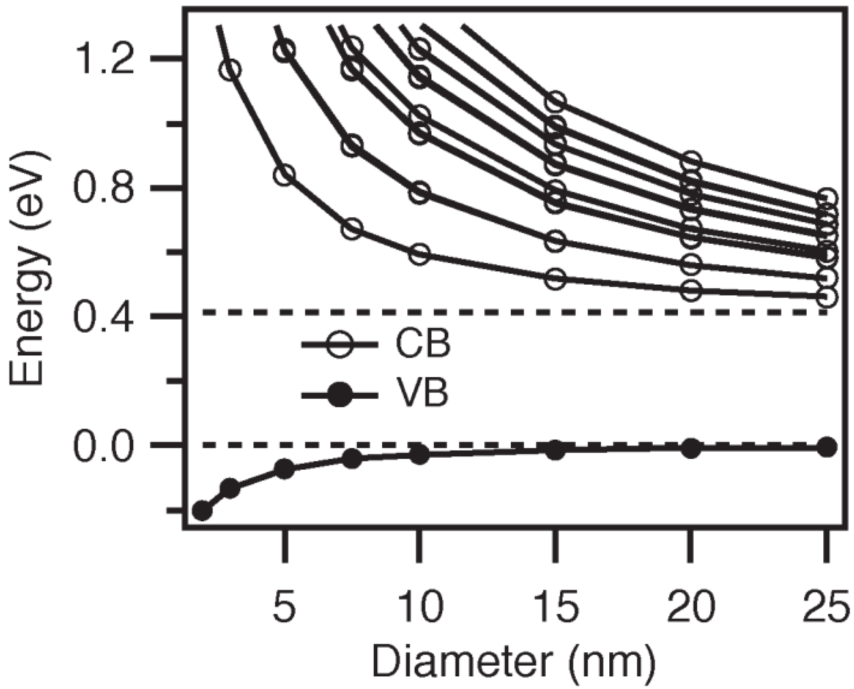
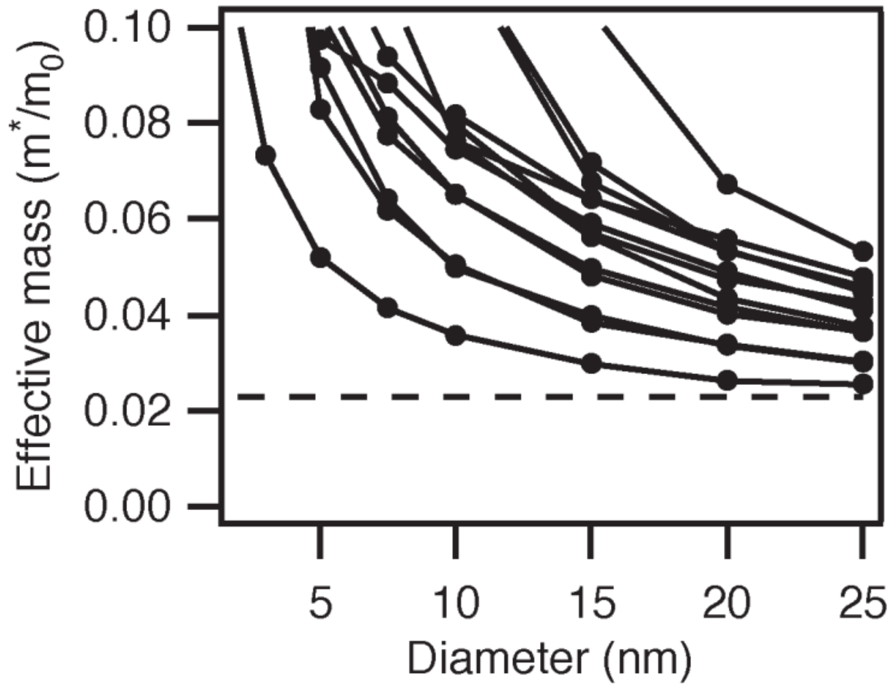
Lecture 6 – 1D FETs

- Nanowire MOSFETs
- Nonparabolicity
- CNT Bandstructure
- CNT FETs

1D Nanowires: Subbands spacing >> kT





1D InAs nanowires – subband separation << kT
~ 10 nm diameter

Effective Mass:

$$E_{nm} = \frac{\hbar^2}{2m^*}\left(\frac{n^2}{W_Z^2} + \frac{m^2}{W_y^2}\right)$$

Nanowire MOSFET: Single Subband

$$n_L^+ = \frac{1}{L}\sum_{k>0} f_0 = \frac{N_{1D}}{2} F_{-\frac{1}{2}}(\eta_F)$$

$$n_L^- = \frac{1}{L}\sum_{k>0} f_0 = \frac{N_{1D}}{2} F_{-\frac{1}{2}}(\eta_F - U_D)$$

$$I_D^+ = \frac{1}{L}\sum_{k>0} v_x f_0 = \frac{2qkT}{h} F_0(\eta_F)$$

$$I_D^- = \frac{1}{L}\sum_{k>0} v_x f_0 = \frac{2qkT}{h} F_0(\eta_F - U_D)$$

$$v^+(0) = v_T \frac{F_0(\eta_F)}{F_{-1/2}(\eta_F)}$$

$$v^-(0) = v_T \frac{F_0(\eta_F - U_D)}{F_{-1/2}(\eta_F - U_D)}$$

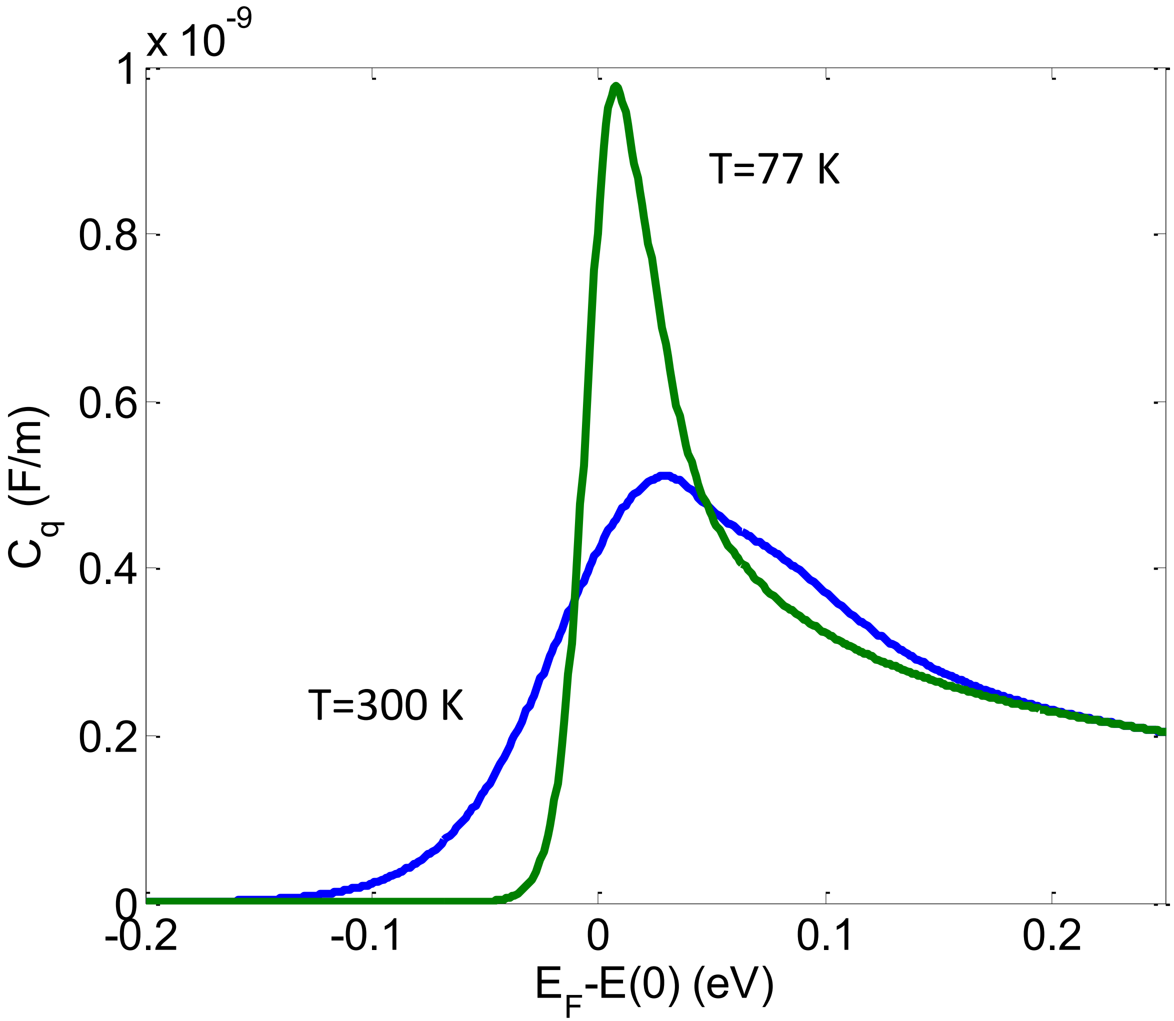
$$D_{1D} = \frac{\sqrt{2m^*}}{\pi\hbar}\frac{1}{\sqrt{E - E_C}}$$

$$N_{1D} = \sqrt{\frac{2m^* kT}{\pi\hbar^2}}$$

$$v_T = \sqrt{\frac{2kT}{\pi m^*}}$$

$$C_{ox} = \frac{2\pi\varepsilon_r\varepsilon_0}{\ln\left(\frac{t_{ox} + r_{wire}}{r_{wire}}\right)}$$

Quantum Capacitance

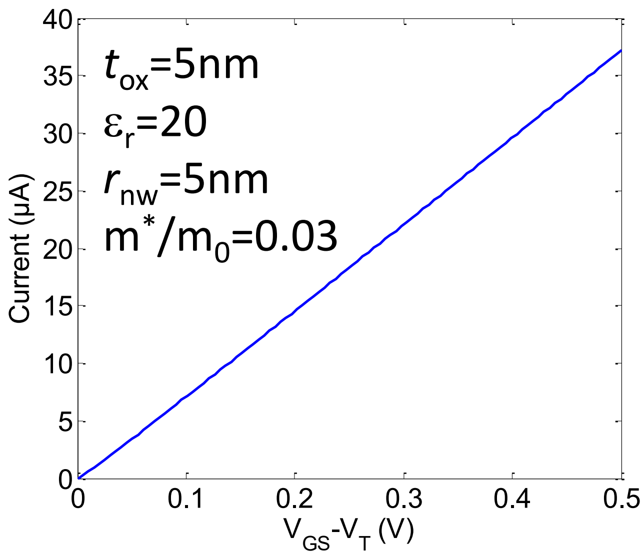


$$C_q = \frac{q^2 N_{1D}}{2kT} F_{-\frac{3}{2}}(\eta_F)$$

Degenerate:

$$C_q = \frac{\sqrt{2m^*}q^2}{\pi\hbar\sqrt{E_F - \varepsilon(0)}}$$

Nanowire MOSFET – Degenerate conditions



A single subband InAs nanowire FET is operating very close to the ballistic limit!

$$qV_{DS,sat} = \left[-\frac{\sqrt{(2m^*)}q^2}{hC_{ox}} + \sqrt{\frac{2m^*q^4}{h^2C_{ox}^2} + q(V_{GS}-V_T)}\right]^2$$

$$I_{D,sat} = \frac{2q^2}{h}V_{DS,sat}$$

$$C_q = \frac{\sqrt{(2m^*)}q^2}{\pi\hbar}\frac{1}{\sqrt{qV_{DS,sat}}}$$

$$I_{D,sat} = \frac{2q^2}{h}\frac{C_{ox}}{C_{ox}+C_q}(V_{GS}-V_T)$$

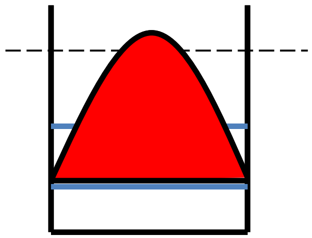
Linear regime

$$I_{DS,lin} = \frac{2q^2}{h}V_{DS}$$

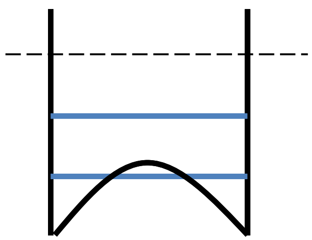
QCL Limit: $$I_{D,sat} = \frac{2q^2}{h}(V_{GS}-V_T)$$

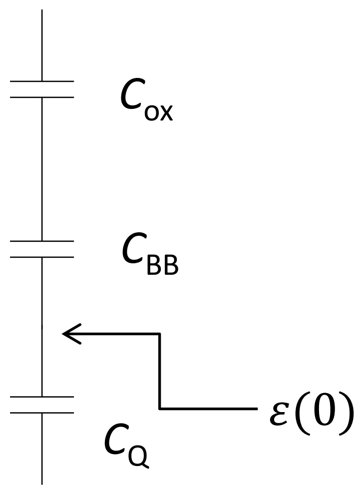
MOS Limit: $$I_{D,sat} = \frac{h}{4qm^*}C_{ox}^2(V_{GS}-V_T)^2$$

$$U(x,y) \approx \frac{16 n_{1D}}{\pi^4} \frac{W_1 W_2}{W_1^2 + W_2^2} \sin\left(\frac{\pi x}{W_1}\right) \sin\left(\frac{\pi y}{W_2}\right)$$



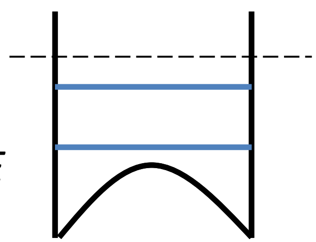
$$\Delta E = \langle \psi_{1,1} | U(x,y) | \psi_{1,1} \rangle = \frac{\{0.164 - 0.29\}}{\varepsilon_r \varepsilon_0} \frac{64 W_1 W_2}{9\pi^2 (W_1^2 + W_1^2)} n_{1D}$$

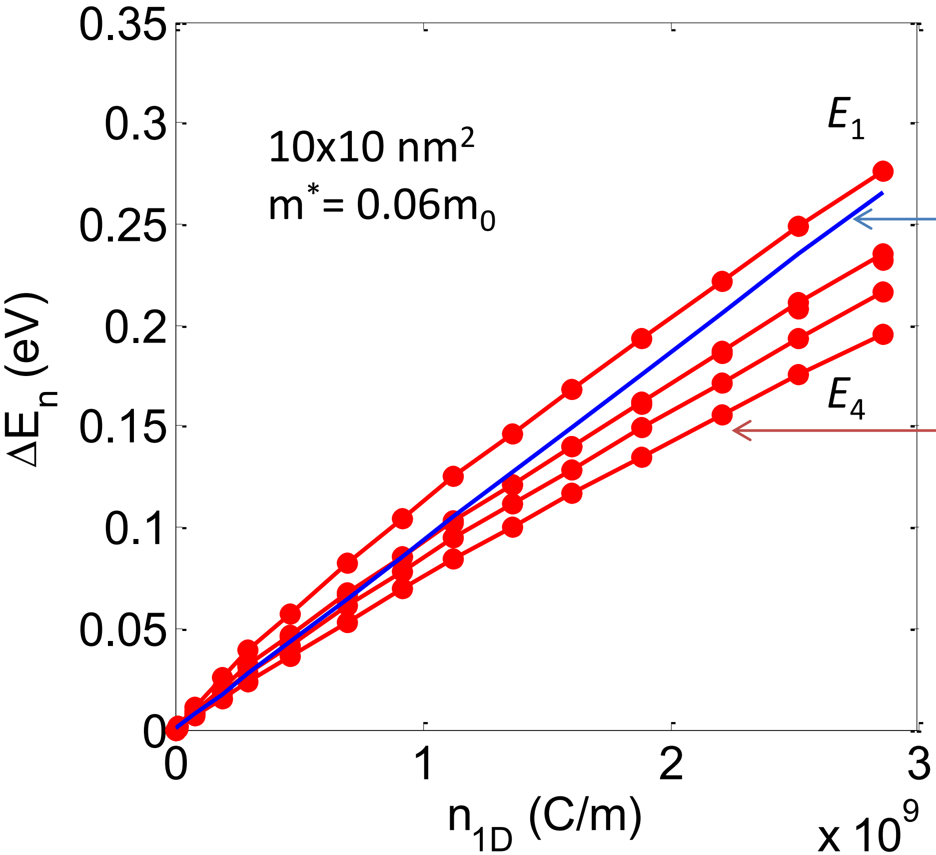




$$C_{BB} \approx 6.94 \varepsilon_r \varepsilon_0 \frac{(W_1^2 + W_2^2)}{W_1 W_2}$$

ΔE

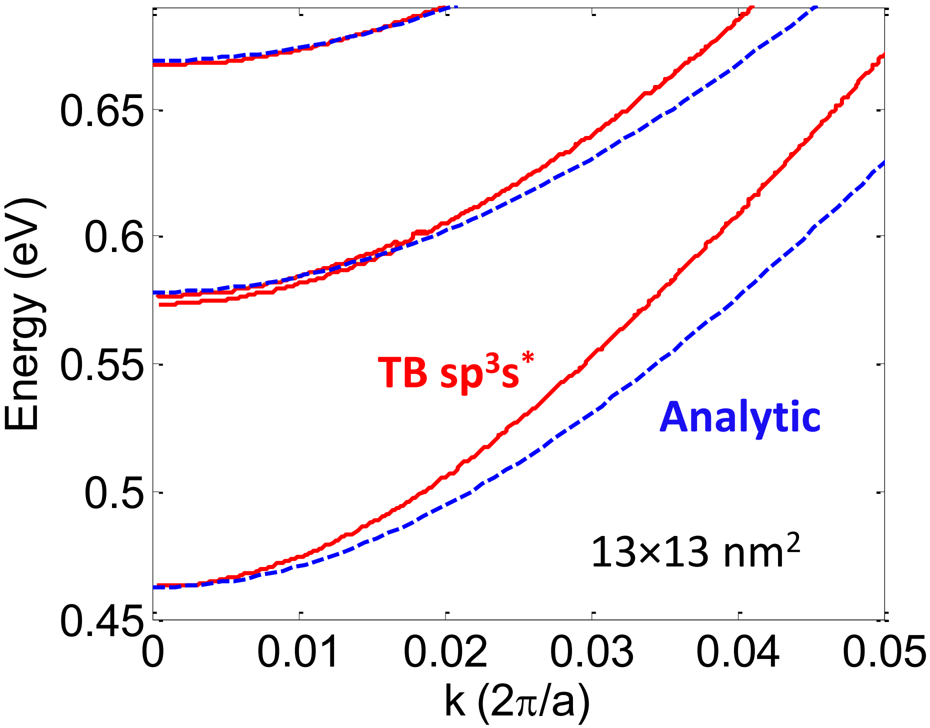


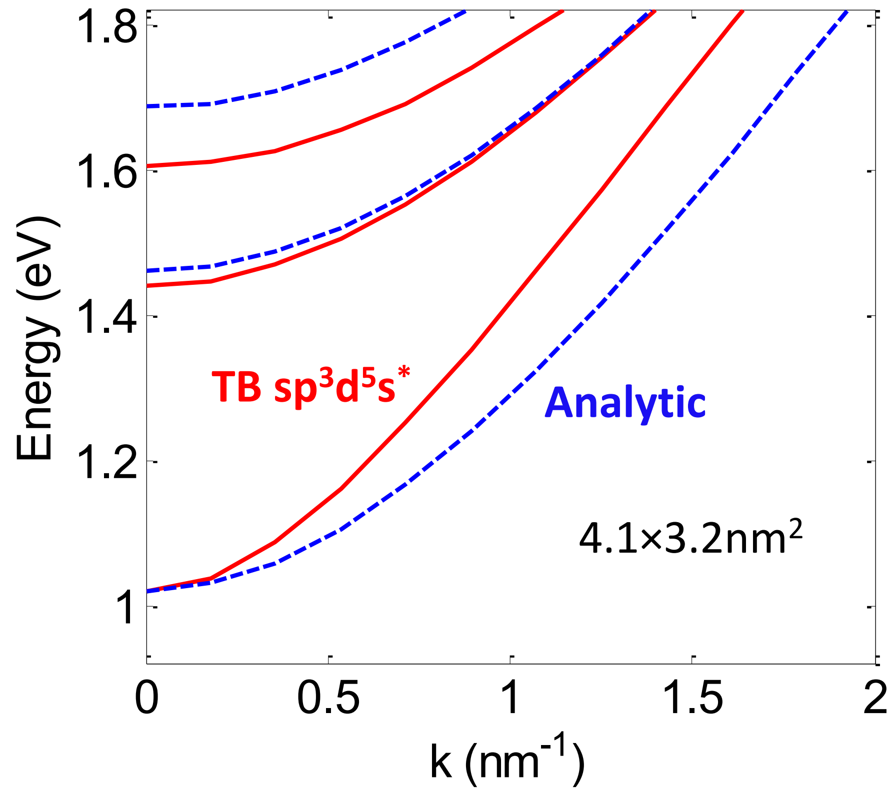


$$\Delta E = \langle \psi_{1,1} | U(x,y) | \psi_{1,1} \rangle$$
$$= \frac{0.2}{\varepsilon_r \varepsilon_0} \frac{64 W_1 W_2}{9\pi^2 (W_1^2 + W_1^2)} n_{1D}$$

Numerical Schrödinger-Possion

Nonparabolicity

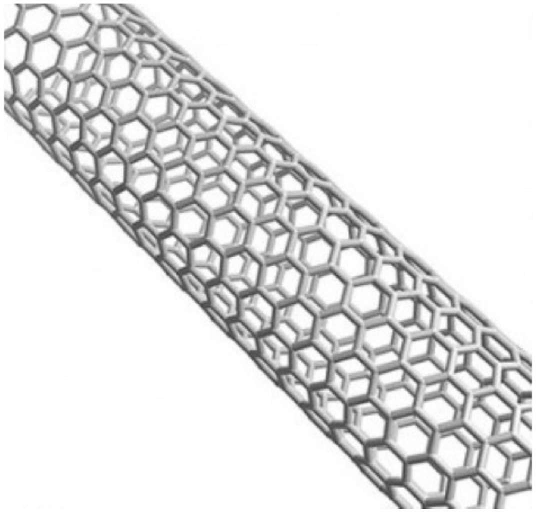


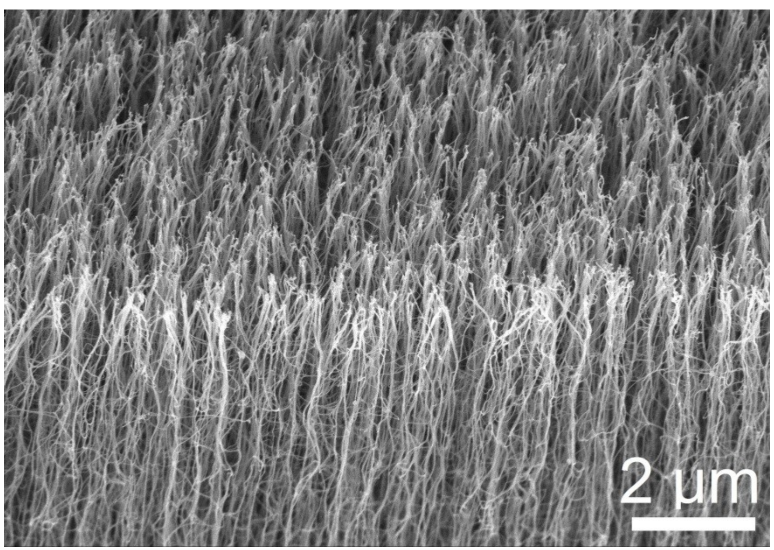


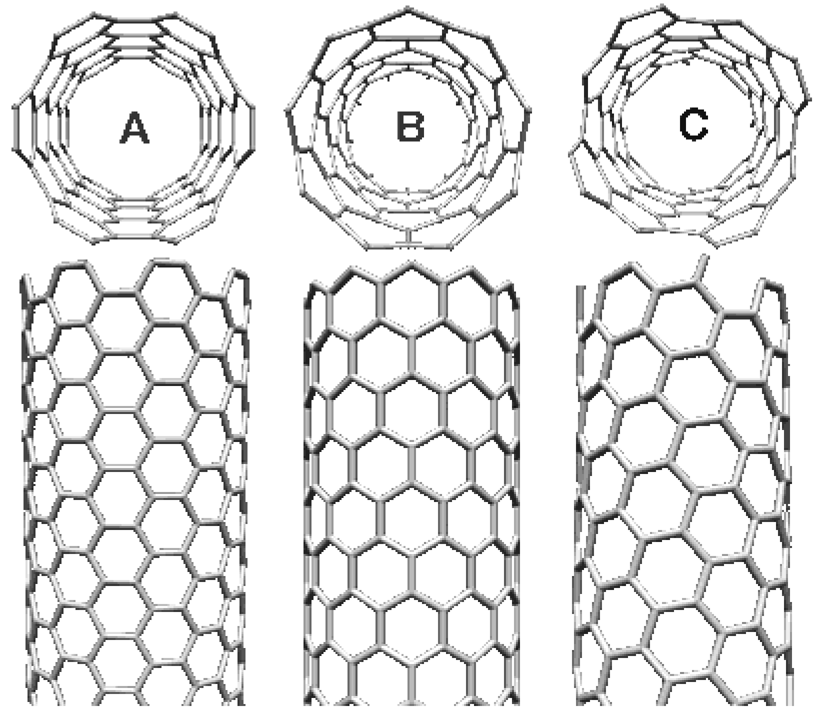
$$E\left(1+\alpha_{n,m}E\right)=\frac{\hbar^2k_x^2}{2m_{n,m}^*}$$

EMA: 13x13: ΔE_{12}= 0.3 eV
4x3: ΔE_{12}= 3 eV (!!)

1D Channels – Carbon Nanotubes







Why CNTs?

Traditional bulk semiconductors:

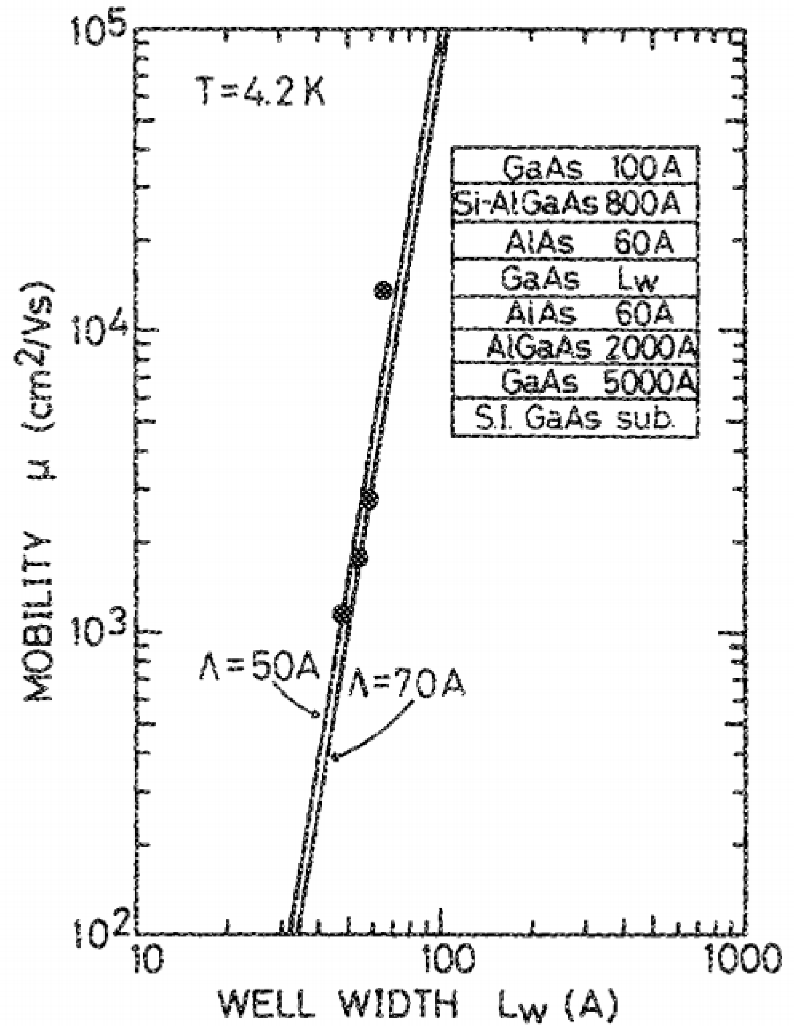
Quantum Well/wire with surface roughness:

Mobility decreases as: $\mu_{eff} \propto L_w^6$

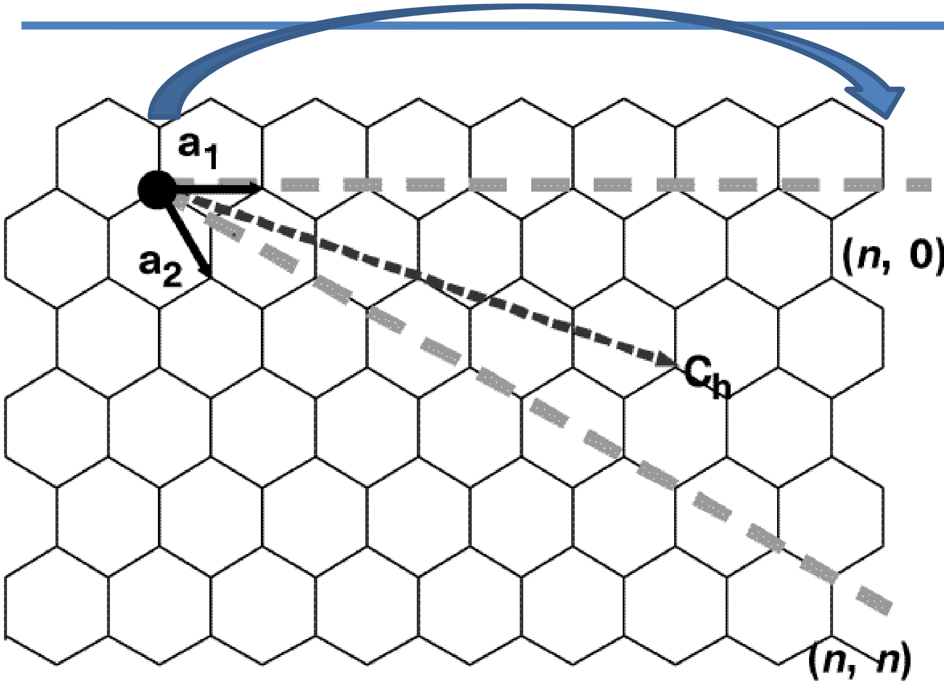
Strong assymetry between electron/hole effective masses

CNTs (& graphene, 2D materials):
No 'dangling' bonds or surface reconstruction. Naturally atomically flat.

H. Sakaki, T. Noda, K. Hirakawa, M. Tanaka and T. Matsusue, Applied Physics Letters 51 (23), 1934-1936 (1987).



CNT formation & bandstructure



$$\hat{C} = \hat{a}_1 n + \hat{a}_2 m$$

$$d = \frac{\sqrt{3}a_{cc}}{\pi}\sqrt{n^2 + m^2 + nm}$$

Metallic if: **(n-m)** is a multiple of 3
Semiconductor otherwise

Armchair: (n,n) always metallic

Zig-zag: (n,-n)=(n,0)

Chiral: (n,m)

$$E_G = \frac{2a_{cc}t}{d} \approx \frac{0.8}{d(in\ nm)}\ eV$$

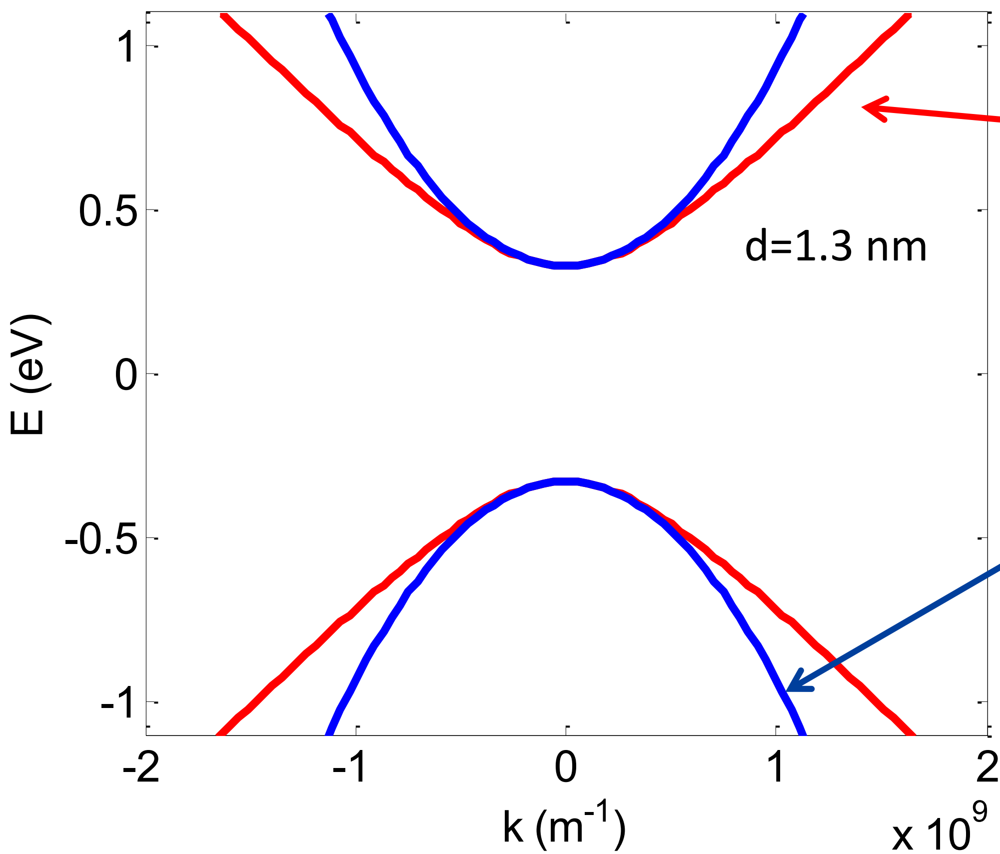
$$E(k) \approx \pm\frac{E_G}{2}\sqrt{1 + \left(\frac{3kd}{2}\right)^2}$$

a_{cc}=1.42 Å
t=3.0 eV

A CNT has a valley degeneracy = 2

$$E_{Gi} = \frac{2a_{cc}t}{d} \times \frac{6i - 3 - (-1)^i}{4}$$

CNT bandstructure



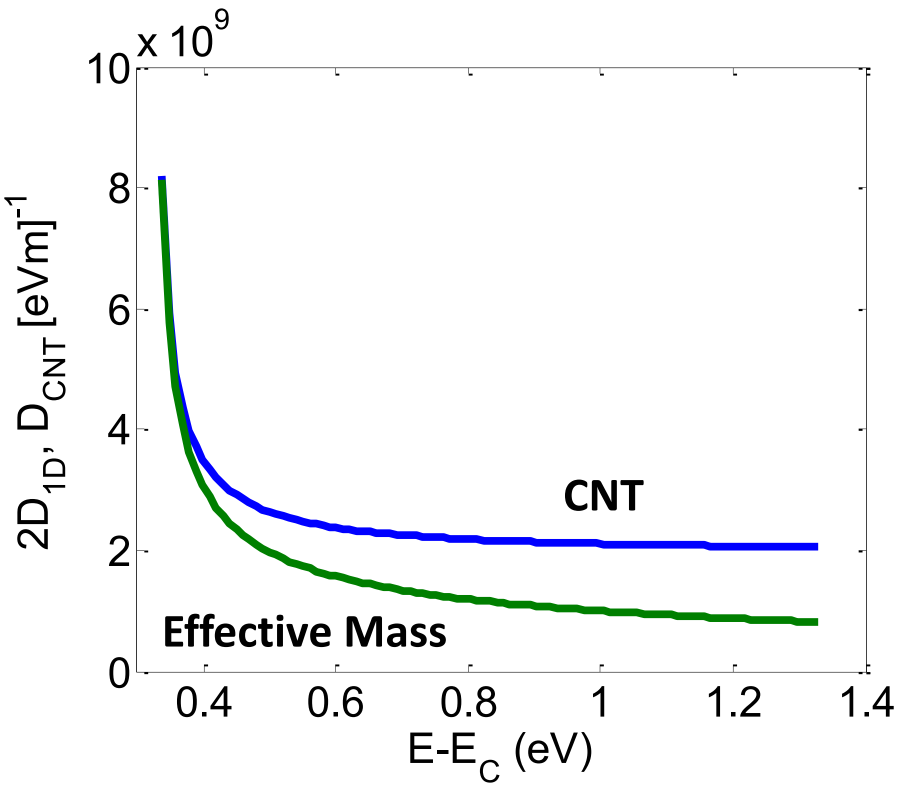
$$E(k) \approx \pm \frac{E_G}{2}\sqrt{1+\left(\frac{3kd}{2}\right)^2}$$

$$\frac{m^*}{m_0} = \frac{0.08}{d(nm)}$$

$$E(k) \approx \pm\left(\frac{E_G}{2} + \frac{\hbar^2 k^2}{2m^*}\right)$$

Non-parabolicity is strong for CNTs. Effective mass only valid around ~ 0.1 eV.

Effect of nonparabolicity



CNT DOS

$$D(E) = \frac{D_0|E|}{\sqrt{E^2 - \frac{E_G^2}{4}}}, |E| \geq \frac{E_G}{2}$$

Effective Mass

$$D_{1D} = \frac{\sqrt{2m^*}}{\pi\hbar} \frac{1}{\sqrt{E - E_C}}$$

Quantum capacitance: C_q – DOS at E_F

Ignoring band structure effects will underestimate C_q!