FUNDAMENTALS OF NANOELECTRONICS

Basic Concepts

1. The New Perspective

Energy Band Model

3. What and Where

is the Voltage?

4. Heat & Electricity:

Second Law & Information

2.1. Introduction

2.2. E(p) or E(k) relation

2.3. Counting States

2.4. Density of states

2.5. Number of modes

2.6. Electron density (n)

2.7. Conductivity vs n

2.8. Quantum Capacitance

2.9. The Nanotransistor

2.10. Summing up ..

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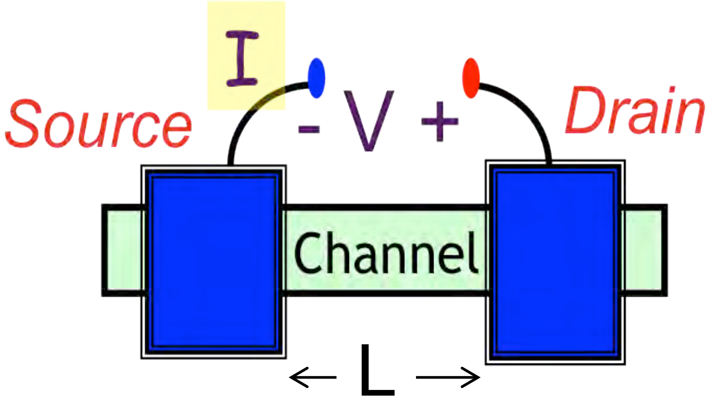
2.1a Introduction



Ballistic conductance

$$G_B = q^2 \frac{D\bar{v}}{2L} = \frac{q^2}{h} M$$

New perspective

$$\sigma = \frac{G_B}{A} \lambda$$

Drude formula

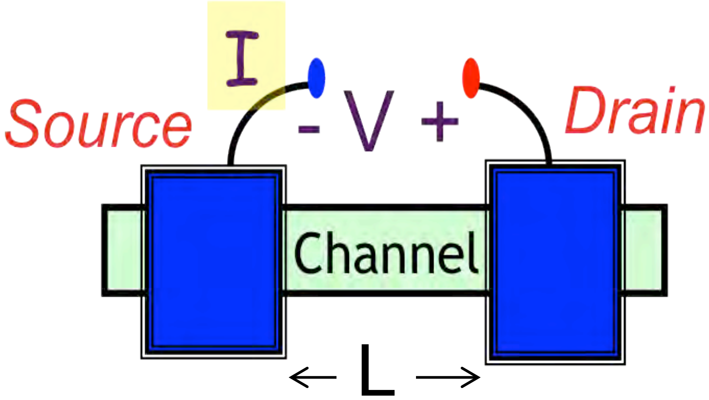
$$\sigma = q^2 \frac{n}{m} \tau$$

$$G = \frac{q^2 D}{2t} = \frac{G_B \lambda}{L+\lambda} = \frac{\sigma A}{L+\lambda}$$

$$I/V \equiv G_0 = \int_{-\infty}^{+\infty} dE \left(-\frac{\partial f_0}{\partial E} \right) G(E)$$

$$I = \frac{1}{q} \int_{-\infty}^{+\infty} dE\, G(E) \left(f_1(E) - f_2(E) \right)$$

2.1b Introduction



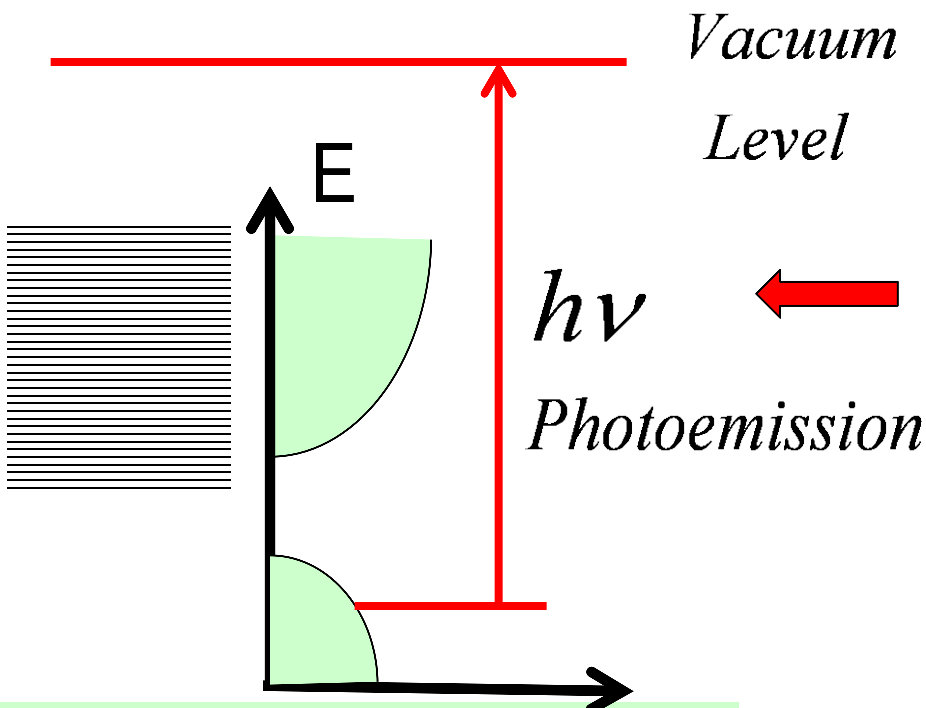
$$G_B = q^2\,\frac{D\bar{v}}{2L} = \frac{q^2}{h}\,M$$

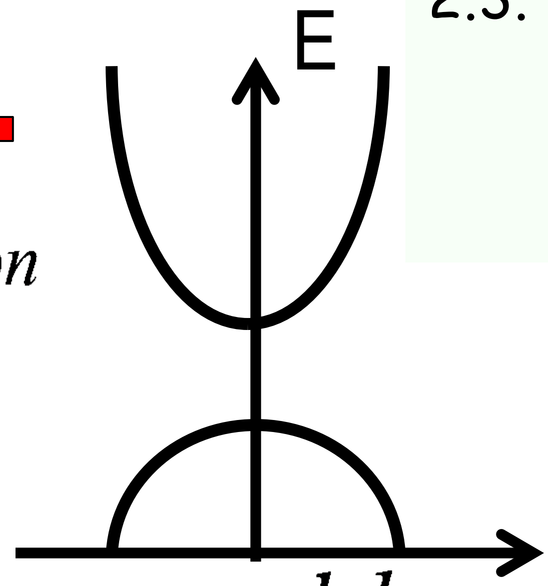
2.2. E(p) or E(k) relation

2.3. Counting states

2.4. D(E)

2.5. M(E)





$$p = \hbar k$$

Density of States, D(E)

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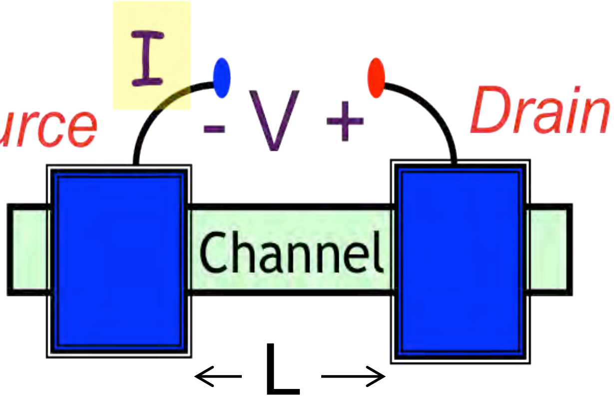


$$G_B = q^2 \frac{D\bar{v}}{2L} = \frac{q^2}{h} M$$

2.2. E(p) or E(k) relation

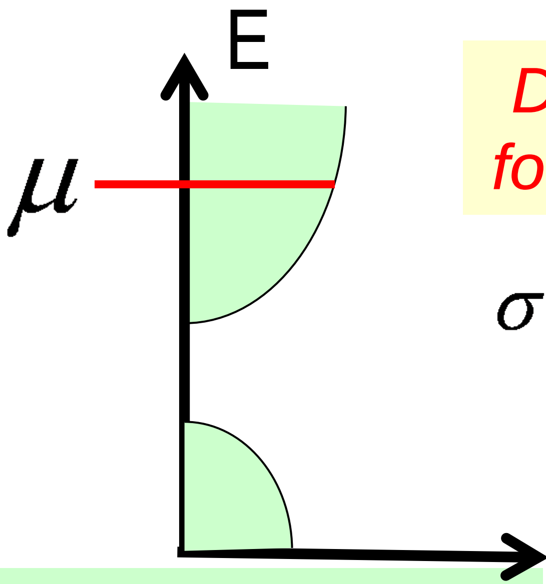
2.3. Counting states

2.4. D(E)

2.5. M(E)

2.6. N(E)

2.7. Conductivity vs n

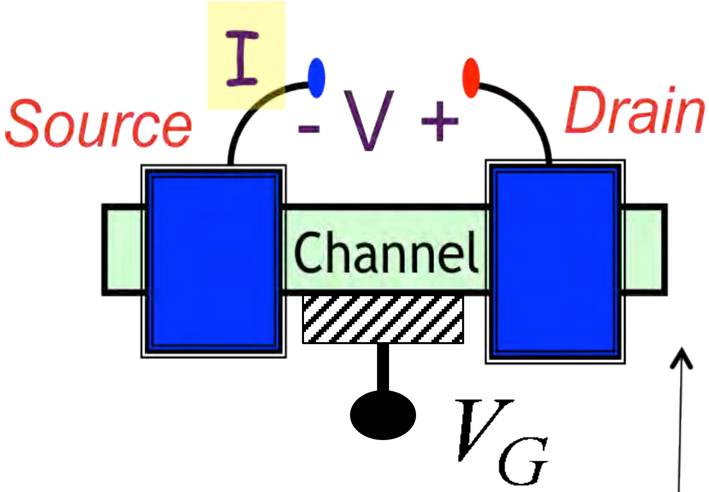


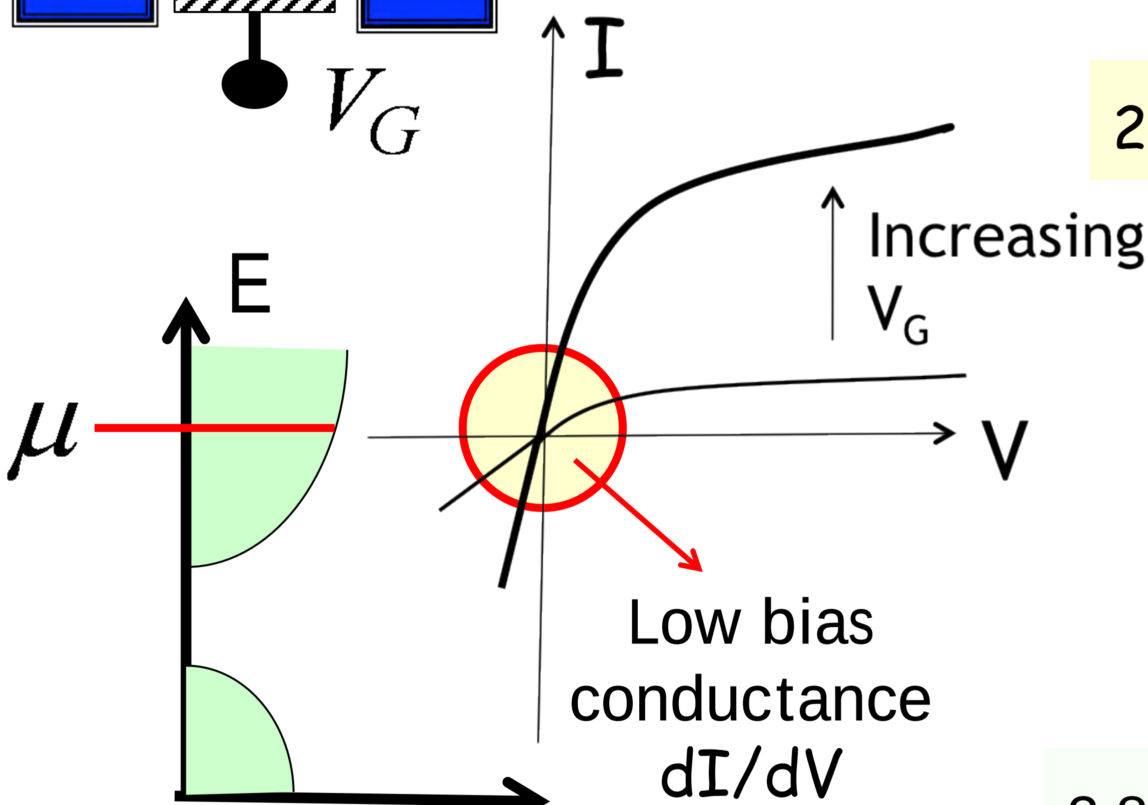
Density of States, D(E)

Drude formula

$$\sigma = q^2 \frac{n}{m} \tau$$

2.1d Introduction





Density of States, D(E)

2.2. E(p) or E(k) relation

2.3. Counting states

2.4. D(E)

2.5. M(E)

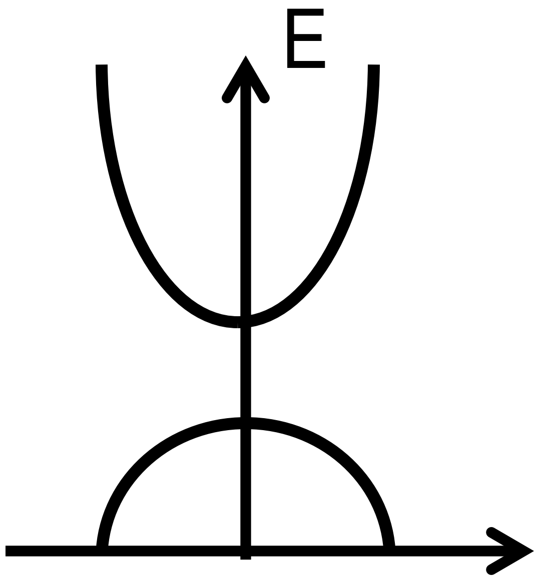
2.6. N(E)

2.7. Conductivity vs n

2.8. Quantum capacitance

2.9. Nanotransistor

Coming up next ..



$$p = \hbar k$$

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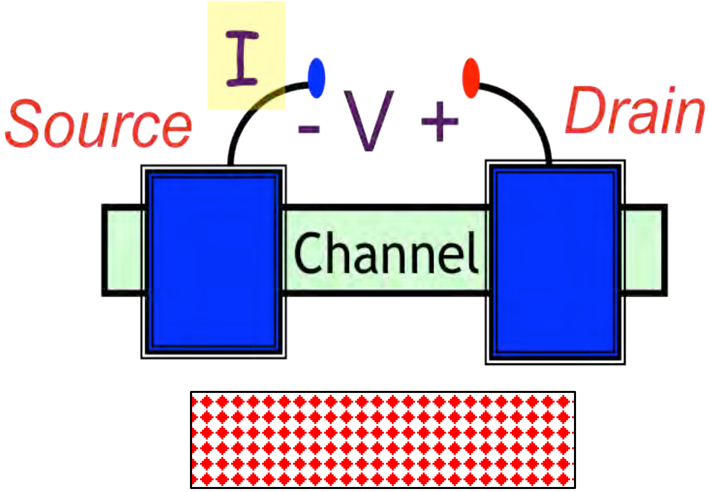
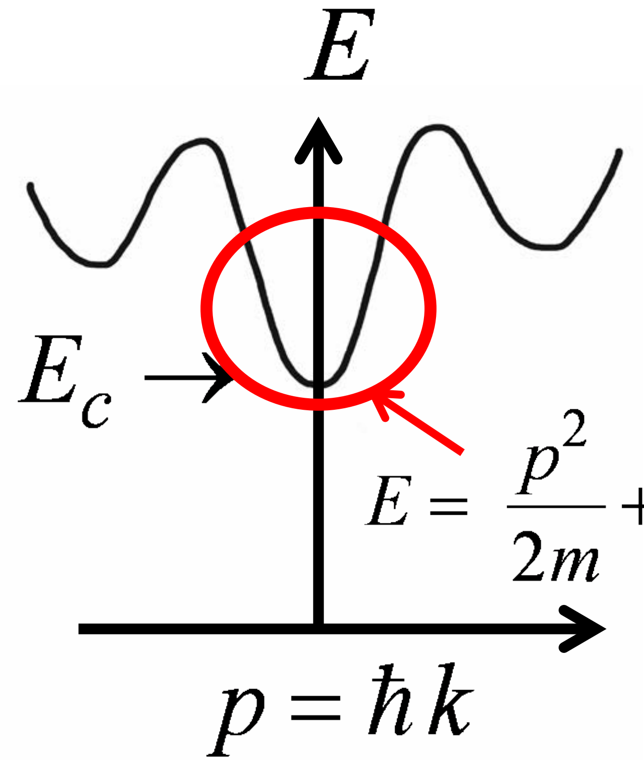
2.2a E(p) or E(k) relation





$$E = \frac{p^2}{2m} + E_c$$

$$KE = \frac{1}{2} m_0 v^2$$

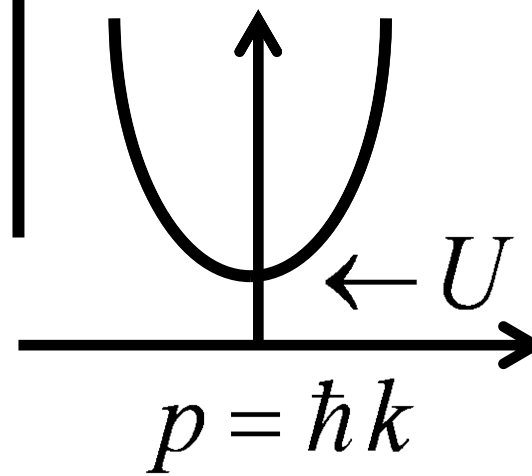
$$= \frac{1}{2} \frac{(m_0 v)^2}{m_0}$$

$$= \frac{1}{2} \frac{p^2}{m_0}$$

$$if \quad p = m_0 v$$

Electrons in vacuum

$$E = \frac{p^2}{2m_0} + U$$



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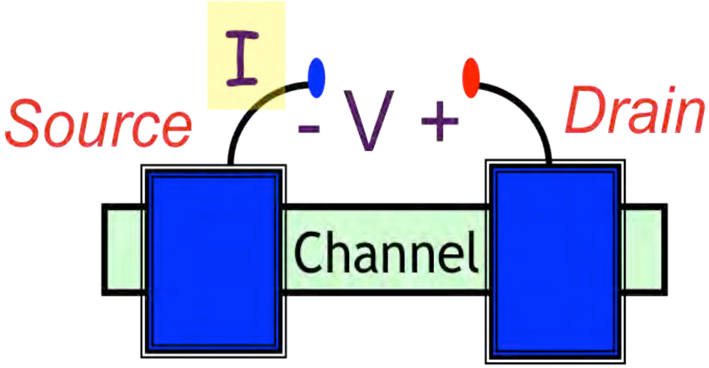
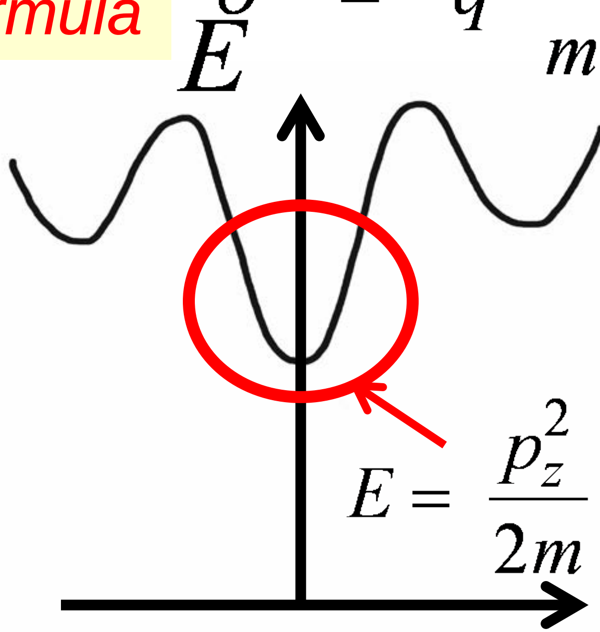
2.2b E(p) or E(k) relation



Drude formula

$$\sigma = q^2 \frac{n}{m} \tau$$



$$E = \frac{p_z^2}{2m} + E_c$$

$$p_z = \hbar k_z$$

"Relativistic" band

$$E^2 = \left(m_0 c^2\right)^2 + c^2 p_z^2$$

$$v_z = \frac{c^2 p_z}{E} \leftarrow 2E \frac{\partial E}{\partial p_z} = 2\, c^2 p_z$$

$$\downarrow$$

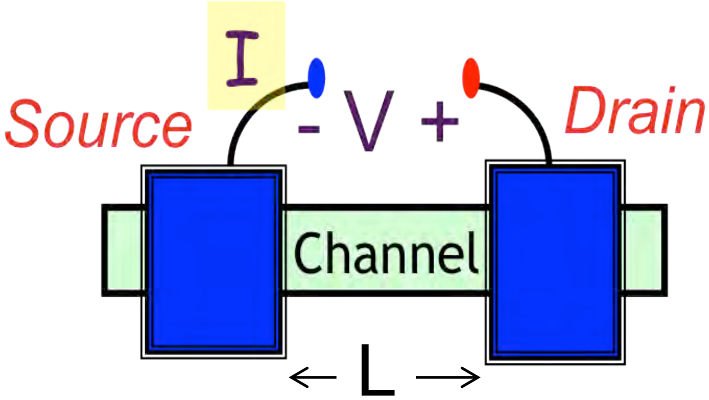
$$m = \frac{p_z}{v_z} = \frac{E}{c^2} \rightarrow \frac{m_0}{\sqrt{1 - \frac{v_z^2}{c^2}}}$$

Parabolic band

$$v_z = \frac{\partial E}{\partial p_z} = \frac{p_z}{m}$$

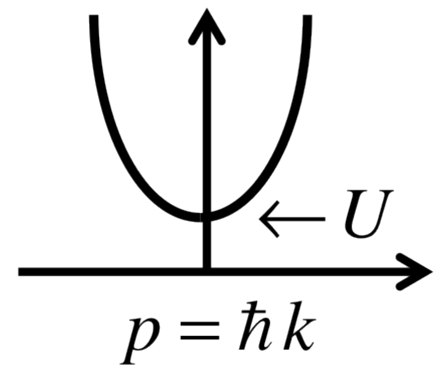
$$\frac{dz}{dt} = \frac{\partial E}{\partial p_z} \quad , \quad \frac{dp_z}{dt} = -\frac{\partial E}{\partial z}$$

2.2c E(p) or E(k) relation

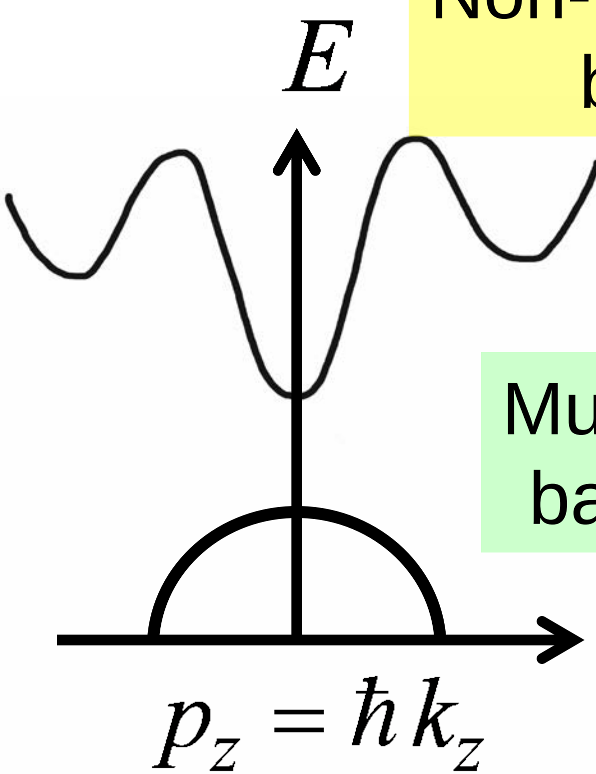


Electrons in vacuum

$$E = \frac{p^2}{2m_0} + U$$



Non-parabolic band



Multiple bands

$$\boxed{\frac{dz}{dt} = \frac{\partial E}{\partial p_z} \quad , \quad \frac{dp_z}{dt} = -\frac{\partial E}{\partial z}}$$

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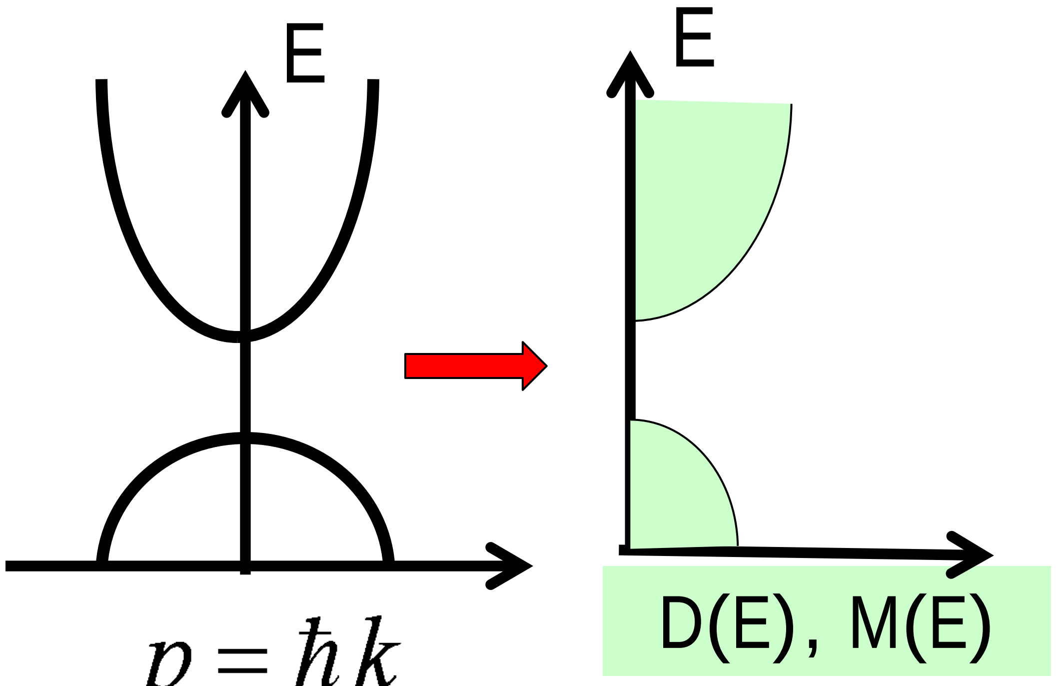

$$p = \hbar k$$

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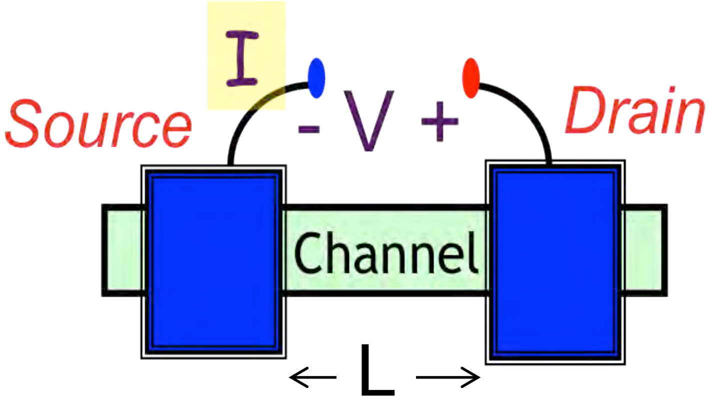
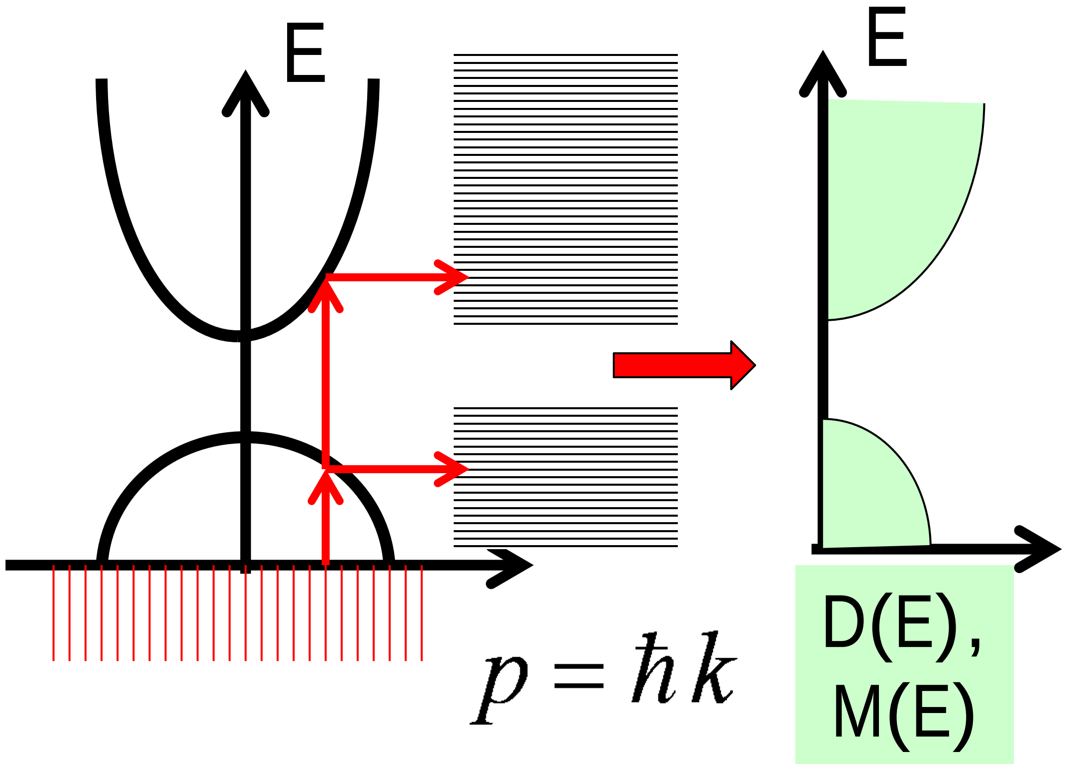
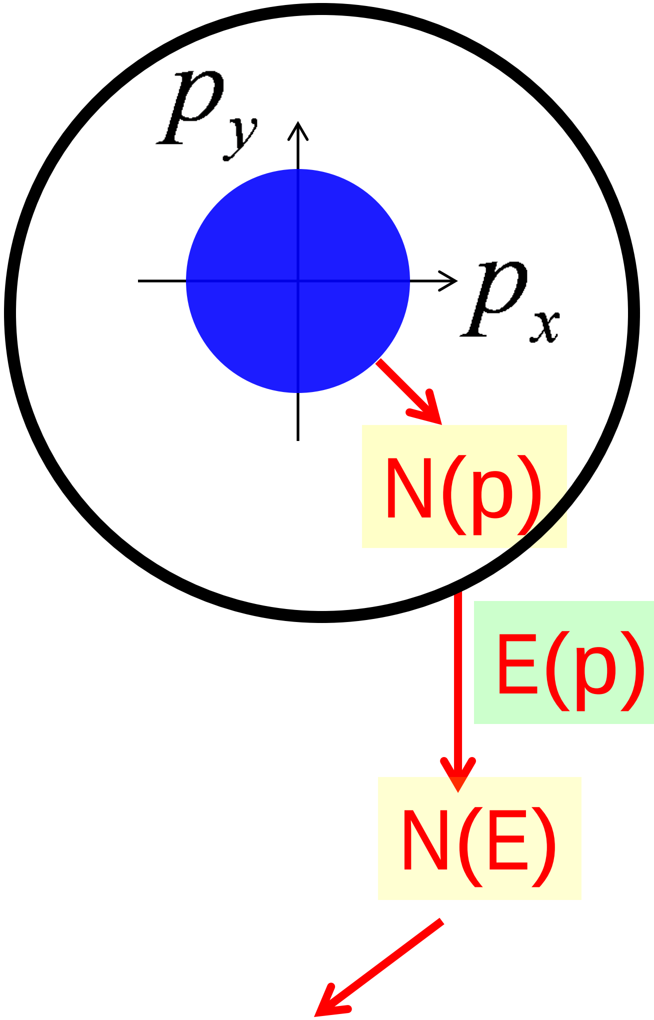
2.3a Counting states





$$p = \hbar k$$



$$D(E) = \frac{dN(E)}{dE}$$

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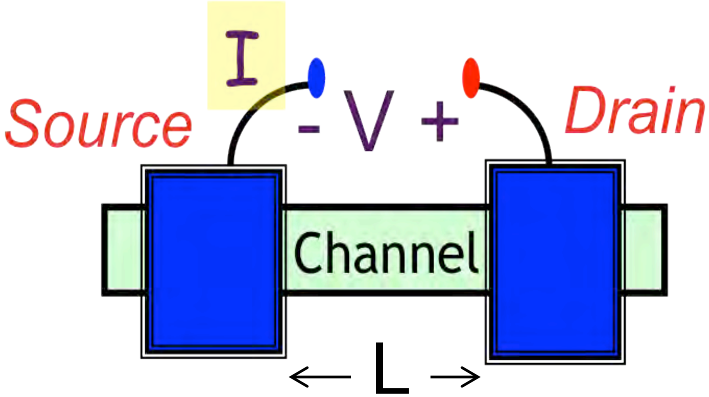
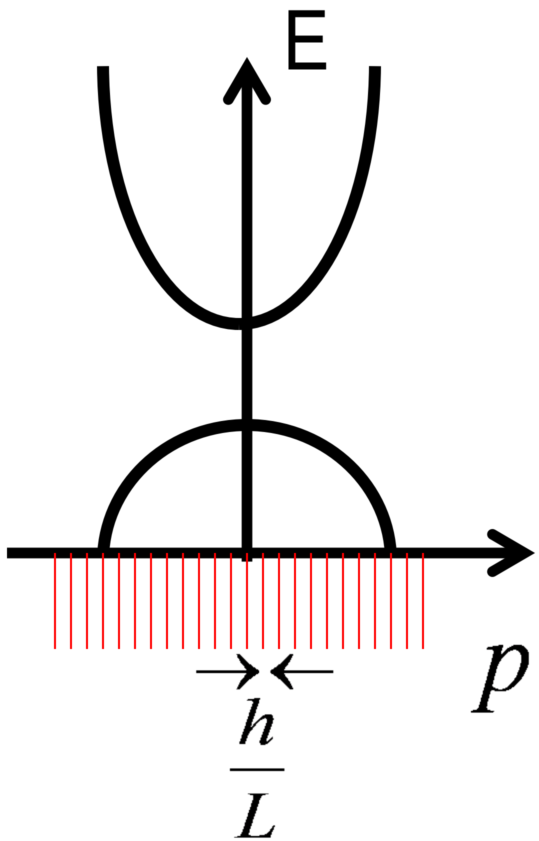
2.3b Counting states



$$\lambda_{De\ Broglie} = \frac{h}{p}$$

$$\boxed{N(p) = \frac{2p}{h/L}}$$

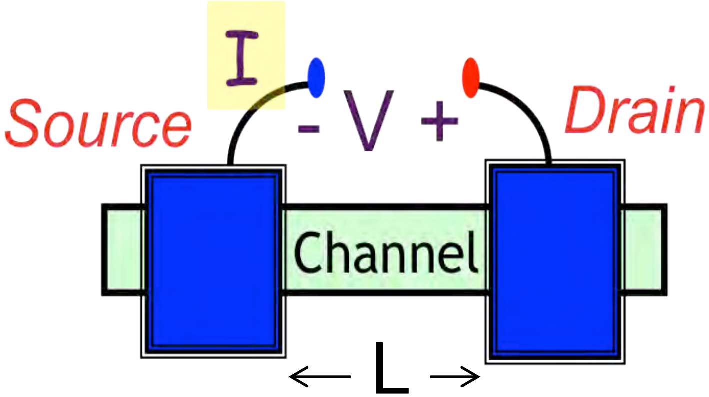


$$L = n\frac{h}{p_n} \rightarrow p_n = n\frac{h}{L}$$

$$\rightarrow k_n = \frac{n}{L}\frac{h}{\hbar} = n\frac{2\pi}{L}$$

$$p = \hbar k \rightarrow \hbar\frac{2\pi}{\lambda_{De\ Broglie}} = \frac{h}{\lambda_{De\ Broglie}}$$

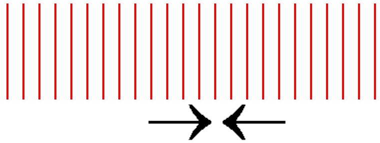
2.3c Counting states



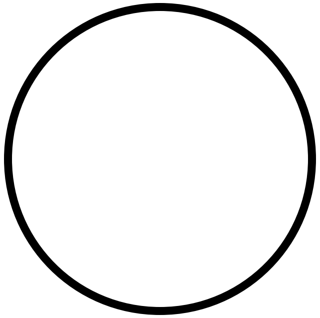
1D $$N(p) = \frac{2p}{h/L}$$

Periodic Boundary Condition PBC

$$L = n\frac{h}{p_n} \rightarrow p_n = n\frac{h}{L}$$



$$\frac{h}{L}$$



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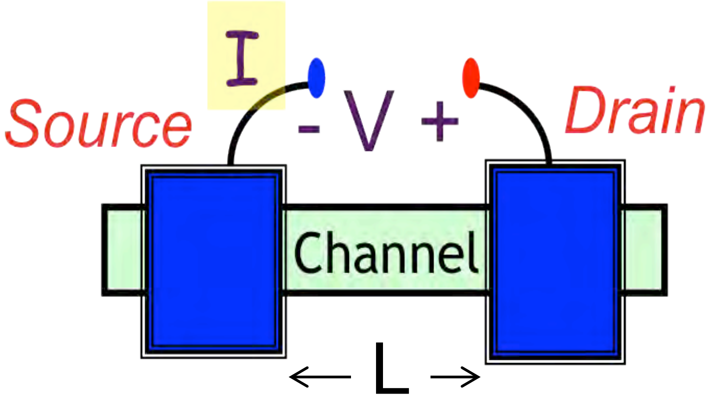
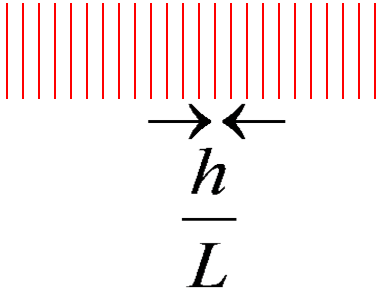
2.3d Counting states



1D

$$N(p) = \frac{2p}{h/L}$$



2D

$$N(p) = \frac{\pi p^2}{(h/L)(h/W)}$$

3D

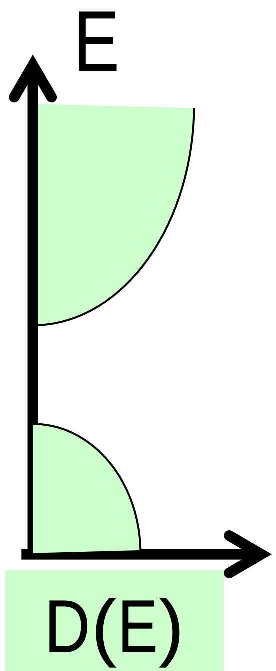
$$N(p) = \frac{4\pi p^3/3}{(h/L)(h^2/A)}$$

$$\boxed{\begin{array}{llll} & 1D & 2D & 3D \\ N(p) = \left(\dfrac{p}{h}\right)^d & \{2L & \pi WL & \dfrac{4\pi}{3}AL\} \end{array}}$$

Periodic Boundary Condition PBC

Coming up next ..

$$\begin{array}{cccc} & 1D & 2D & 3D \\ N(p) = \left(\dfrac{p}{h}\right)^d & \Big\{ 2L & \pi WL & \dfrac{4\pi}{3} AL \Big\} \end{array}$$



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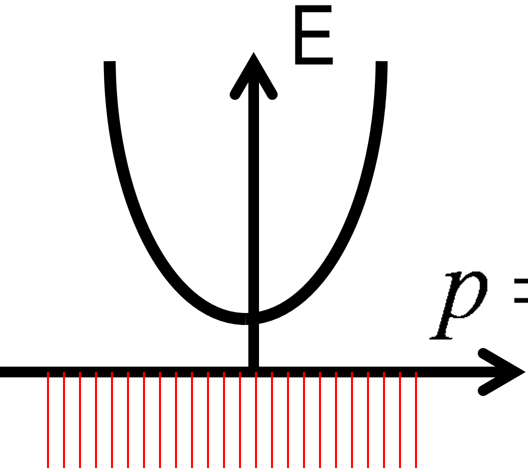
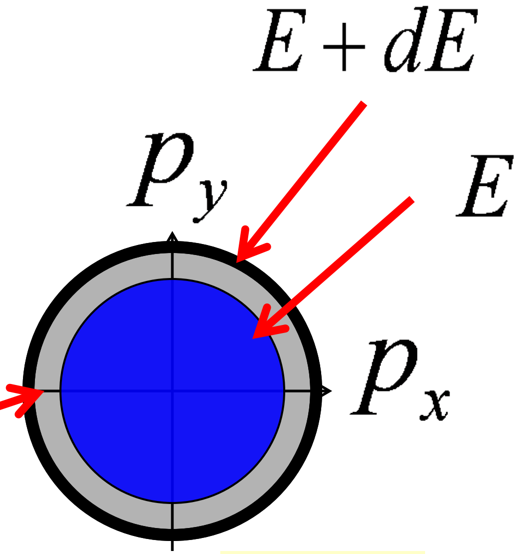
2.4a Density of states

$$N(p) = \left(\frac{p}{h}\right)^d \begin{cases} 2L & 1D \\ \pi WL & 2D \\ \dfrac{4\pi}{3}AL & 3D \end{cases}$$



$$p = \hbar k$$



$$dN(E) = D(E)\, dE$$

N(p)

$\downarrow$ E(p)

N(E)

$$D(E) = \frac{dN(E)}{dE}$$

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2.4b Density of states

$$N(p) = \left(\frac{p}{h}\right)^d \begin{Bmatrix} 1D & 2D & 3D \\ 2L & \pi WL & \dfrac{4\pi}{3}AL \end{Bmatrix}$$

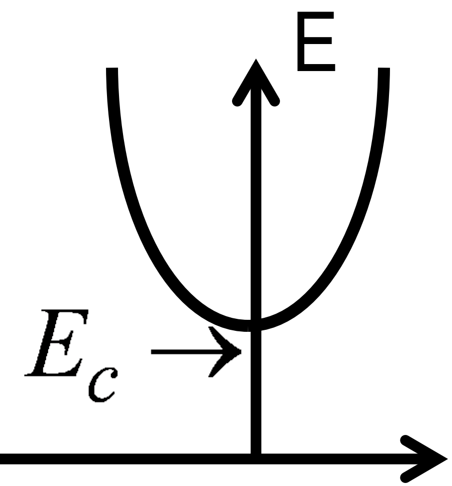
$$N(p) = A\, p^d$$

$$E(p) = E_c + B\, p^\alpha$$

$$N(E) = A\left(\frac{E - E_c}{B}\right)^{\frac{d}{\alpha}}$$

$$D(E) \sim \left(E - E_c\right)^{\frac{d}{\alpha} - 1}$$

$$D(E) = \frac{dN(E)}{dE}$$



$$p = \hbar k$$

N(p)

E(p)

N(E)

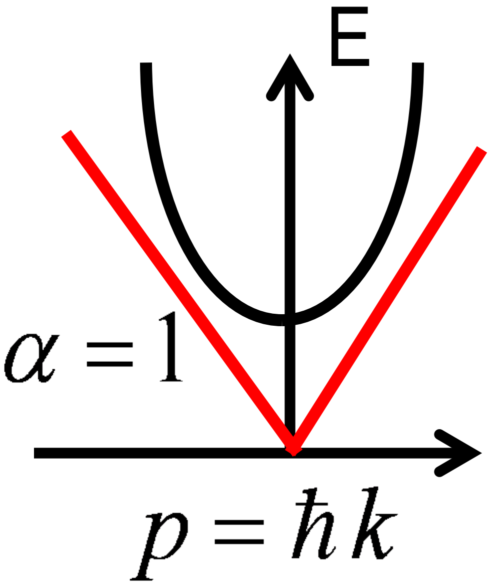
2.4c Density of states

$$N(p) = A\,p^{d}$$

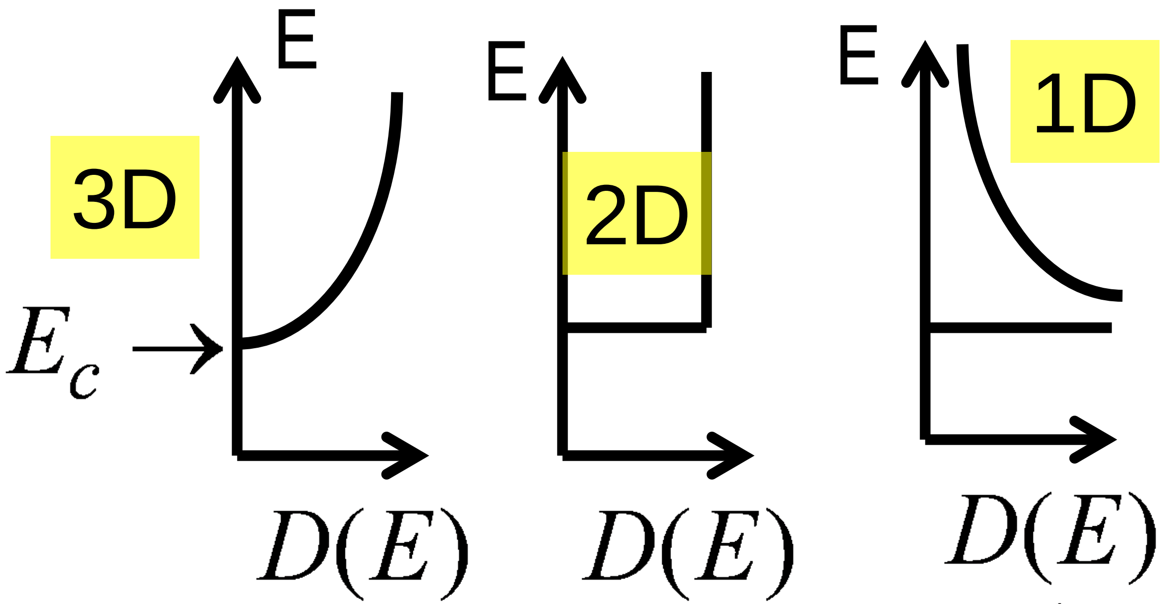
$$E(p) = E_c + B\,p^{\alpha}$$

$$D(E) \sim \left(E - E_c\right)^{\frac{d}{\alpha} - 1}$$

$$E(p) = \sqrt{E_g^2 + v_0^2 p^2}$$



$$\boxed{\alpha = 2}$$

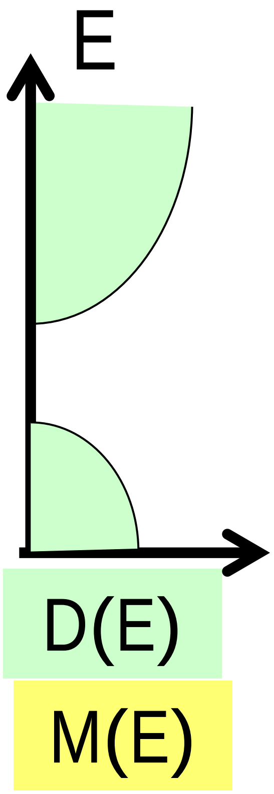


$$\sim \sqrt{E - E_c} \qquad\qquad \sim \frac{1}{\sqrt{E - E_c}}$$

Coming up next ..

$$N(p) = \left(\frac{p}{h}\right)^{d} \begin{Bmatrix} 1D & 2D & 3D \\ 2L & \pi WL & \dfrac{4\pi}{3}AL \end{Bmatrix}$$

$$E(p)$$



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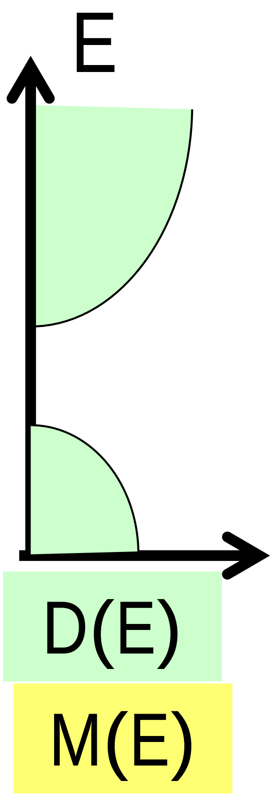
2.5a Number of modes

$$N(p) = \left(\frac{p}{h}\right)^d \begin{Bmatrix} 1D & 2D & 3D \\ 2L & \pi WL & \dfrac{4\pi}{3}AL \end{Bmatrix}$$

$E(p)$



Ballistic conductance

$$G_B = q^2 \frac{D\bar{v}}{2L} = \frac{q^2}{h} M$$

$$M = \frac{hDv}{2L} \left\{ 1 \; , \; \frac{2}{\pi} \; , \; \frac{1}{2} \right\}$$

General Relation valid for all E(p)

$$D\,v\,p = N\,d$$

2.5b Number of modes

$$\begin{array}{cccc} & 1D & 2D & 3D \\ N(p) = \left(\dfrac{p}{h}\right)^d & \{2L & \pi WL & \dfrac{4\pi}{3}AL\} \end{array}$$

$$p \times \frac{dN}{dE}\frac{dE}{dp} = \frac{dN}{dp} = d\,\frac{p^{d-1}}{h^d}\left\{2L \quad \pi WL \quad \frac{4\pi}{3}AL\right\} \times p$$

$$\boxed{D\,v\,p \;=\; N\,d}$$

General Relation valid for all E(p)

2.5c Number of modes

$$N(p) = \left(\frac{p}{h}\right)^d \begin{Bmatrix} 1D & 2D & 3D \\ 2L & \pi WL & \dfrac{4\pi}{3}AL \end{Bmatrix}$$

$$\boxed{D\,\nu\,p \;=\; N\,d}$$

$$M = \frac{hD\nu}{2L}\left\{1 \;,\; \frac{2}{\pi} \;,\; \frac{1}{2}\right\}$$

$$= \frac{h}{2L}\frac{N}{p}\,d\left\{1 \;,\; \frac{2}{\pi} \;,\; \frac{1}{2}\right\}$$

$$= \frac{1}{2L}\left(\frac{p}{h}\right)^{d-1}\left\{2L \;,\; 4WL \;,\; 2\pi AL\right\}$$

$$M = \left(\frac{p}{h}\right)^{d-1}\left\{1 \;,\; 2W \;,\; \pi A\right\}$$

2.5d Number of modes

$$\begin{array}{cccc} & 1D & 2D & 3D \end{array}$$

$$N(p) = \left(\frac{p}{h}\right)^{d} \left\{ 2L \quad \pi WL \quad \frac{4\pi}{3}AL \right\}$$

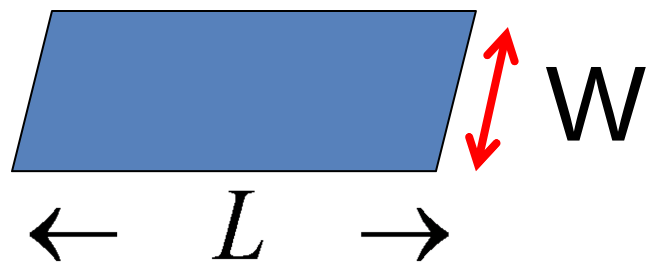
$$\left\{ \frac{L}{h/2p} \quad , \quad \frac{\pi}{4}\frac{WL}{(h/2p)^2} \quad , \quad \frac{\pi}{6}\frac{AL}{(h/2p)^3} \right\}$$

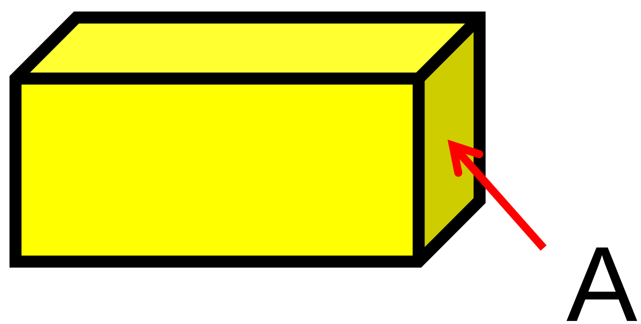
$$\left\{ 1 \quad , \quad \frac{W}{h/2p} \quad , \quad \frac{\pi}{4}\frac{A}{(h/2p)^2} \right\}$$

$$M = \left(\frac{p}{h}\right)^{d-1} \left\{ 1 \quad , \quad 2W \quad , \quad \pi A \right\}$$

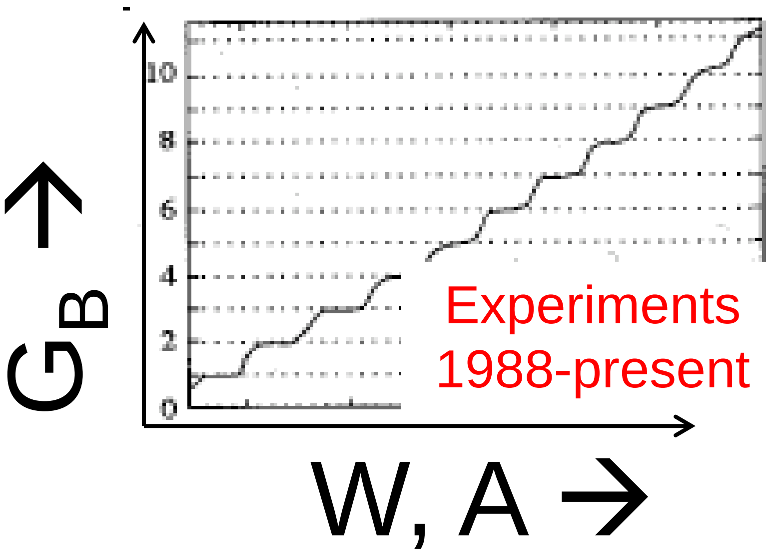
$$\boxed{D\,\nu\,p \quad = \quad N\,d}$$

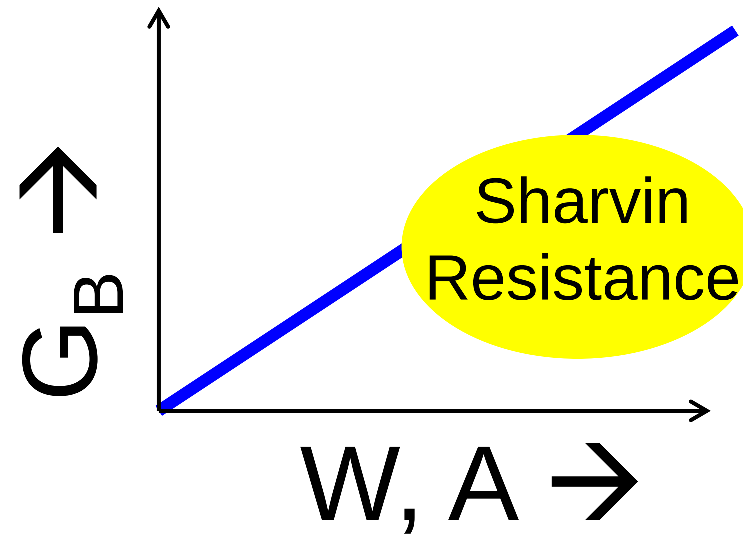
$$M = \frac{hD\nu}{2L}\left\{ 1 \quad , \quad \frac{2}{\pi} \quad , \quad \frac{1}{2} \right\}$$





2.5e Number of modes



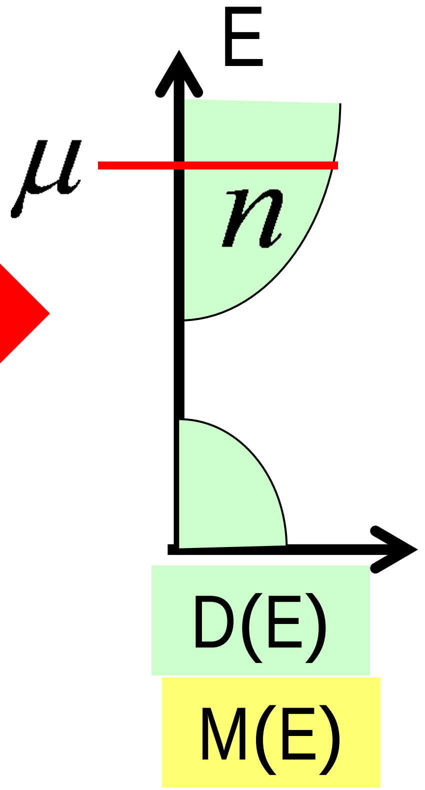


$$\text{Int}\left\{1 \quad , \quad \frac{W}{h/2p} \quad , \quad \frac{\pi}{4}\frac{A}{(h/2p)^2}\right\}$$

$$M \quad = \quad \left(\frac{p}{h}\right)^{d-1} \left\{1 \quad , \quad 2W \quad , \quad \pi A\right\}$$

Coming up next ..

$$
N(p) = \left(\frac{p}{h}\right)^{d} \begin{array}{c} \\ \left\{ \right. \end{array} \begin{array}{ccc} 1D & 2D & 3D \\ 2L & \pi WL & \dfrac{4\pi}{3}AL \end{array} \begin{array}{c} \\ \left. \right\} \end{array}
$$



FUNDAMENTALS OF NANOELECTRONICS

Basic Concepts

1. The New Perspective

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3. What and Where is the Voltage?

4. Heat & Electricity: Second Law & Information

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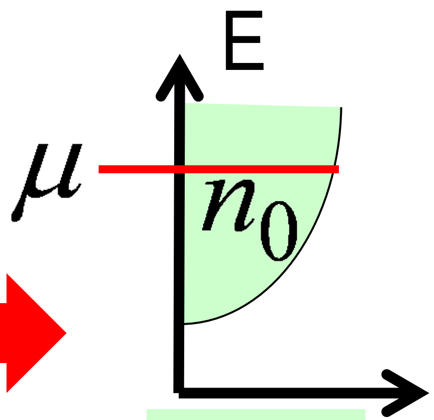
2.6a Electron density

$$N(p) = \left(\frac{p}{h}\right)^d \begin{array}{ccc} 1D & 2D & 3D \\ \Big\{ 2L & \pi WL & \dfrac{4\pi}{3} AL \Big\} \end{array}$$

$E(p)$



D(E)

M(E)

$$n(p) = \left(\frac{p}{h}\right)^d \begin{array}{ccc} 1D & 2D & 3D \\ \Big\{ 2 & \pi & \dfrac{4\pi}{3} \Big\} \end{array}$$

E(p)

$$n(E) \xrightarrow[T=0K]{E=\mu} n(\mu)$$

2.6b Electron density

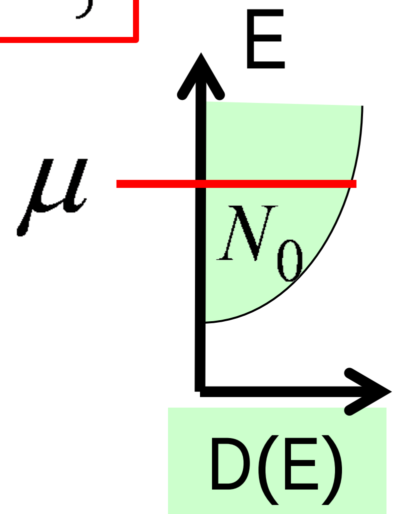
$$\boxed{N(p) = \left(\frac{p}{h}\right)^d \left\{\begin{matrix} 1D & 2D & 3D \\ 2L & \pi WL & \dfrac{4\pi}{3}AL \end{matrix}\right\}}$$

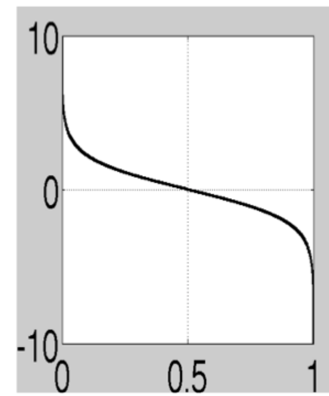
$$N_0 = \int_{-\infty}^{+\infty} dE\, D(E)\, f_0(E)$$

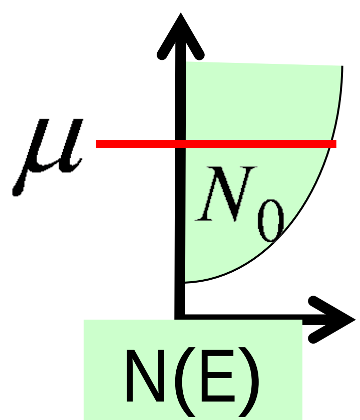
$$= \int_{-\infty}^{+\infty} dE\, \frac{dN}{dE}\, f_0(E)$$

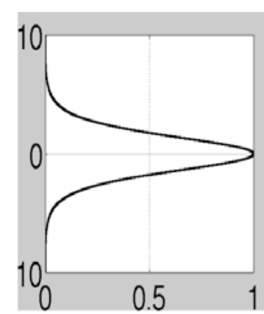
$$= \cancel{\left[N f_0\right]_{-\infty}^{+\infty}}$$

$$+ \int_{-\infty}^{+\infty} dE\, N(E)\left(-\frac{\partial f_0}{\partial E}\right)$$







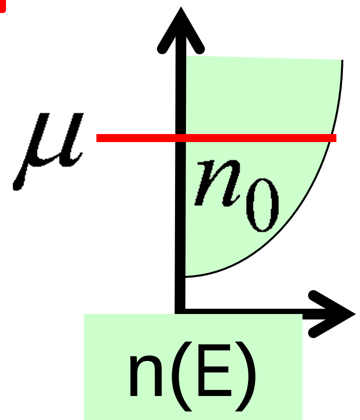


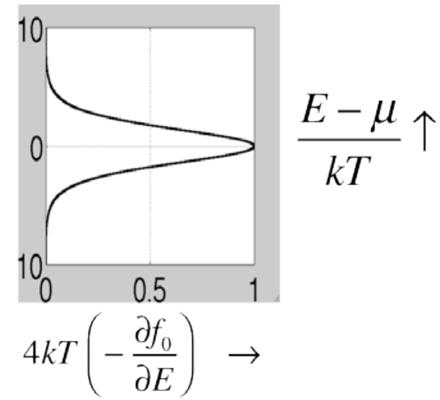
2.6c Electron density

$$N(p) = \left(\frac{p}{h}\right)^d \begin{Bmatrix} 1D & 2D & 3D \\ 2L & \pi WL & \dfrac{4\pi}{3}AL \end{Bmatrix}$$

$$n(p) = \left(\frac{p}{h}\right)^d \left\{ 2 \quad \pi \quad \frac{4\pi}{3} \right\}$$

$$n_0 = \int_{-\infty}^{+\infty} dE\, n(E) \left(-\frac{\partial f_0}{\partial E} \right)$$





$$G_B = \frac{q^2 D \bar{v}}{2L} = \frac{q^2}{h} M$$

Recall $G_0 = \int_{-\infty}^{+\infty} dE \left(-\frac{\partial f_0}{\partial E} \right) G(E) \rightarrow \frac{G_B \lambda}{L + \lambda}$

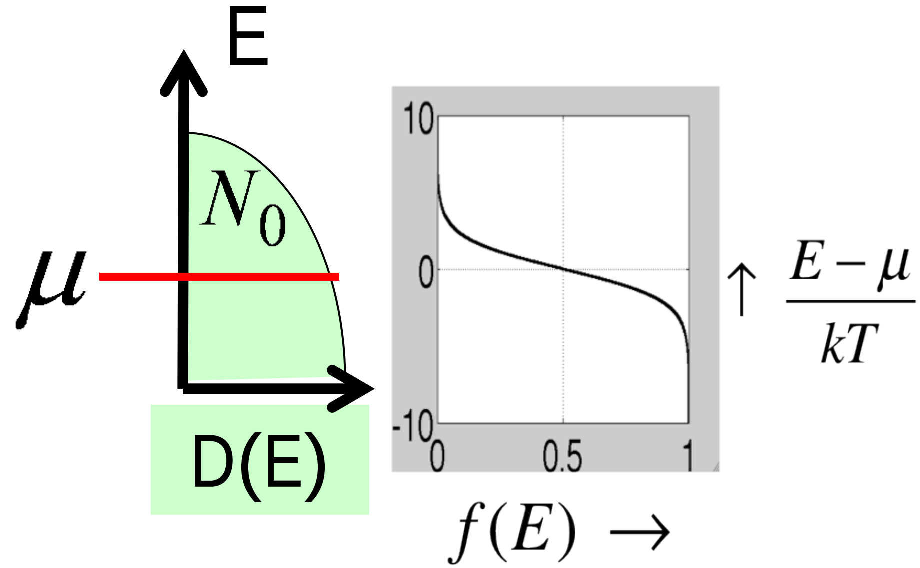
2.6d Electron density

$$N_0 = \int_{-\infty}^{+\infty} dE\, D(E)\,(1 - f_0(E))$$

$$= \int_{-\infty}^{+\infty} dE \left(-\frac{dN}{dE} \right) (1 - f_0(E))$$

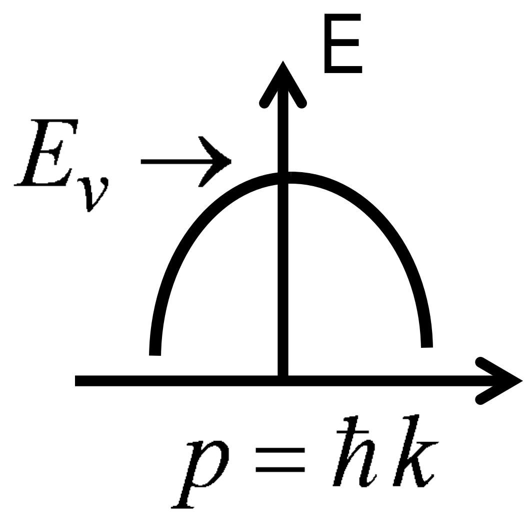
$$= \left[-N(1 - f_0) \right]_{-\infty}^{+\infty}$$

$$+ \int_{-\infty}^{+\infty} dE\, N(E) \left(-\frac{\partial f_0}{\partial E} \right)$$



$$N(1 - f_0) = 0 \quad as \quad E \rightarrow -\infty$$

$$N f_0 \neq 0 \quad as \quad E \rightarrow -\infty$$



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$$n(p) = \left(\frac{p}{h}\right)^d \left\{2 \quad \pi \quad \frac{4\pi}{3}\right\}$$

$$n_0 = \int_{-\infty}^{+\infty} dE \; n(E) \left(-\frac{\partial f_0}{\partial E}\right)$$

New perspective

$$\sigma = \frac{G_B}{A} \lambda$$

Drude formula

$$\sigma = q^2 \frac{n}{m} \tau$$

Coming up next ..

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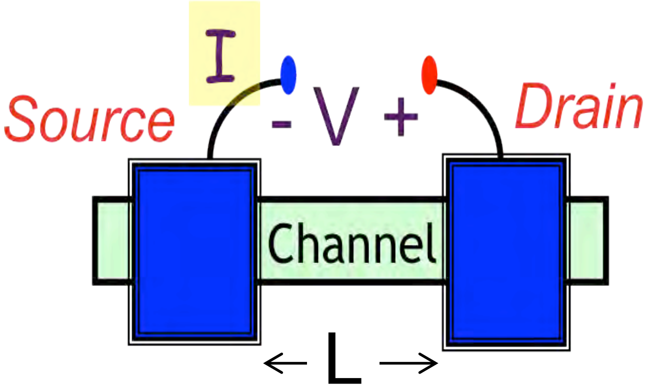
2.7a Conductivity versus n



$$M = \left(\frac{p}{h}\right)^{d-1} \left\{1 \quad 2W \quad \pi A\right\}$$

$$\frac{G_B}{A} = \frac{q^2}{h}\left(\frac{p}{h}\right)^{d-1} \left\{1 \quad 2 \quad \pi\right\}$$

$$n = \left(\frac{p}{h}\right)^{d} \left\{2 \quad \pi \quad \frac{4\pi}{3}\right\}$$

$$N(p) = \left(\frac{p}{h}\right)^{d} \left\{2L \quad \pi WL \quad \frac{4\pi}{3}AL\right\}$$

New perspective

$$\sigma = \frac{G_B}{A} \lambda$$

$$\sigma = q^2 \frac{n}{m} \tau$$

Drude formula

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2.7b Conductivity versus n

New perspective

$$\sigma = \frac{G_B}{A} \lambda$$

$$\sigma = q^2 \frac{n}{m} \tau$$

Drude formula

$$\frac{G_B}{A} = \frac{q^2}{h}\left(\frac{p}{h}\right)^{d-1} \{1 \quad 2 \quad \pi\}$$

$$\frac{q^2 n}{m} = \frac{q^2}{m}\left(\frac{p}{h}\right)^{d} \left\{2 \quad \pi \quad \frac{4\pi}{3}\right\}$$

$$\frac{G_B/A}{q^2 n/m} = \frac{m}{p}\left\{\frac{1}{2} \quad \frac{2}{\pi} \quad \frac{3}{4}\right\}$$

$$\frac{\lambda}{\tau} = \frac{v\tau}{\tau}\left\{2 \quad \frac{\pi}{2} \quad \frac{4}{3}\right\}$$

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2.7c Conductivity versus n

$$\frac{1}{m} = \frac{dv}{dp} \quad \times$$

- $$\frac{1}{m} = \frac{v}{p}$$

$$I/A = q\,n\,v \quad , \quad \frac{dp}{dt} + \frac{p}{\tau} = qF$$

$$v = \frac{p}{m} \qquad p = qF\tau$$

New perspective

$$\sigma = \frac{G_B}{A}\,\lambda$$

$$\sigma = q^2\,\frac{n}{m}\,\tau$$

Drude formula

$$\frac{G_B\,\lambda / A}{q^2\,n\,\tau / m} = \frac{m\,v}{p} \rightarrow 1$$

$$\frac{G_B / A}{q^2\,n / m} = \frac{m}{p}\left\{\frac{1}{2} \quad \frac{2}{\pi} \quad \frac{3}{4}\right\}$$

$$\frac{\lambda}{\tau} = \frac{v\,\tau}{\tau}\left\{2 \quad \frac{\pi}{2} \quad \frac{4}{3}\right\}$$

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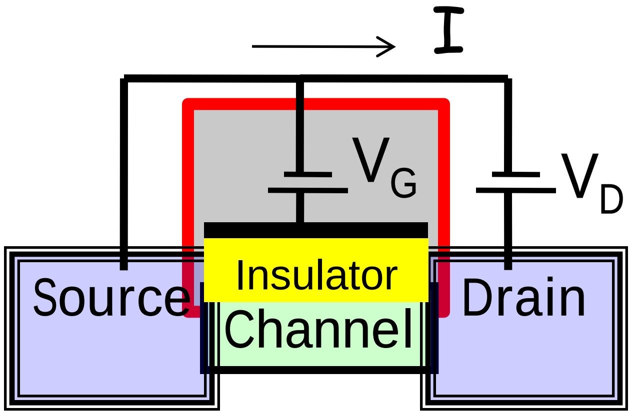
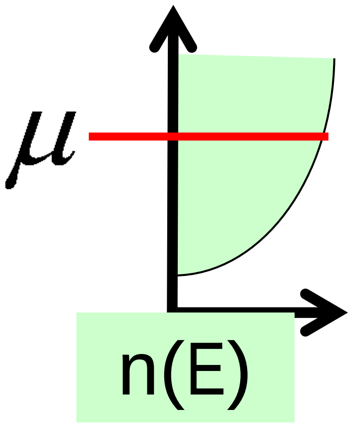
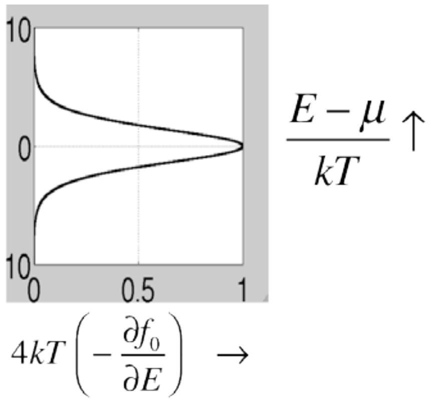
Coming up next ..







FUNDAMENTALS OF NANOELECTRONICS

Basic Concepts

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2.1. Introduction

2.2. E(p) or E(k) relation

2.3. Counting States

2.4. Density of states

2.5. Number of modes

2.6. Ballistic Conductance vs n

2.7. Conductivity vs n

2.8. Quantum Capacitance

2.9. The Nanotransistor

2.10. Summing up ..

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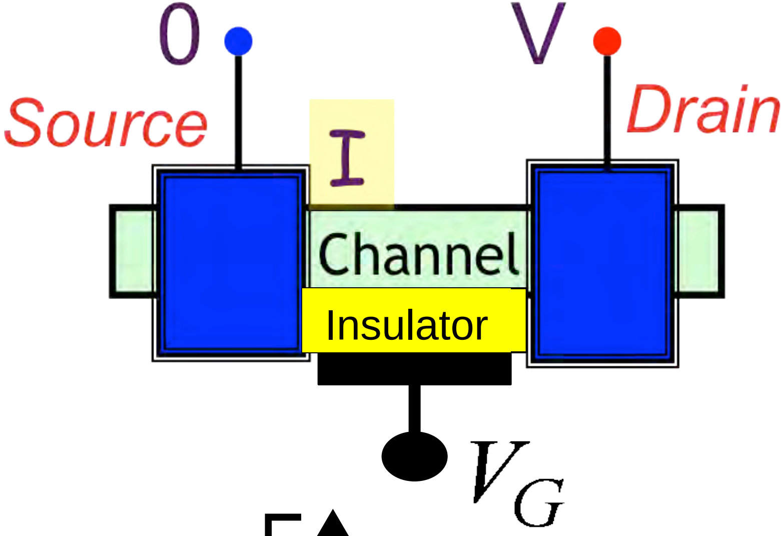
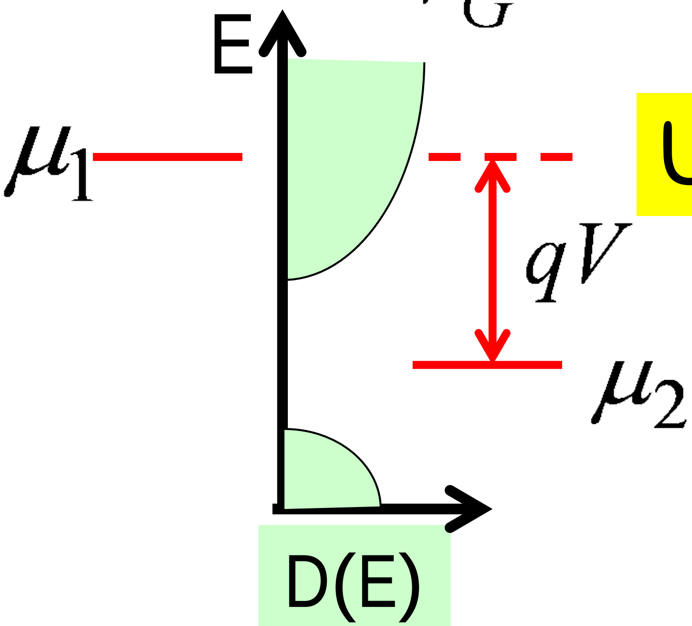
2.10a Summing up ..





Density of States (DOS)

Unit 1

New perspective

$$\sigma = \frac{G_B}{A}\lambda$$

Drude formula

$$\sigma = q^2 \frac{n}{m} \tau$$

$$I = \frac{1}{q}\int_{-\infty}^{+\infty} dE\, G(E)\, \big(f_1(E) - f_2(E) \big)$$

$$I/V = \int_{-\infty}^{+\infty} dE \left(-\frac{\partial f_0}{\partial E} \right) G(E)$$

$$G = \frac{q^2 D}{2t} = \frac{G_B\, \lambda}{L+\lambda} \rightarrow \frac{\sigma A}{L+\lambda}$$

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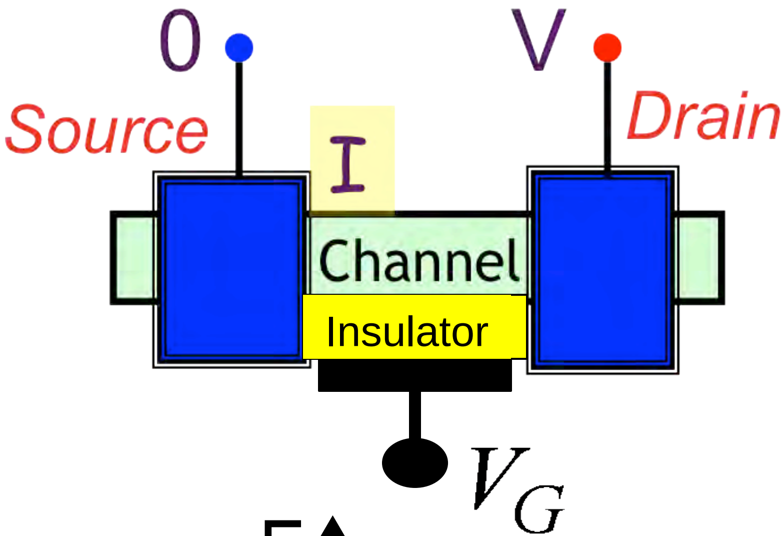
2.10b Summing up ..

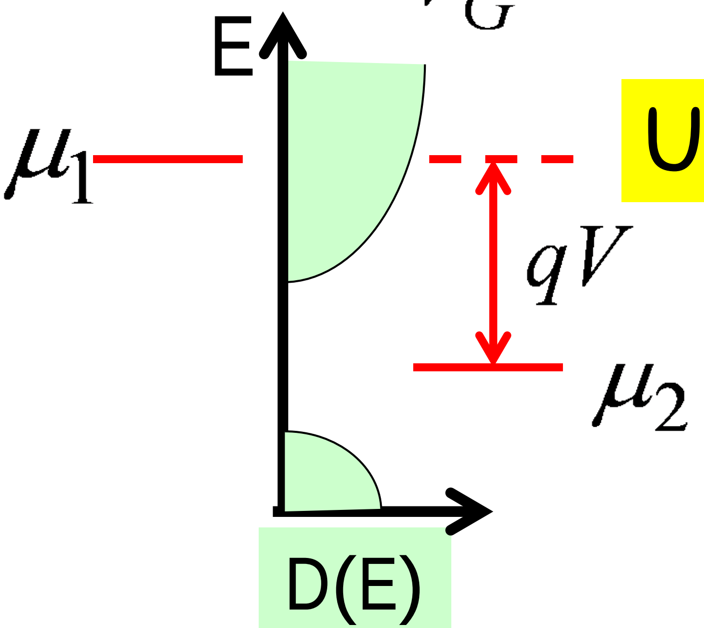


New perspective

$$\sigma = \frac{G_B}{A}\lambda$$

Drude formula

$$\sigma = q^2\frac{n}{m}\tau$$



Unit 2

Density of States (DOS)

2.2 E(p)

2.3 N(p)

2.4 D(E)

2.5 M(E)

2.6 n(E)

2.7 Drude

2.8 Gate

2.9 I - V

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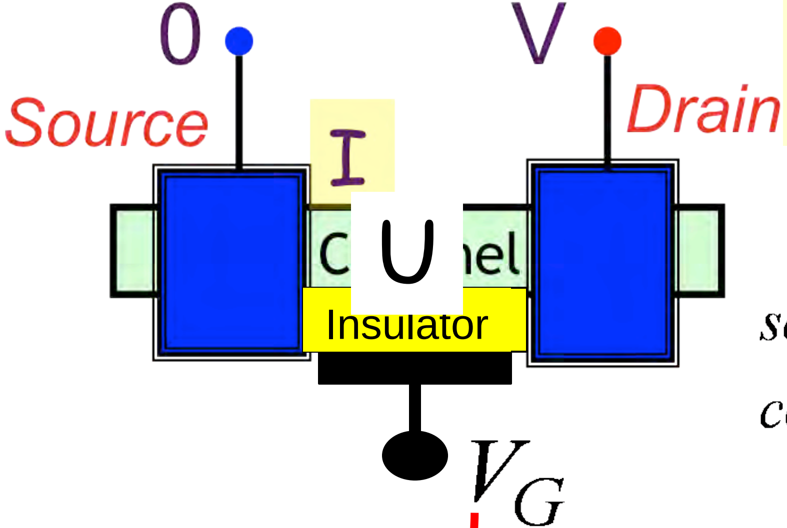
2.10c Summing up ..



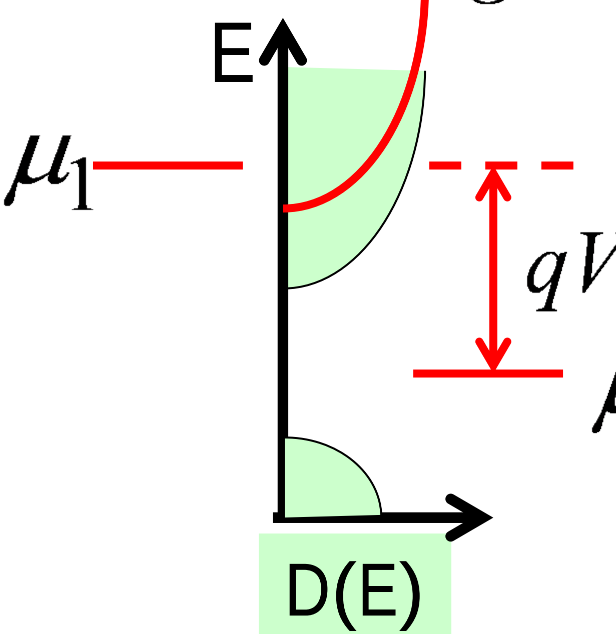
Single-electron charging energy

$$U = U_0(N - N_0) + \beta(-qV_G) + \alpha(-qV)$$

self - consistent

$$N = \int_{-\infty}^{+\infty} dE\, D(E-U)\, \frac{f_1(E) + f_2(E)}{2}$$

$$I = \frac{1}{q} \int_{-\infty}^{+\infty} dE\, G(E-U)\, \left(f_1(E) - f_2(E) \right)$$



Unit 2

2.2 E(p)

2.3 N(p)

2.4 D(E)

2.5 M(E)

2.6 n(E)

2.7 Drude

2.8 Gate

2.9 I - V

Density of States (DOS)

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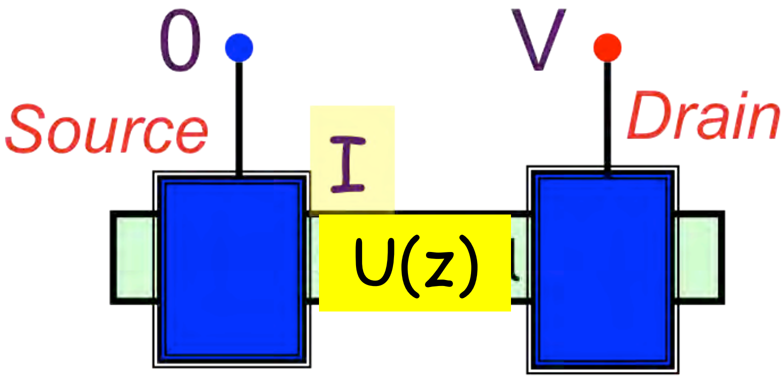
2.10d Summing up ..



$$\frac{R_B}{2} \qquad R_B\frac{L}{\lambda} \qquad \frac{R_B}{2}$$

$$R = R_B\left(\frac{L+\lambda}{\lambda}\right) = R_B\frac{L}{\lambda} + R_B$$

$$G = \frac{G_B\,\lambda}{L+\lambda} \rightarrow \frac{\sigma A}{L+\lambda}$$

$$I = \frac{1}{q}\int_{-\infty}^{+\infty} dE\, G(E-U)\,\big(f_1(E) - f_2(E)\big)$$

$$N = \int_{-\infty}^{+\infty} dE\, D(E-U)\,\frac{f_1(E)+f_2(E)}{2}$$

Boltzmann Transport Equation (BTE)

self – consistent

Drift Diffusion Equation

$$I = -\frac{\sigma(z)}{q}\frac{d\mu}{dz}$$

$$\frac{dI}{dz} = 0$$

Poisson Equation

$$\frac{d}{dz}\left(\varepsilon\frac{dU}{dz}\right) = q^2(n-n_0)$$

$$U = U_0(N-N_0) + \beta(-qV_G) + \alpha(-qV)$$

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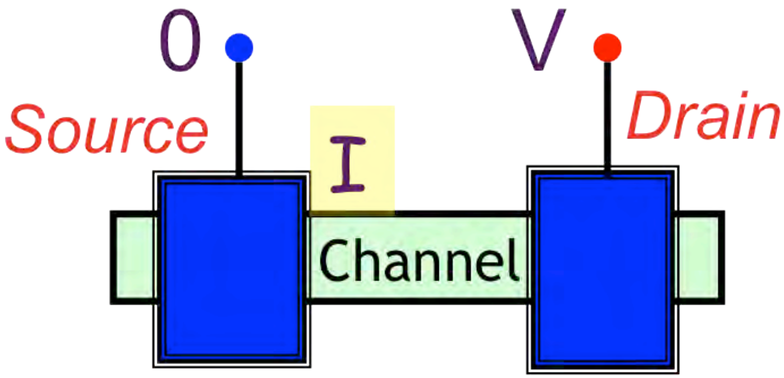

$$\frac{R_B}{2} \quad R_B\frac{L}{\lambda} \quad \frac{R_B}{2}$$

$$R = R_B\left(\frac{L+\lambda}{\lambda}\right) = R_B\frac{L}{\lambda} + R_B$$

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