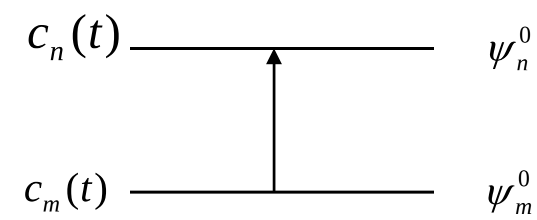
Optical processes in Semiconductor

Discussion of Fermi golden rule

$$w_{nm} = \frac{2\pi}{\hbar}\left|W_{nm}\right|^2 \delta\left(E_n^0 - E_m^0 - \hbar\omega\right)$$

$$\left|W_{n,m}\right|^2 = A_0^2\left|< n \,|\, D \,|\, m >\right|^2 = A_0^2\left|< n \,|\, -er \,|\, m >\right|^2$$

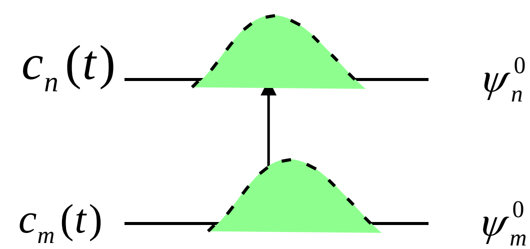


Energy conservation

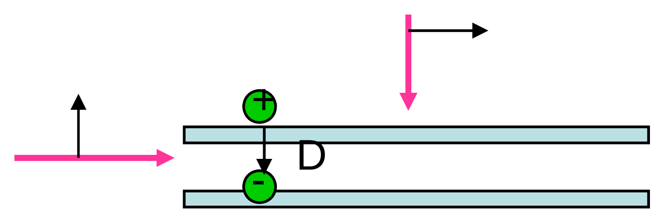
$$\delta\left(E_n^0 - E_m^0 - \hbar\omega\right)$$

Selection rules

Wavefunction overlap



Polarization selection rule



$$W = \frac{2\pi}{\hbar}\left|\left\langle \psi_m^0 \middle| V_0 \middle| \psi_n^0 \right\rangle\right|^2 \rho(\hbar\omega)$$

Fermi-Golden rule

$$W_{nm} = \frac{2\pi}{\hbar}\left|\left\langle \psi_m^0 \middle| V_0 \middle| \psi_n^0 \right\rangle\right|^2 \delta(E_m - E_k - \hbar\omega)$$

Fermi-Golden rule

Absorption coefficient

$$\alpha = -\frac{dI}{Idx}$$

$$\alpha = -\frac{1}{I}\frac{dI}{dt}\frac{dx}{dt} = \frac{1}{I_0} W c_r$$

Small absorption approximation

In semiconductors

$$W_{c\leftarrow v} = \frac{2\pi}{\hbar}\left|\left\langle \psi_c^0 \middle| H' \middle| \psi_v^0 \right\rangle\right|^2 \rho(\hbar\omega)(1-f_c)\,f_v$$

$$\alpha_{c\leftarrow v} = \frac{c_r}{I_0}W_{c\leftarrow v} = \frac{c_r}{I_0}\frac{2\pi}{\hbar}\left|\left\langle \psi_c^0 \middle| H' \middle| \psi_v^0 \right\rangle\right|^2 \rho_{red}(\hbar\omega)(1-f_c)\,f_v$$

$$f_c = \frac{1}{e^{(E_c - E_{Fc})/kT}+1} \qquad f_v = \frac{1}{e^{(E_v - E_{Fv})/kT}+1}$$

$$\rho_{red}(\hbar\omega) = \left(\frac{2m_r}{\hbar^2}\right)^{3/2}(\hbar\omega - E_g)$$

$$\frac{dI_\nu}{dx} = \frac{n}{c}\,\Delta x\, h\nu \cdot B_{21}\, f_{ph}(h\nu)\, \rho_{red}\left[f_n(E_2) - f_p(E_2 - h\nu)\right]$$

$$= \frac{n}{c} h\nu\, B_{21} \cdot I_\nu \cdot \rho_{red}\left[f_n(E) - f_p(E - h\nu)\right]$$

$$\Rightarrow\ g = B_{21} \cdot \frac{n}{c} \cdot \rho_{red}(h\nu)\left[f_n(E) - f_p(E - h\nu)\right]$$

- injection current level to reach threshold.

$\rightarrow n = n_0\, e^{qV/kT}$, $V = E_{Fn} - E_{Fp}$.

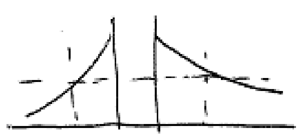
$\Rightarrow$ minority carrier concentration.

$n_p \gtrsim n_{p0}\, e^{qE_g/kT}$, build-in potential $V_0 = E_g + \frac{kT}{q}\ln\frac{N_A N_D}{N_C N_V}$

injection current

$$J = J_n + J_p$$

$$= q\left(\frac{D_n n_p}{L_n} + \frac{D_p p_n}{L_p}\right)\left[e^{qV/kT} - 1\right]$$



threshold level

$$J_n(x) = J_n(0)\, e^{-x/L_n}$$

$$J_p(x) = J_p(0)\, e^{-x/L_p}$$

hw: 4.4, 4.5, 4.6, 4.8, 4.9

Considering stimulated emission, the net emission rate:

$$W_{c\to v} - W_{c\leftarrow v} = \frac{2\pi}{\hbar}\left|\left\langle \psi_c^0 \middle| H' \middle| \psi_v^0 \right\rangle\right|^2 \rho_{red}(\hbar\omega)\left[f_v(1-f_v)-(1-f_c)\right]$$

Gain coefficient

$$G = \frac{c_r}{I_0}(W_{c\to v} - W_{c\leftarrow v}) = \frac{c_r}{I_0}\frac{2\pi}{\hbar}\left|\left\langle \psi_c^0 \middle| H' \middle| \psi_v^0 \right\rangle\right|^2 \rho_{red}(\hbar\omega)\left[f_c - f_v)\right]$$

$$G \geq 0 \qquad E_{fc} - E_{fv} > E_c - E_v$$

Gain

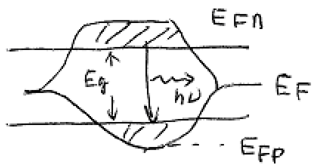
$$R_{st}^{21} > G_{12} \Rightarrow f_n(E_2)\cdot(1-f_p(E_1)) > [1-f_n(E_1)]\cdot f_p(E_2)$$

$$\Rightarrow \left[\frac{1}{e^{(E_2-E_{Fn})/kT}+1}\right]\left[1-\frac{1}{e^{(E_1-E_{Fp})/kT}+1}\right]$$

$$> \frac{1}{e^{(E_1-E_{Fp})/kT}+1}\cdot\left[1-\frac{1}{e^{(E_2-E_{Fn})/kT}+1}\right]$$

$$\Rightarrow e^{-(E_2-E_{Fn})/kT} < e^{-(E_{Fp}-E_1)/kT}$$

$$E_{Fn} - E_{Fp} > E_2 - E_1 \gtrsim E_g$$



Gain coefficient in semiconductor

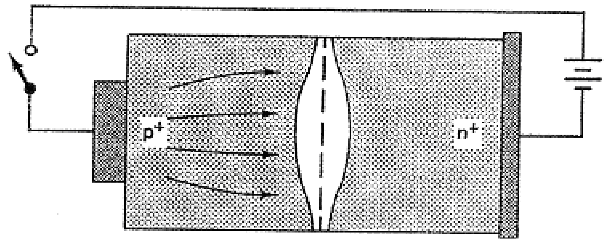
$$\frac{dN_{ph}}{dt} = B_{12}(N_2-N_1)\,\rho_{ph}(h\nu) \quad \leftarrow \text{two level system}$$

in semiconductor:

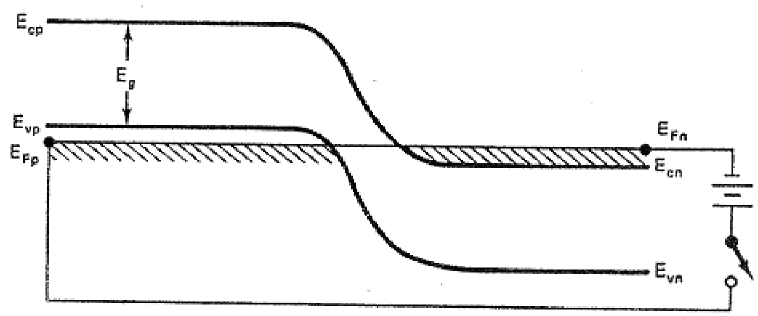
I_ν ← optical power, $\frac{\text{energy}}{\text{unit area}\cdot\text{sec}}$

$$\frac{dI_\nu}{dt} = h\nu\,\frac{dN_{ph}}{dt}\,(dx)$$

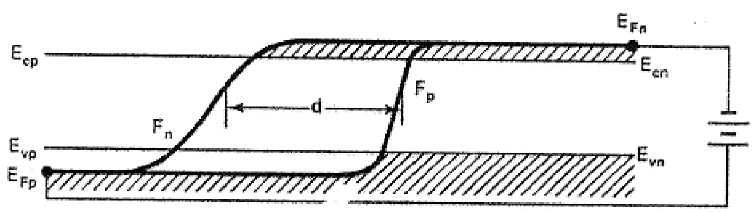
$$\frac{dI_\nu}{dx} = \frac{dI_\nu}{dt}\cdot\frac{dt}{dx} = \frac{n}{c}\cdot h\nu\,\frac{dN_{ph}}{dt}\cdot\Delta x$$


p+
n+

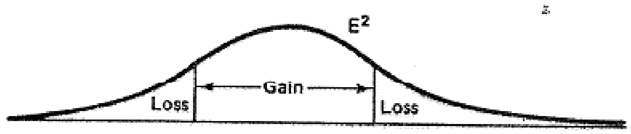
(a)


Ecp
Eg
Evp
EFp
EFn
Ecn
Evn

(b)


EFn
Ecp
Ecn
Fp
d
Fn
Evp
EFp
Evn

(c)


E2
Gain
Loss
Loss

(d)

if $r_1 = r_2 = R^{1/2}$

$$I = I_0 \frac{1}{(1-R)^2 + 4R\sin^2 n\beta L},$$

resonant condition

Maximum : $\beta L = m\pi$, $I = \frac{I_0}{(1-R)^2}$

minimum : $\beta L = m\pi + \frac{\pi}{2}$, $I = \frac{I_0}{(1+R)^2}$

$$I = \frac{I_0}{(1-R)^2 + 4R\sin^2\beta L}$$

$$= \frac{I_0/(1-R)^2}{1 + \frac{4R}{(1-R)^2}\sin^2 n\beta L}$$

$$F \equiv \frac{\pi R^{1/2}}{1-R} \Rightarrow I = \frac{I_0/(1-R)^2}{1 + \frac{4F^2}{\pi^2}\sin^2\beta L \cdot n} = \frac{I_0/(1-R)^2}{1 + \left(\frac{2F}{\pi}\sin n\beta L\right)^2}$$

when $\frac{2F}{\pi}\sin n\beta L = 1$, $I = I_{max} \cdot \left(\frac{1}{2}\right)$

$$\Delta\beta nL = \left(\frac{\pi}{2}\right)\cdot(F)^{-1} = \frac{\pi}{2F}$$

$$\Delta\left(\frac{2\pi}{\lambda}\right)\cdot nL = \frac{\pi}{2F}$$

$$\Delta\left(\frac{1}{\lambda}\right) = \frac{1}{4F}\cdot\frac{1}{nL} = \frac{1}{2F}\cdot\frac{1}{2nL}$$

$$\Rightarrow \Delta\nu = \frac{1}{2F}\cdot\left(\frac{c}{2nL}\right), \quad \Delta\lambda = \frac{1}{2F}\cdot\left(\frac{\lambda^2}{2nL}\right)$$

↑ spectrum width.

Example : For a cavity of 1mm long, calculate the R needed for a spectral width of 30 KHz

Longitude mode separation $\Delta\nu_m = 150\,\text{GHz}$

$$\Rightarrow \quad 2F = \frac{150\,\text{G}}{30\,\text{KHz}} = 5\times10^6 = \frac{2\pi\cdot R^{1/2}}{1-R}$$

$$\Rightarrow \quad R = 99.9999\%$$

4. Quantum Well Lasers

1). density of states

Quantum effect.

$k_z = \frac{2\pi}{a} n$

$E = \frac{\hbar^2 (k_x^2 + k_y^2)}{2m} + \frac{\hbar^2}{2m} k_z^2$

$= \frac{\hbar^2}{2m} \left[k_x^2 + k_y^2 + \left(\frac{2\pi}{a}\right)^2 n^2 \right]$

# of states available $k \rightarrow k + \Delta k$

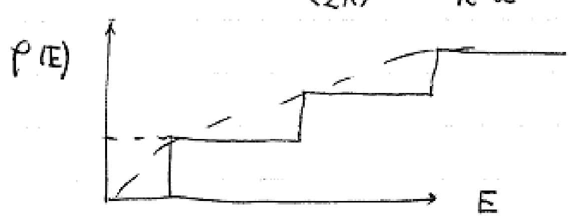
$k_{xy} + dk_{xy}$, k_z

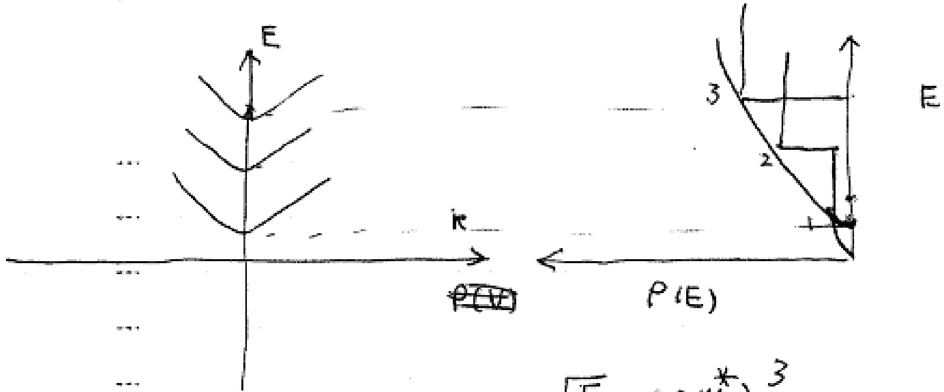
# of states available $N = \frac{\left(\frac{2\pi}{a}\right) 2\pi k_{xy} \cdot dk_{xy}}{\left(\frac{2\pi}{a}\right) \cdot \left(\frac{2\pi}{L_x}\right) \left(\frac{2\pi}{L_y}\right) S} = \rho(E)\, dE$

$\Rightarrow$ N of states available per unit ~~volume~~ area.

@ a specific $E \rightarrow \Delta E + E$

$\rho(E)\, dE = \left(\frac{1}{2\pi}\right) \cdot \frac{2m^*}{\hbar^2 a} dE = \frac{m^*}{2\hbar^2 \pi a} dE$





$$\rho(E)\Big|_{bulk} = \frac{\sqrt{E}}{4\pi^2}\left(\frac{2m^*}{\hbar^2}\right)^{\frac{3}{2}} = \rho(E)\Big|_{well}\ \frac{a}{2\pi}\sqrt{k_x^2+k_y^2+\left(\frac{2\pi}{a}n\right)^2}$$

$$\rho(E)\Big|_{well} = \frac{m^*}{2\pi\hbar^2}\cdot\left(\frac{1}{a}\right)$$

Reduced density of states for optical Transition.

$$\rho_{red}(E)\Big|_{Q.W} = \frac{m_r^*}{2\pi\hbar^2}\left(\frac{1}{a}\right)(h\nu - E_g).$$

Note : 1). in Q. W. Less injection current needed to reach a energy level ← Low threshold.

2). $\rho_{red}(h\nu)\Big|_{Q.W}$ depends on well thickness

2). density of states & reduced density of States in Quantum Dots.

$$E = \left(\frac{2\pi}{L_x} n_x\right)^2 + \left(\frac{2\pi}{L_y} n_y\right)^2 + \left(\frac{2\pi}{L_z} n_z\right)^2$$

discrete energy level.

$$\rho(E)\, dE = \delta(E - E_{level}) N/V_0$$

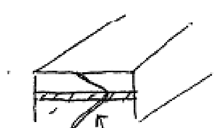
$\frac{N}{V_0}$ ← Numbers of QDs per unit volume.

Example: calculate reduced density of state in a 100 Å GaAs Quantum Well

$$\rho_{red}(E) = \frac{m_r^*}{\pi \hbar^2 L_z} = 2\times10^{19}\ (eV)^{-1} \cdot cm^{-3}$$

3). Multi-quantum Well (MQW).

Γ ← confinement factor.



$$\Gamma = \frac{a}{d}$$

a ← QW width

d ← optical beam width.

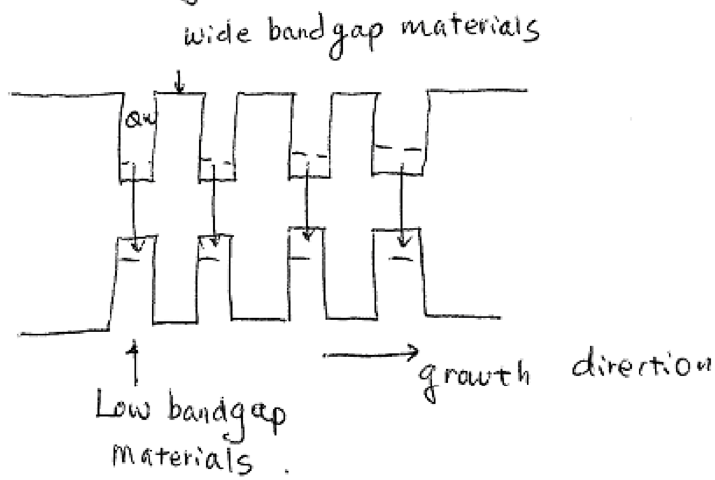
↑ waveguid size.

For single QW, Γ is small $\sim \frac{100Å}{1\mu m} = 10^{-2}$.

⇒ optical beam not effectively amplified.

MQW, $\Gamma_{MQW} = n\Gamma_{single}$

4). Band diagram of MQW



Example.

Consider GaAs QW. $m_e^* = 0.07 m_e$.

Calculate 1). first two electron energy levels for QW thickness = 10nm, 2). hole energy below E_v $m_h^* = 0.50 m_e$. 3). Change of emission wavelength compared with bulk GaAs $E_g = 1.42$ eV

Solution: 1).

$$\varepsilon_n = \frac{(\hbar k)^2}{2m_e^*} = \frac{\hbar^2}{2m_e^*}\left(\frac{2\pi}{d}n\right)^2$$

$$= \frac{h^2 \cdot n^2}{8m_e^* d^2} = \begin{cases} 0.0537 \text{ eV}, & n=1 \\ 0.215 \text{ eV}, & n=2 \end{cases}$$

2).

$$\varepsilon_v = \frac{h^2 n^2}{8m_h^* d^2} = 0.0075 \text{ eV}.$$

much smaller than conduction band

3). QW. emission wavelength

$$\lambda_{QW} = \frac{h\nu}{E_g + \varepsilon_1 + \varepsilon_1'} = 839 \text{ nm}$$

bulk emission wave length

$$\lambda_{bulk} = \frac{h\nu}{E_g} = 874 \text{ nm}.$$

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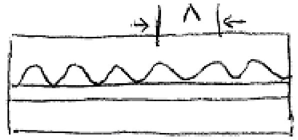
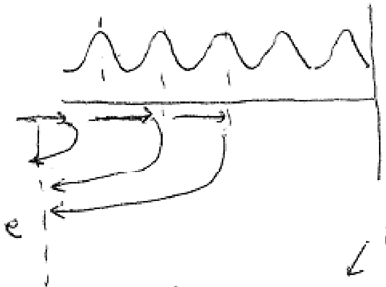
5. distribute feedback Laser (DFB Laser)





Constructively interference

~~[illegible]~~

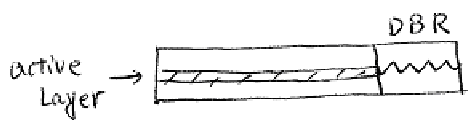
$$m \lambda = 2 \Lambda n$$ (n: index)

$$\Lambda = \frac{m\lambda}{2n}$$ ← period, m is the order of Grating

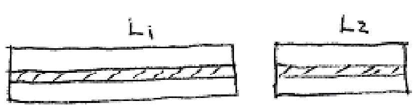
$$\Rightarrow \Delta\lambda_m = \frac{\lambda_B^2}{2nL}$$

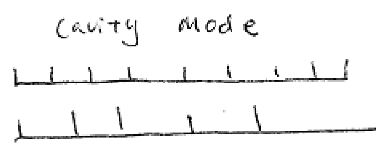
$$\lambda_m = \lambda_B \pm \frac{\lambda_B^2}{2nL}(m+1), \quad m = 0, 1, 2, \cdots$$

Distribute Bragg reflector ~~mirror~~ (DBR)

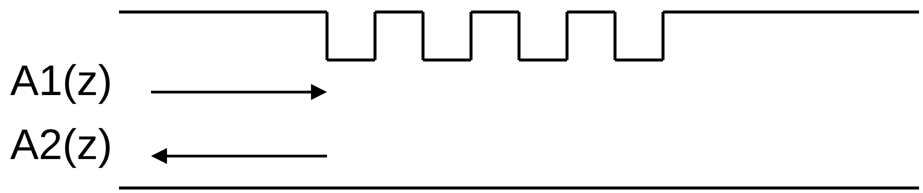


6. Cleaved - coupled - cavity (C^3).





Waveguide gratings



$$\frac{dA_1(z)}{dz} = i\kappa A_2(z)$$

$$\frac{dA_2(z)}{dz} = -i\kappa A_1(z)$$

$$\frac{d\,|A_1(z)|^2}{dz} = A_1^*(z)\frac{dA_1(z)}{dz} + A_1(z)\frac{dA_1^*(z)}{dz}$$

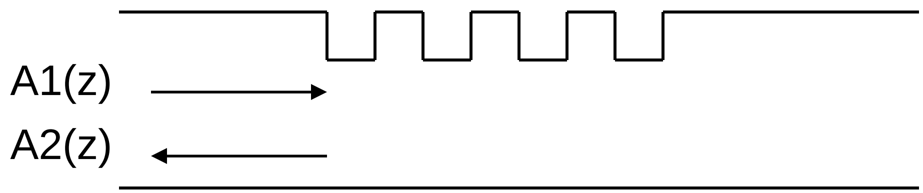
$$= A_1^*(z) i\kappa A_2(z) + A_1(z)(-i\kappa A_2^*(z))$$

$$\frac{d\,|A_2(z)|^2}{dz} = A_2^*(z)\frac{dA_2(z)}{dz} + A_2(z)\frac{dA_2^*(z)}{dz}$$

$$= A_2^*(z)(-i\kappa A_1(z) + A_2(z)(i\kappa A_1^*(z))$$

$$\frac{d}{dz}\left(\left|A_1(z)\right|^2 - \left|A_2(z)\right|^2\right) = 0$$

Waveguide gratings



$$\frac{dA_1(z)}{dz} = i\kappa A_2(z)$$

$$\frac{dA_2(z)}{dz} = -i\kappa A_1(z)$$

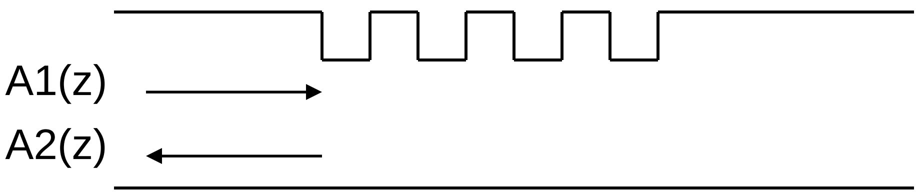
$$\frac{d^2 A_1(z)}{dz^2} = i\kappa \frac{d}{dz} A_2(z) = \kappa^2 A_1(z)$$

$$A_1(z) = A\cosh(\kappa z) + B\sinh(-\kappa z)$$

$$A_2(z) = C\cosh(\kappa z) + D\sinh(-\kappa z)$$

A, B, C, D are determined by the initial conditions

Waveguide gratings



A1(z)$|_{z=0}$ = A1(0)

A2(z))$|_{z=L}$ = 0

$$\frac{dA_1(z)}{dz} = i\kappa A_2(z)$$

$$\frac{dA_2(z)}{dz} = -i\kappa A_1(z)$$

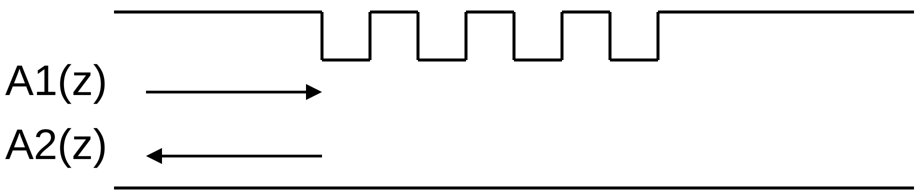
$$A_1(z) = A1(0)\cosh(\kappa z) + B\sinh(\kappa z)$$

$$A1(0)\sinh(\kappa L) + B\cos(\kappa z L) = 0$$

$$A_1(z) = A1(0)\left[\cosh(\kappa z) - \frac{\sinh(\kappa L)}{\cosh(\kappa L)}\sinh(\kappa z)\right] = A1(0)\frac{\cosh\kappa(z-L)}{\cosh(\kappa L)}$$

$$A_2(z) = A_1(0)\frac{\sinh\kappa(z-L)}{\cosh(\kappa L)}$$

Waveguide gratings



$A1(z)|_{z=0} = A1(0)$

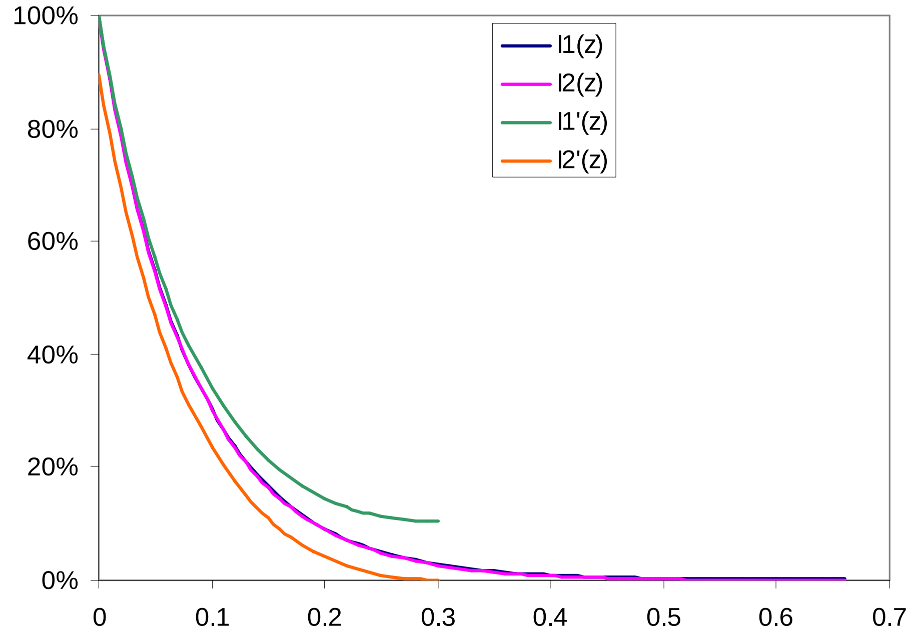
$A2(z)\,)|_{z=L} = 0$

$$\frac{dA_1(z)}{dz} = i\kappa A_2(z)$$

$$\frac{dA_2(z)}{dz} = -i\kappa A_1(z)$$

$$A_1(z) = A1(0)\frac{\cosh\kappa(z-L)}{\cosh(\kappa L)}$$

$$A_2(z) = A_1(0)\frac{\sinh\kappa(z-L)}{\cosh(\kappa L)}$$



Example :

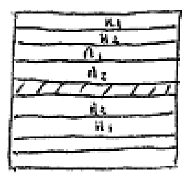
a DFB Laser has grating period $\Lambda = 0.22\,\mu m$ and grating length of $400\,\mu m$, $n = 3.5$, first order

Calculate λ_B. λ_B.

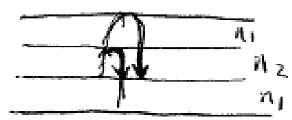
$$\lambda_B = \frac{2\Lambda n}{q} = 2\cdot\Lambda\cdot n = 1.54\ \mu m$$

$$\lambda_m = \lambda_B \pm \frac{\lambda_B^2}{2nL}(m+1) \Rightarrow \lambda = \begin{cases} 1.5392\ nm \\ 1.5408\ nm \end{cases}$$

I. Vertical cavity Surface emitting Laser (VCSEL)



active layer



$$2n_1 d_1 = \frac{\lambda}{2}, \quad 2n_2 d_2 = \frac{\lambda}{2}$$

$$\Rightarrow d_1 = \frac{\lambda}{4n_1}, \quad d_2 = \frac{\lambda}{4n_2}$$ ← Quarter Wavelength Layer.

Transmission & reflectivity of DBR mirrors.

Can be calculated using transmission Matrix.

- Low power output. → short gain
- design issue,

$$g = \alpha + \frac{1}{2L} \ln \frac{1}{R_1 R_2}$$

since L is usually very small ~ 1 μm

R_1, & R_2 have to be very high. ~ 99.99%.

- application of VCSEL.
  - Low threshold, Low power Laser
  - Low cost.

hw # 4.11, 4.13, 4.14, 4.15, 4.16

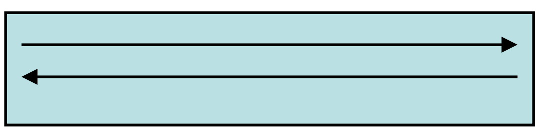
Rate equations:

$$\begin{cases} \dfrac{dN}{dt} = \dfrac{J}{qd} - \dfrac{N}{\tau} - \Omega(N - N_0)N_{ph} \\[2ex] \dfrac{dN_{ph}}{dt} = \Omega(N - N_0)N_{ph} + \dfrac{\theta N}{\tau_r} - \dfrac{N_{ph}}{\tau_{ph}} \end{cases}$$

θ Fraction of spontaneous into the specific mode

τ_{ph} Photon lifetime

$$\tau_{ph} = \frac{2n_r L}{c}\frac{1}{1 - R_1 R_2}$$



$$\frac{dN_{ph}}{dt} = -\frac{N_{ph}}{\tau_{ph}}$$

$$N_{ph}\left(t = \frac{2Ln_r}{c}\right) = N_{ph}(t=0)e^{-\frac{t=\frac{2Ln_r}{c}}{\tau_{ph}}} = N_{ph}(t=0)R_1R_2$$

$$\frac{t = \dfrac{2Ln_r}{c}}{\tau_{ph}} = -\ln(R_1R_2) \qquad \tau_{ph} = \frac{2Ln_r}{c\ln\left(\dfrac{1}{R_1R_2}\right)} \qquad \ln\left(\frac{1}{R_1R_2}\right) \approx 1 - R_1R_2$$

Rate equations:

$$\begin{cases} \dfrac{dN}{dt} = \dfrac{J}{qd} - \dfrac{N}{\tau} - \Omega(N - N_0)N_{ph} \\ \dfrac{dN_{ph}}{dt} = \Omega(N - N_0)N_{ph} + \dfrac{\theta N}{\tau_r} - \dfrac{N_{ph}}{\tau_{ph}} \end{cases}$$

θ Fraction of spontaneous into the specific mode

τ_{ph} Photon lifetime

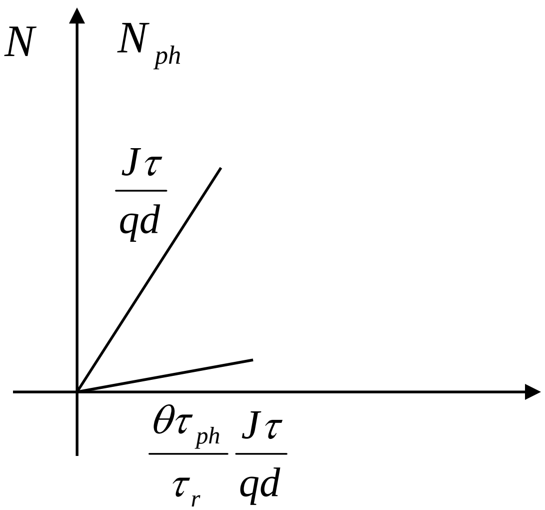
Steady state:

$$\begin{cases} \dfrac{J}{qd} = \dfrac{N}{\tau} + \Omega(N - N_0)N_{ph} \\ \dfrac{\theta N}{\tau_r} = \dfrac{N_{ph}}{\tau_{ph}} - \Omega(N - N_0)N_{ph} \end{cases}$$

Below threshold: $N_{ph} \approx 0$

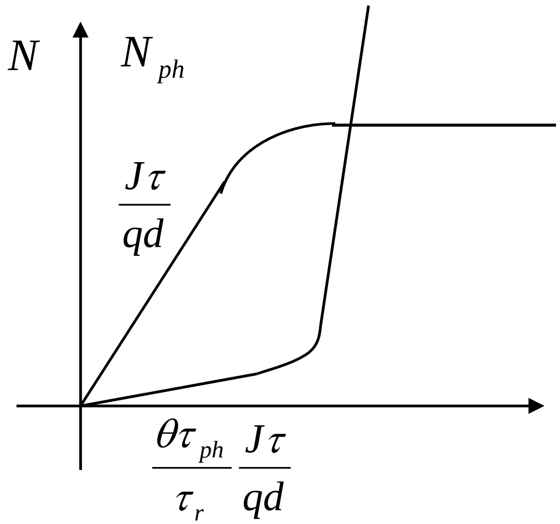
$$\begin{cases} \dfrac{J}{qd} \approx \dfrac{N}{\tau} \\ \dfrac{N_{ph}}{\tau_{ph}} = \dfrac{\theta N}{\tau_r} = \dfrac{\theta J \tau}{\tau_r qd} \end{cases}$$

$$N_{ph} = \frac{\theta J \tau \tau_{ph}}{\tau_r qd}$$



Steady state:

$$\begin{cases} \dfrac{J}{qd} = \dfrac{N}{\tau} + \Omega(N - N_0)N_{ph} \\[2ex] \dfrac{\theta N}{\tau_r} = \dfrac{N_{ph}}{\tau_{ph}} - \Omega(N - N_0)N_{ph} \end{cases}$$



Above threshold: $\dfrac{\theta N}{\tau_r} << \Omega(N - N_0)N_{ph}$

$$\begin{cases} \dfrac{J}{qd} = \dfrac{N}{\tau} + \Omega(N - N_0)N_{ph} \\[2ex] \dfrac{N_{ph}}{\tau_{ph}} = \Omega(N - N_0)N_{ph} \end{cases}$$

$$\frac{J}{qd} = \frac{N}{\tau} + \frac{N_{ph}}{\tau_{ph}}$$

$$N = N_0 + \frac{1}{\tau_{ph}\Omega} = \overline{N}$$

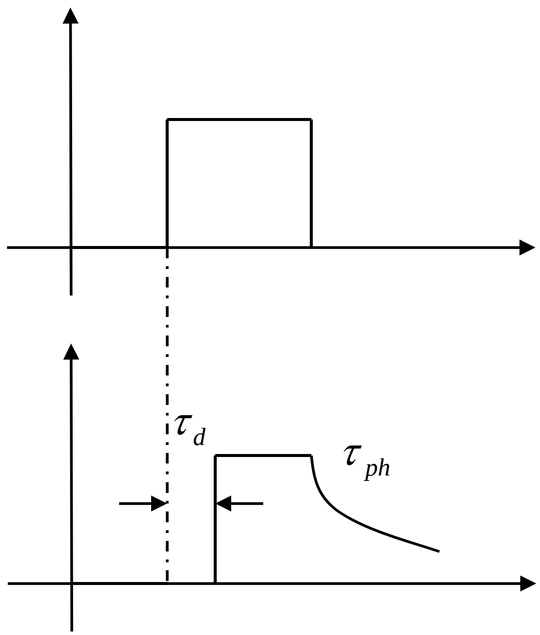
$$N_{ph} = \frac{J\tau_{ph}}{qd} - \frac{N\tau_{ph}}{\tau} = \frac{\tau_{ph}}{qd}(J - J_{th})$$

$$J_{th} = \frac{\overline{N}qd}{\tau}$$

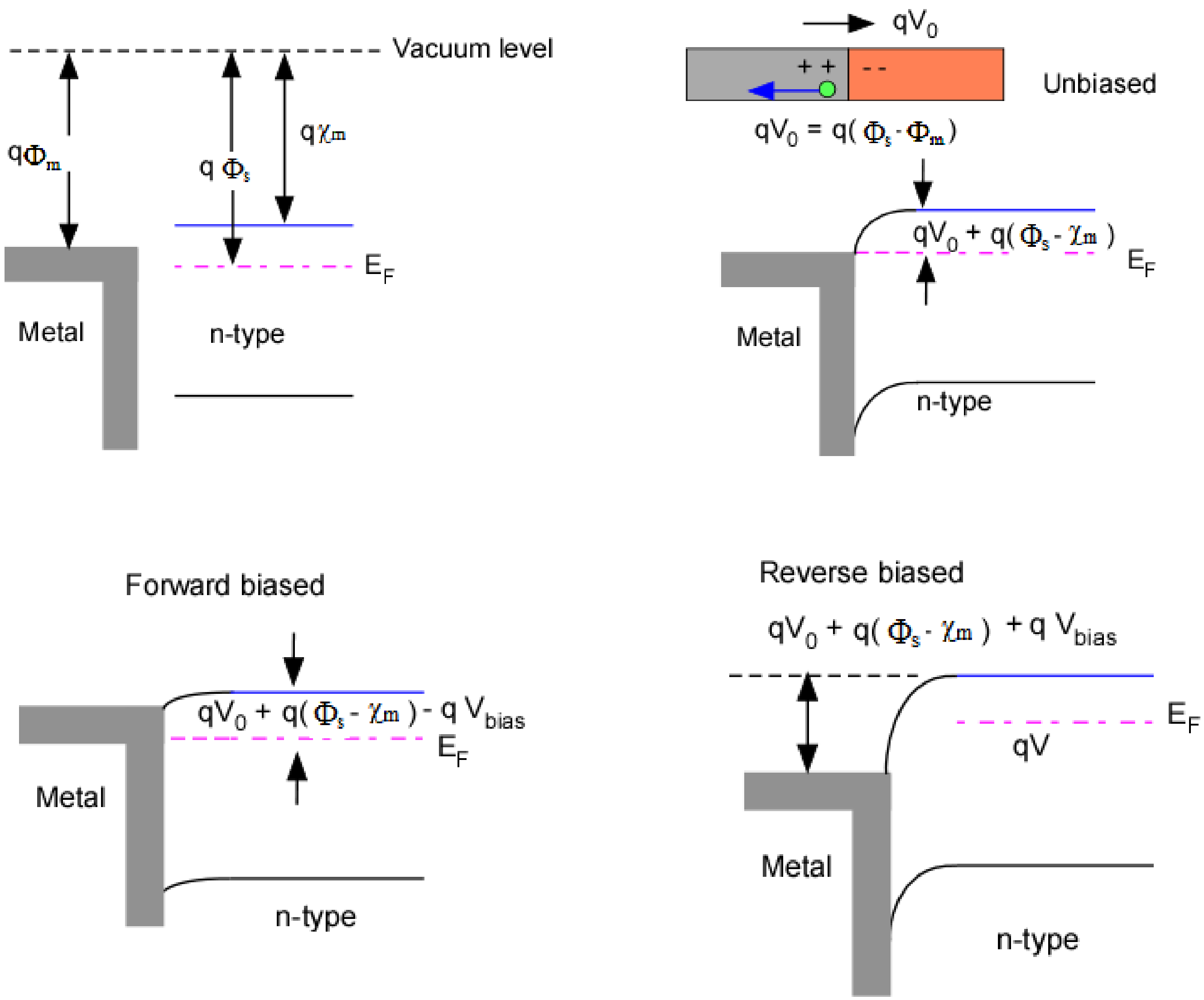
Turn-on delay

$$\frac{dN}{dt} = \frac{J}{qd} - \frac{N}{\tau} - \Omega(N - N_0)N_{ph}$$

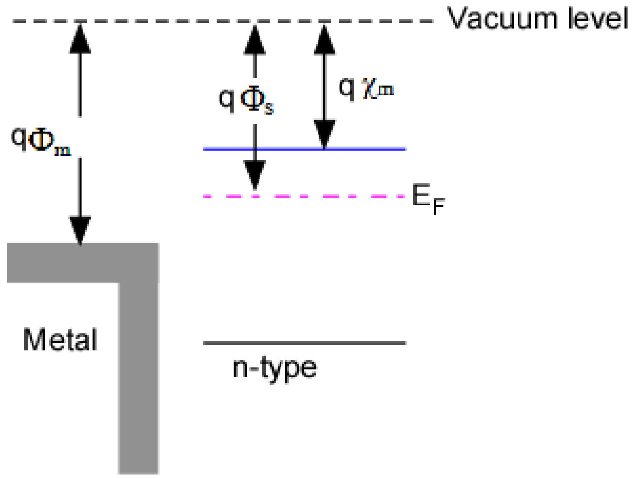
$$\frac{dN}{dt} = \frac{J}{qd} - \frac{N}{\tau} \qquad \tau_d = N_{th} / \frac{J}{qd} = \frac{\overline{N}}{J/qd} = \frac{\tau J_{th}/qd}{J/qd} = \tau\frac{J_{th}}{J}$$

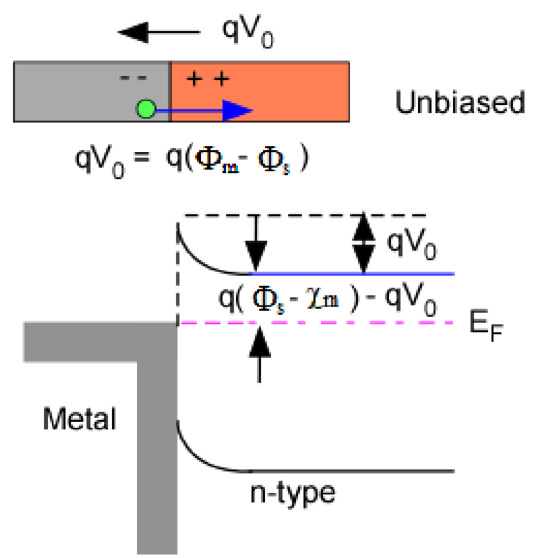


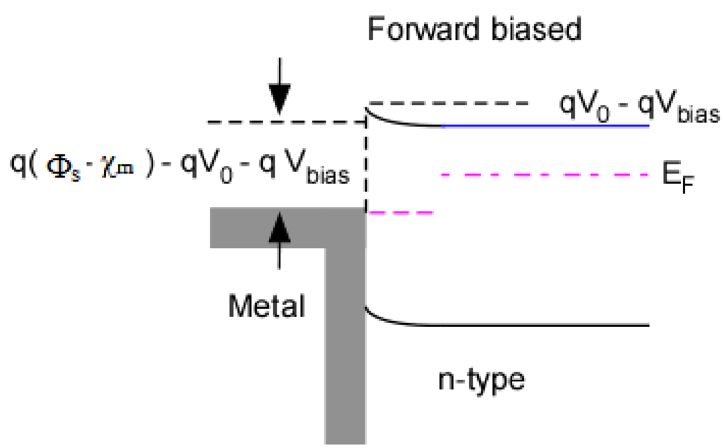
Ohmic contact

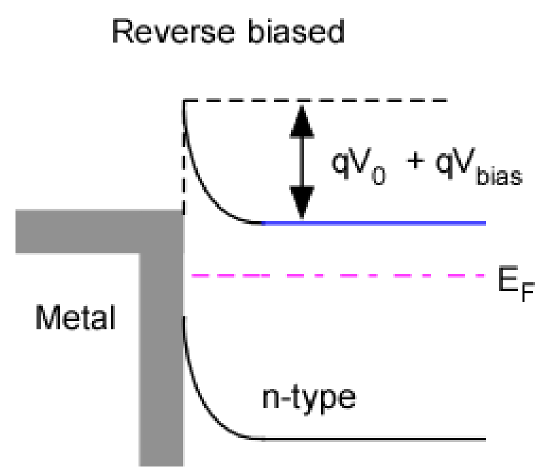


Schottky barrier

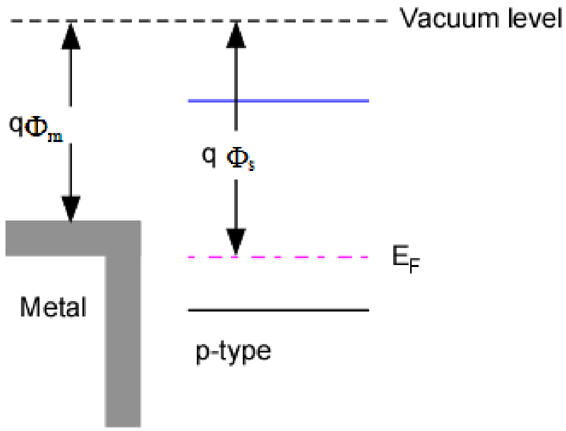


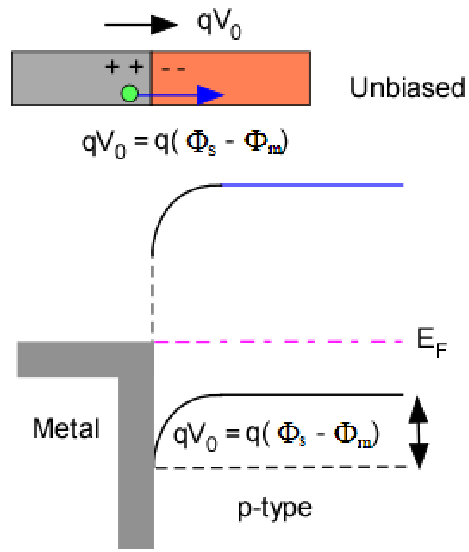


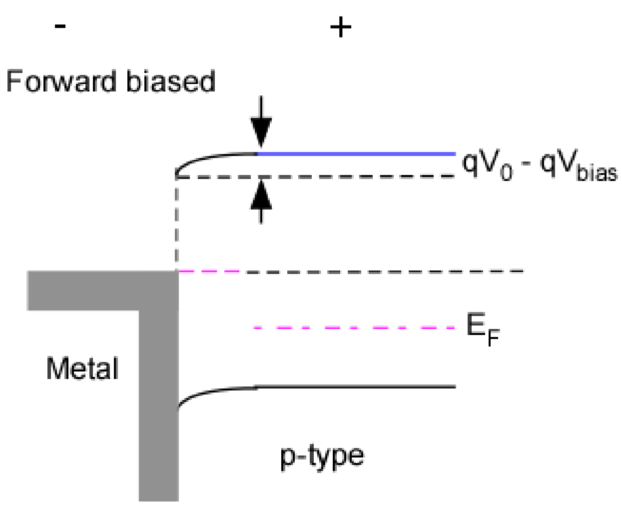


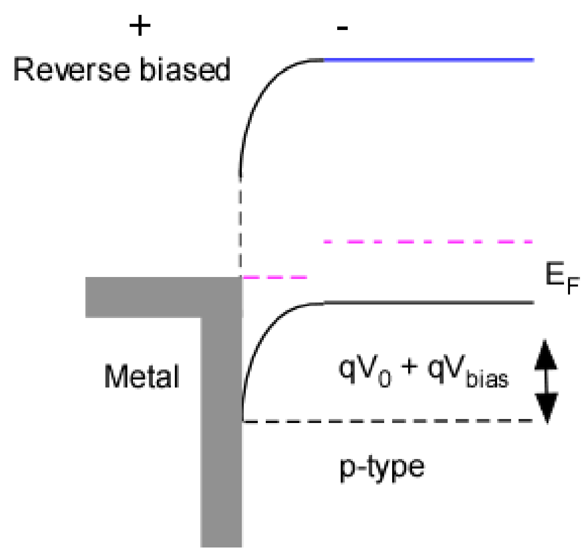


Schottky barrier

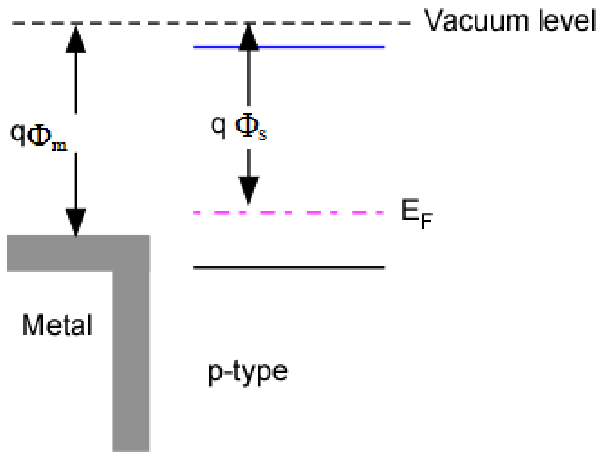


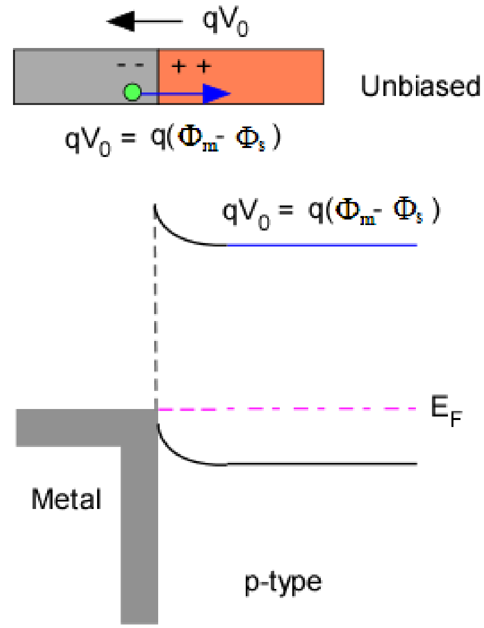


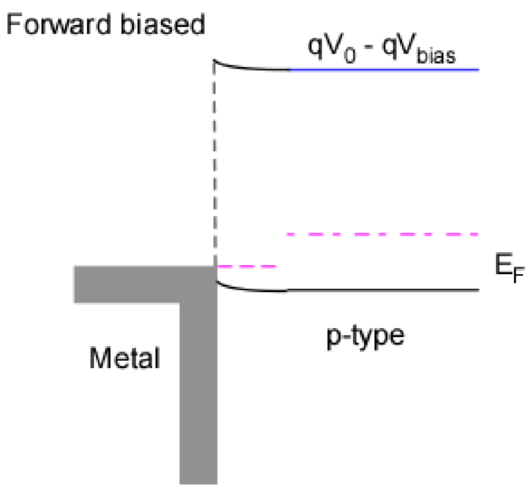


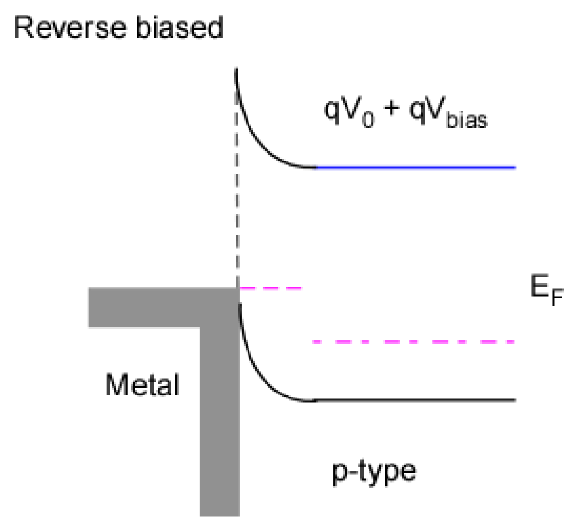


Ohmic contact









typical method for forming ohmic contacts is by doping the semiconductor heavily in the contact region, which reduces depletion width. When depletion width small enough carriers can be tunneling through the barriers.

hw: 1. A schottky barrier is formed between a metal having a work function of 4.3 eV and a p-type Si with electron affinity = 4 eV. The acceptor doping in Si is $10^{17}\ cm^{-3}$ (a) draw the equilibrium band diagram, show a numerical value for qV_0

(b) draw the band diagram for 0.3 V forward bias. Repeat 2 V reverse bias.

2. what's the conductivity of a piece of Ge ($n_i = 2.5\times10^{13}\ cm^{-3}$) doped with $5\times10^{13}\ cm^{-3}$ donors $D_n = 100\ cm^2/s$. If the electron affinity of Ge = 4.0 eV and we put down a metal electrode with work function = 4.5 eV. what's the work function difference Do you expect this to be a schottky or an Ohmic contact ?