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 \( \text{c}_{96}\text{H}_{54} \) 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.2 Why 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.

<table>
<thead>
<tr>
<th>n-Channel CNT-FET</th>
<th>p-Channel CNT-FET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use <em>p</em>-type CNTs</td>
<td>Use <em>n</em>-type CNTs</td>
</tr>
</tbody>
</table>

Vacuum annealing or Oxygen exposure makes CNTs as n-type.

Potassium Doping of CNTs

Makes them *p*-type nanotubes.

Resulting in n-channel CNT FET. 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).
Q3(b). Identify n-FET and p-FET in 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](image.png)

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.

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
Q1 The simulation shows transmission probability for 60Å (solid) and 70 Å (dashed) barriers. Note that the probability is 1.0 at $E/V_0 = 1$. That is, when the incident electron energy becomes equal to $V_o$ or $\Delta E_c$.

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, \( m_e = 0.066 \times m_0 = 0.066 \times 9.11 \times 10^{-31} \) kg.

These levels are: \( \frac{(h n_x)^2}{8m_e L_x^2} \times 3 = \frac{1}{8} \times \frac{6.63 \times 10^{-34}}{100 \times 10^{-10}}^2 \times 3 \)

For \( n_x = 1 = n_y = n_z \),

\[ E_{e111} = \left( \frac{10^{-31}}{8 \times 0.066 \times 9.11} \right) \times \left( \frac{6.63 \times 10^{-34}}{100 \times 10^{-10}} \right)^2 \times 3 = 27.44 \times 10^{-21} \text{ Joules} \]

\[ = 27.44 \times 10^{-21} / (1.6 \times 10^{-19}) \text{ in electron Volt} = 0.17 \text{ eV}. \]

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

\[ 1.6 \times 10^{-19} / (2 \times 5 \times 10^{-15}) = 1.6 \times 10^{-5} \text{ V}. \]

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 \( qe/2C_g \). \( C_g \) is the gate capacitance.

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

\[ 1.6 \times 10^{-19} / (2 \times 1.1 \times 10^{-15}) = 0.72 \times 10^{-4} \text{ eV}. \]

\( 1/2kT \) 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

\[ (1/2)kT = (1/2) 8.651 \times 10^{-5} \text{ eV} \times T < 0.72 \times 10^{-4} \text{ eV} \]

or, \( T < [0.72 \times 10^{-4}] / 4.325 \times 10^{-5} \)

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