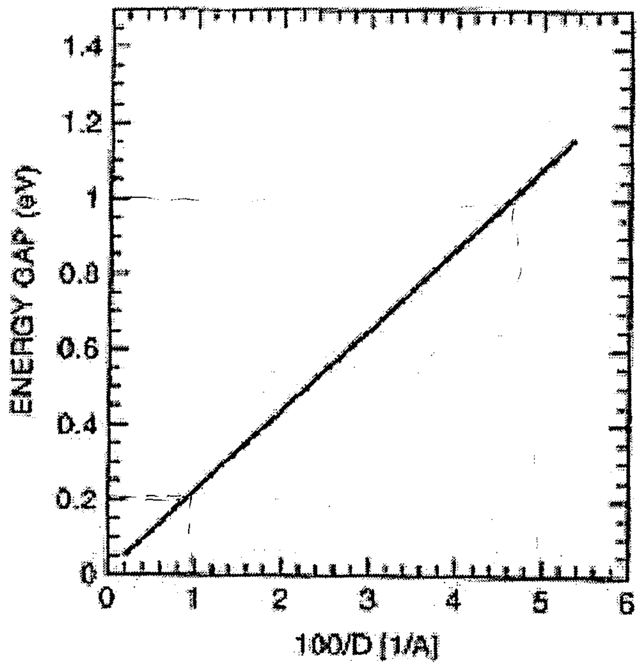
Rules: Close book. NO Notes. All questions worth 20 points



$a = |a_1| = |a_2| = \sqrt{3}a_{C-C}$:

$|C_h| = a\sqrt{n^2 + m^2 + nm}$

$$\cos\theta = \frac{C_h \cdot a_1}{|C_h||a_1|} = \frac{n + m/2}{\sqrt{n^2 + m^2 + nm}}$$

Diameter $D = \dfrac{|C_h|}{\pi}$

Bond length of the 2D graphene is 1.42 A

Problem 1:

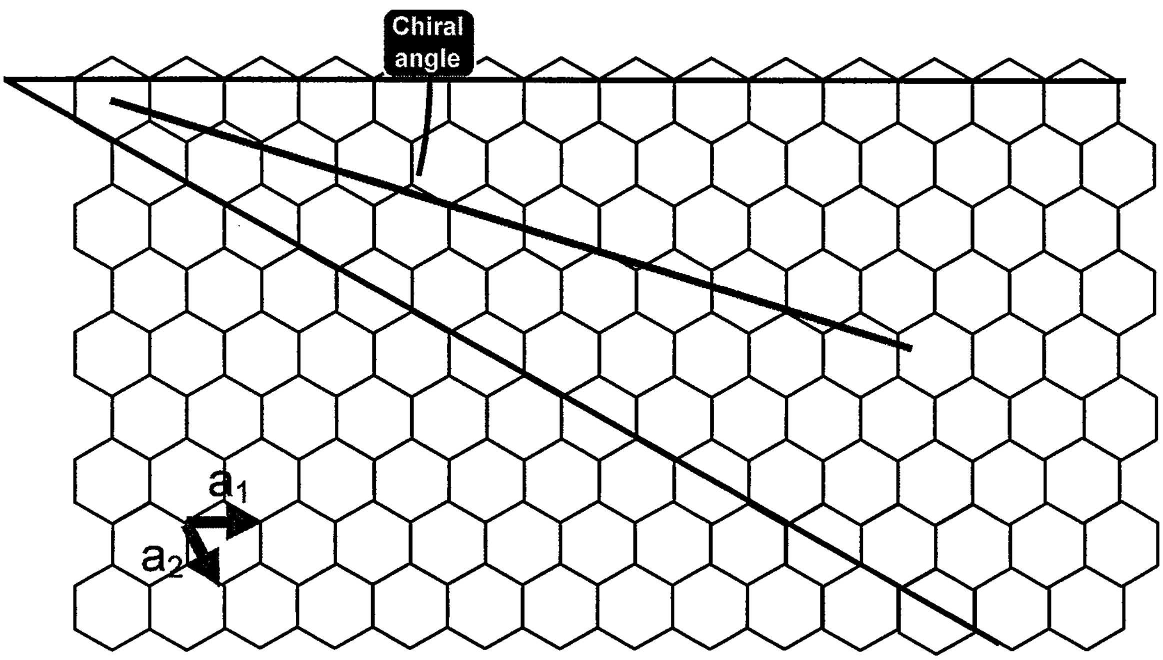
- Give (n,m) for a semiconductor nanotubes with a band gap ~1.0eV.

Answer: $\sqrt{n^2+m^2+nm} \cong 25.54$

a particular CNT can be ~(25,0)

for $m=0$ a zigzag SWCNT which is not metallic & consistent with 1eV badgap

Identify Carbon Nanotubes



For 1.0 eV we refer the plot given with slope $\sim \frac{0.2\,\text{eV}}{\left(\frac{100}{D}\left[\frac{1}{\text{Å}}\right]\right)}$

so we need $\frac{100}{D} \cong \frac{1.0\,\text{eV}}{0.2\,\text{eV}} \cong 5\left[\frac{1}{\text{Å}}\right]$ then $D = 20\,\text{Å}$ ✓

where $D = \frac{|C_h|}{\pi}$ $\Rightarrow |C_h| = 62.8\,\text{Å}$

$|C_h| = \sqrt{3}\, a_{cc} \sqrt{n^2+m^2+nm}$

$62.9\,\text{Å} = \sqrt{3} \times 1.42\,\text{Å} \sqrt{n^2+m^2+nm}$

so we have $\sqrt{n^2+m^2+nm} = 25.54$

Problem 2:

- Give (n,m) and bandgap for one zigzag and one arm chair nanotubes

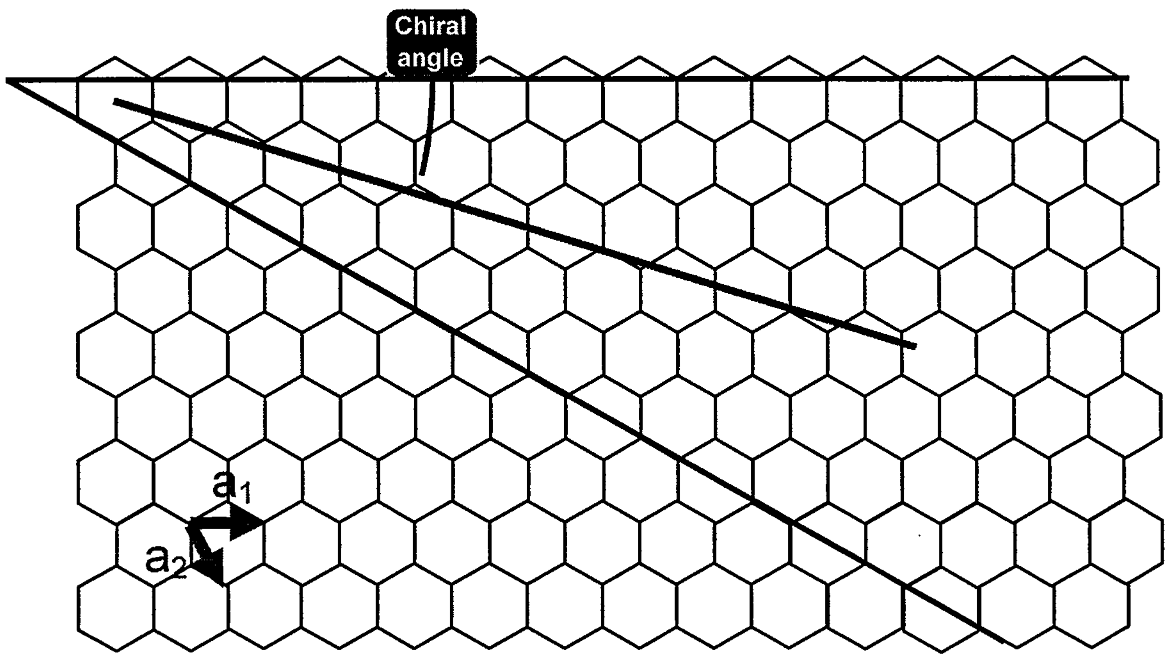
Answer: zigzag (n,m), bandgap : for $m=0 \rightarrow (n,0)$ ex: $(3,0) \rightarrow$ metallic 0eV Bandgap

$(25,0) \rightarrow$ semiconducting 1eV Bandgap

Answer: armchair (n,m), bandgap : for $n=m \rightarrow (n,n)$

a particular example (3,3) which is metallic with 0eV bandgap

Identify Carbon Nanotubes



Problem 3:

- Label (7,4) carbon nanotube. For this tube, calculate the chiral angle and band gap (be careful)

Answer: chiral angel : $\theta = 21^\circ$

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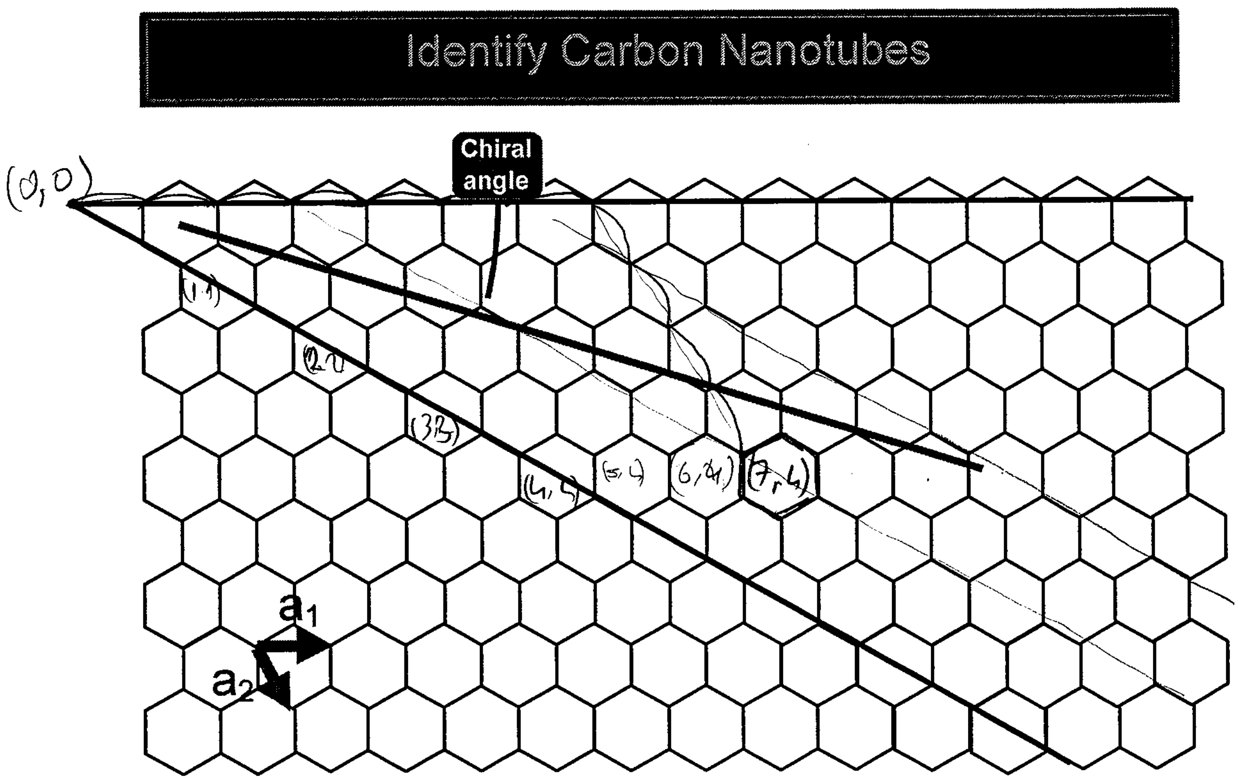
Answer: bandgap : $n-m \rightarrow 7-4=3 \rightarrow$ multiple of 3 / so metallic / with 0 eV bandgap



$$\cos\theta = \frac{2n+m}{2\sqrt{n^2+m^2+nm}} = \frac{\overset{9}{\cancel{14+4}}}{\cancel{2}\sqrt{49+16+28}} = 21^\circ$$

Problem 4:

How does the frequency of the fastest ring oscillator fabricated with carbon nanotube transistors compare to Si ring oscillators fabricated in 90's and today? (i.e. higher (faster) or lower (slower) and explain why).

90's: $f_{CNT} \ll f_{Si}$ because the external capacitive effects by interconnecting metallization and insulation oxide is to large for CNT to drive quickly.

today: $f_{CNT} \sim f_{Si}$ by application of better high conductivity metals, S/D contacts & low-k insulation dielectrics.

List 3 techniques for carbon nanotube growth. State which technique is best suited for integration with microelectronics and which technique was used in the discovery of carbon nanotubes by NEC in the early 90's.

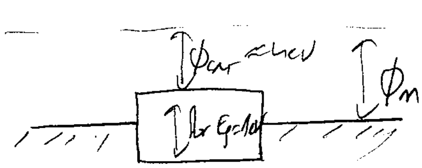
Laser Ablation

Arc Discharge → used by Ijima during the discovery of CNTs

CVD → best suited for integration with μelectronic technology

What is the ambipolar effect in carbon nanotube transistors?

Due to Schottky contacts between CNT channel & metal S/D the conduction is based on tunnelling through Schottky barriers.



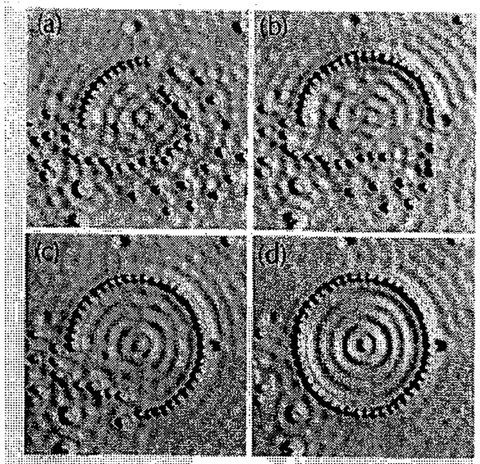
$\phi_m \approx 4.5eV$ (symmetric NMOS, PMOS characteristics)

for $\phi_m \to 5.0eV$ we have PMOS like characteristics with weak NMOS behavior.

lack of metals with $\phi_m \to 4.0eV$ restricts fabrication of high performance NMOS like CNT FETs

Problem 5: Briefly describe how these images were taken

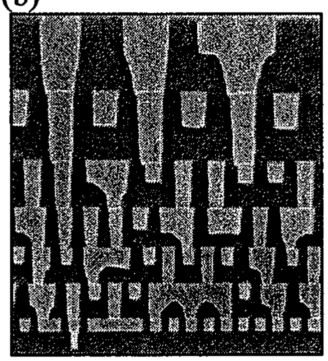
(a)



AFM tip → manuplaton mode to move individual atoms

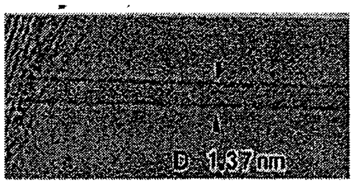
→ constant current mode to AFM imaging

(b)



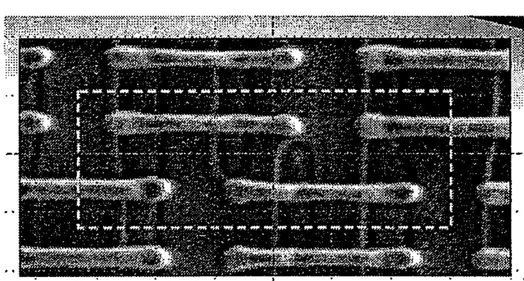
wafer is cracked along the channel axis (probably) and exposed to e-beam to achieve SEM image

(c)



wafer is back etched to a thickness less than ~60nm then exposure to e-beam & capturing transmitted ones result in this TEM image.

(d)



wafer is not cracked or back etched since this looks like SEM top layout image. The shadows caused by shallow trenches can be used as a proof that it is an SEM image.