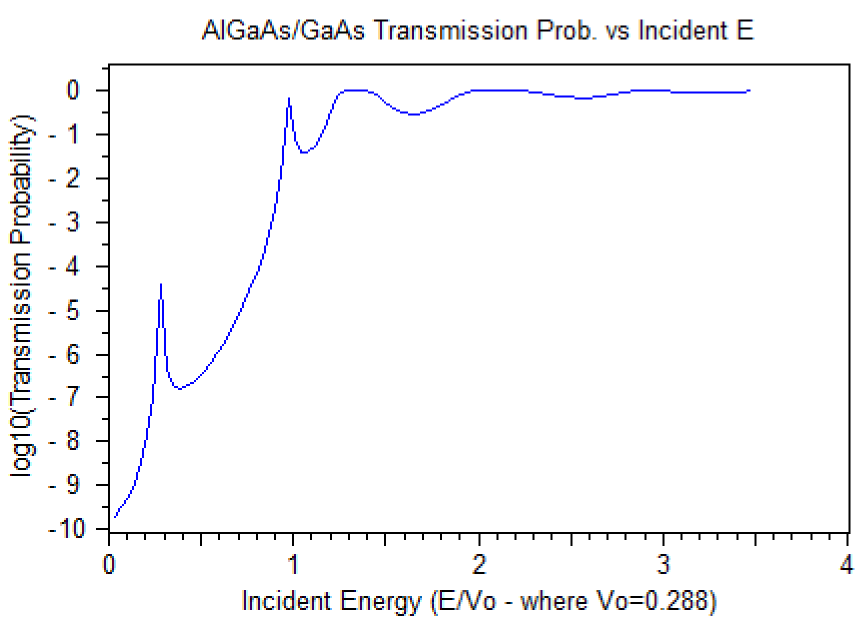
Potential Barrier, Resonant Tunneling in Double Barriers, Coulomb Blockade, Single Electron Transistor (SETs)

Q1 The simulation shows transmission probability for 60Å (solid) and 70 Å (dashed) barriers. Note that the probability is 1.0 at $E/V_o = 1$. That is, when the incident electron energy becomes equal to V_o or ΔE_c.



Q2: plotted below is the transmission probability showing two peaks which corresponds to two energy levels that are bound and correspond to two energy levels in the GaAs well.



Q.3. Here, the GaAs well of Q.2 is replaced by a quantum dot 100x100x100 Å. Also the barriers are 200Å thick. We need to find the energy levels in a dot and this will give the energy levels. The applied voltage will drop across the barriers. The quantum dot also will have an electric field that we will neglect to simply the energy level calculations.

We need to find the energy levels in a finite quantum well like we did in an earlier homework set #2.

We are taking a short cut by finding the energy levels in an infinite well and multiplying by 3 to get energy levels in quantum dots. GaAs, $m_e = 0.066 * m_o = 0.066 * 9.11 * 10^{-31}$

These levels are: $(h\, n_x)^2/(8m_e\, L^2{}_x)*3 = [1/(8m_e)]*[6.63x10^{-34}/100x\, 10^{-10}]^2 *3$
For $n_x = 1 = n_y = n_z$,
$E_{e111} = [10^{31}/(8* 0.066 * 9.11)]* [6.63x10^{-34}/100* 10^{-10}]^2 *3 = 27.44*10^{-21}$ Joules
$= 27.44*10^{-21}/(1.6*10^{-19})$ in electron Volt = 0.17eV.

The next level E_{e222} got $n_x = n_y = n_z = 2$ will be 4 times larger and will be out of the barrier. The voltage needed is 0.17Volt to lower the Fermi level. But there is a drop across two barriers as well. So voltage needed is 5 times this value. The width of barriers is 2 x 200 Å and the well is 100 Å .
So 0.85V needs to be applied.

In case of Coulomb blockade, when the well is very thick (like 200 Å) then the voltage is q/2C and any drop across the barriers.

Q.4 Derivation is in the notes.

Q.5(a) The Coulomb blockade voltage is e/(2C) or q/2C. This comes out to be
$1.6\, x10^{-19}/(2* 5\, x\, 10^{-15}) = 1.6\, x\, 10^{-5}$ V.

Q.5(b) The role of the gate is influence the charge in the island as the island charge is shared with two tunnel junction. The location of a Coulomb diamond (Fig. 7.25) depends on $q_e/2C_g$. C_g is the gate capacitance.

Q.6. The charging energy above the Coulomb blockade is q *[q/2C] = q/2C electron Volt. For a capacitor of 1.1x10-15 F, the charging energy to transfer the electron is

$1.6\, x10^{-19}/(2* 1.1\, x\, 10^{-15}) = 0.72\, x\, 10^{-4}$ eV.

1/2kT at room temperature 300 °K is 0.0259/2= 0.01285 eV.
This value should be less than $0.72\, x\, 10^{-4}$ eV to observe the Coulomb blockade or single electron transistor operation. This requires temperature to be reduced from 300°K to

$(1/2)kT = (1/2)\, 8.651x10^{-5}\, eV *T < 0.72\, x\, 10^{-4}$ eV

or, $T < [0.72\, x\, 10^{-4}]/4.325x10^{-5}$

$T < 1.66$ °K to observe Coulomb blockade effect in $1.1\, x\, 10^{-15}$ F capacitor.