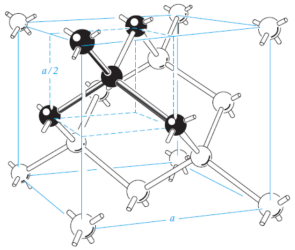
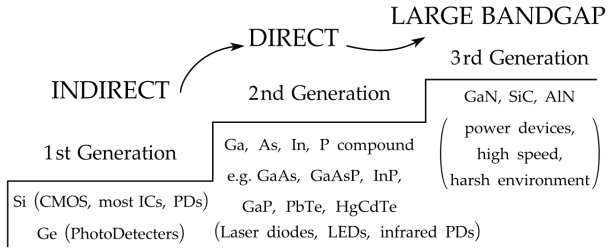
Semiconductor Midterm CheatSheet (chapter1–4)

	$e = 1.602 \times 10^{-19}$C
Boltzmann's constant	$k = 8.62 \times 10^{-5}$eV/K $= 1.38 \times 10^{-23} J/K$
ppm/ppb/ppt	partpermillion/billion/trillion

Si	Ge
E_g(Si) = 1.1eV	E_g(Ge) = .67eV
5×10^{22}atoms/cm^3	
$n_i \approx 1.5 \times 10^{10}$cm^{-3}	$n_i = 2.4 \times 10^{13}$cm^{-3}
$\mu_n = 1350$cm^3/V-s, $\mu_p = 480$cm^3/V-s	$\mu_n = 3900$cm^3/V-s, $\mu_n = 1900$cm^3/V-s

three types of solids: Crytalline(silicon wafer), Polycrytalline(Poly-Si), Amorphous(glass) Primitive Cell, Unit Cell,Miller Indices (hkl) Diamond Lattice, Zinc Blende Structure, Wurtzite Structure. packing fraction $= \frac{V_{\text{atom}} \cdot N_{\text{atom}}}{V_{\text{cell}}} = \frac{\frac{4}{3}\pi(\frac{d_{\text{atom,min}}}{2})^3 \cdot N_{\text{atom}}}{(\text{lattice constant})^3}$





Czochralski Growth (CZ) for Si:
$k_d = \frac{C_s}{C_l} = \frac{\text{[impurity in solid]}}{\text{[impurity in liquid]}}$,MASS $= \frac{\text{[number of atoms]}}{\text{(Avogadro's constant)}}$(atomic mass)
Liquid Encapsulated Czochralski Growth (LEC), Bridgman Growth (BR) for GaAs

Atom structure

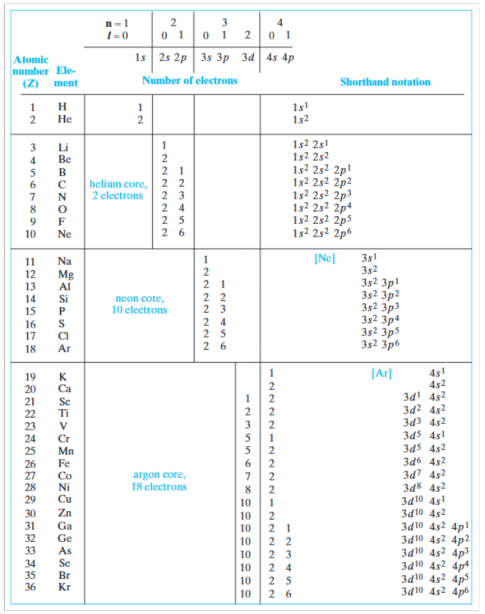
Heisenberg Uncertainty Principle: $(\Delta x)(\Delta p_x) \geq \hbar/2$, $(\Delta E)(\Delta t) \geq \hbar/2$ The probability sum of finding a particle over the entire space $\int_{-\infty}^{\infty} \Psi^* \Psi \mathrm{d}x\mathrm{d}y\mathrm{d}z = 1$. Average value $\langle Q \rangle = \int_{-\infty}^{\infty} \Psi^* Q_{\text{op}} \Psi \mathrm{d}x\mathrm{d}y\mathrm{d}z$, where Q_{op} is defined as,

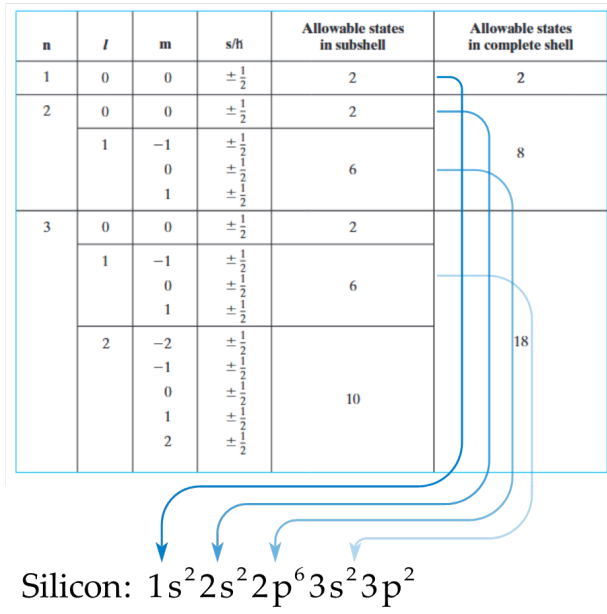
classical variable	quantum operator
$x, f(x)$	$x, f(x)$
momentum $p(x)$	$\frac{\hbar}{j}\frac{\partial}{\partial x}$
energy E	$-\frac{\hbar}{j}\frac{\partial}{\partial t}$

Schrödinger equation $E_k(\frac{p^2}{2m}) + E_p(V) = E_{\text{total}}(E)$, by replacing p and E with operators, we can derive $-\frac{\hbar^2}{2m}\frac{\partial^2 \psi(x)}{\partial x^2}\phi(t) + V(x)\psi(x)\phi(t) = -\frac{\hbar}{j}\psi(x)\frac{\partial \phi(t)}{\partial t}$.

Quantum Numbers for $\Psi(r,\theta,\phi) = R_n(r)\Theta_l(\theta)\Phi_m(\phi)$		
n	principal quantum number, shell	$1, 2, \dots$
l	angular momentum quantum number, subshell	$0, 1, \dots, n-1$ $(s, p, d, f, g, \dots)$
m	magnetic quantum number, orientation of orbitals (within the subshells)	$0, \pm 1, \dots, \pm(n-1)$
s	electron spin	$\pm\frac{1}{2}$

Pauli exclusion principle No two electrons in an interacting system with the same n, l, m, s. The only two electrons with same n, l, m must have opposite spins





Energy Band and Carriers

Octet Rule, LCAO(antisymmetric/anti-bonding, parallel spin, high energy; symmetric/bonding); hybridization (Paoli exclusion principle, split energy levels → continuous energy bands) **E-k diagram**: parabolic $E = \frac{\hbar^2}{2m^*}k^2 + E_c$, $k = \frac{2\pi}{\lambda}$

effective mass	$m^* = \frac{\hbar^2}{\mathrm{d}^2E/\mathrm{d}k^2}$
density-of-states (Si)	conductivity
geometric mean	harmonic average
$(m_n^*)^{3/2} = 6(m_l m_t^2)^{1/2}$	$\frac{1}{m_n^*} = \frac{1}{3}(\frac{1}{m_l} + \frac{2}{m_t})$

Energy Levels and Concentrations

carrier concentrations = (Fermi distribution)(available states density)

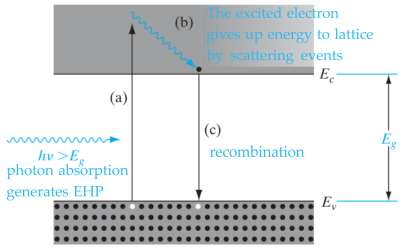
$$n_0 = \int_{E_c}^{\infty} f(E)N(E)\mathrm{d}E = N_c f(E_c) \approx N_c e^{-(E_c - E_F)/kT}$$

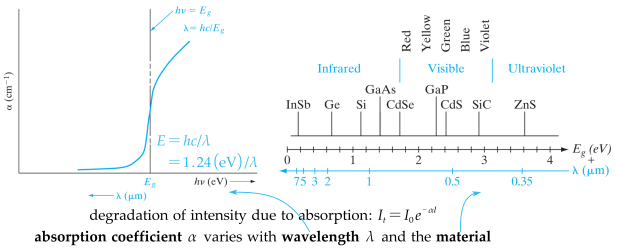
$$p_0 = \int_0^{E_v} (1 - f(E))N(E)\mathrm{d}E = N_v(1 - f(E_v)) \approx N_v e^{-(E_F - E_v)/kT}$$

intrinsic $\begin{cases} n_i = \sqrt{N_c N_v}e^{-E_g/2kT} \\ n_0 p_0 = n_i^2 \end{cases}$ doped, equilibrium $\begin{cases} n_0 = n_i e^{(E_F - E_i)/kT} \\ p_0 = n_i e^{(E_i - E_F)/kT} \end{cases}$

excess carriers, quasi-Fermi level $\begin{cases} n = n_i e^{(F_n - E_i)/kT} \\ p = n_i e^{(E_i - F_p)/kT} \end{cases}$ (for majority carriers $F_n/F_p \approx E_i$)

Excess Carriers



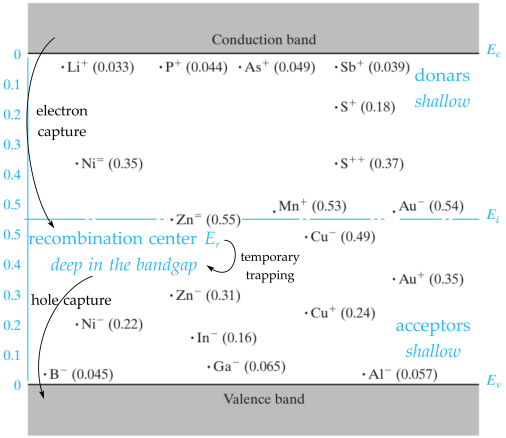


Fluorescence (direct recombination) most energy directly into photon, fast(10^{-10}s)
Phosphorescence (indirect recombination) needs extra (deep) energy level between E_g, gives smaller $h\nu$, slow(s); application: UV excites phospors to generate white light instead of smooth spectrum
equilibrium no stimulate
steady state can have stimulation inputs, stabilises after a long time

Recombination and Generation Balance

excess carrier concentrations $\delta n(t) = \delta p(t)$, initial values $\Delta n = \Delta p$.

low-level injection (linear)	n-type	p-type
$\frac{\mathrm{d}\delta n(t)}{\mathrm{d}t} = -\alpha_r(n_0+p_0)\delta n(t)$ minority carrier lifetime $\tau_n = \frac{1}{\alpha_r(n_0+p_0)}$	$\delta n(t) = \Delta n e^{-t/\tau}$ $\tau_n = (\alpha_r n_0)^{-1}$	$\tau_p = (\alpha_r p_0)^{-1}$
$g_{\text{op}} = \alpha_r[(n_0+p_0)\delta n(t) + \delta n^2(t)]$	$\delta n = \delta p = g_{\text{op}}\tau_n$	



photoconductive decay:

$$\sigma(t) = q[n(t)\mu_n + p(t)\mu_p]$$

$$\Delta\sigma = qg_{\text{op}}(r_n\mu_n + r_p\mu_p) = q(\delta n\mu_n + \delta p\mu_p)$$

Direct Recombination:

net change = thermal generation − recombination

$$\frac{\mathrm{d}n(t)}{\mathrm{d}t} = \alpha_r n_i^2 - \alpha_r n(t)p(t)$$
$$= -\alpha_r[(n_0+p_0)\delta n(t) + \delta n^2(t)]$$

steady state EHP G–R balance:

$$\text{generation} = \text{recombination}$$
$$[\text{equilibrium}]G(T) = \alpha_r n_0 p_0 = \alpha_r n_i^2$$
$$[\text{steady state}]G(T) + g_{\text{op}} = \alpha_r n_0 p_0 + \alpha_r[(n_0+p_0)\delta n(t) + \delta n^2(t)]$$

Drift and Diffusion

Trade − off:
high $N_a, N_d \Rightarrow$
high σ and low μ_n, μ_p

(at equilibrium)

$$\langle v_x \rangle = -\mu_n \mathscr{E}_x = -\frac{q\bar{t}}{m_n^*}\mathscr{E}_x$$

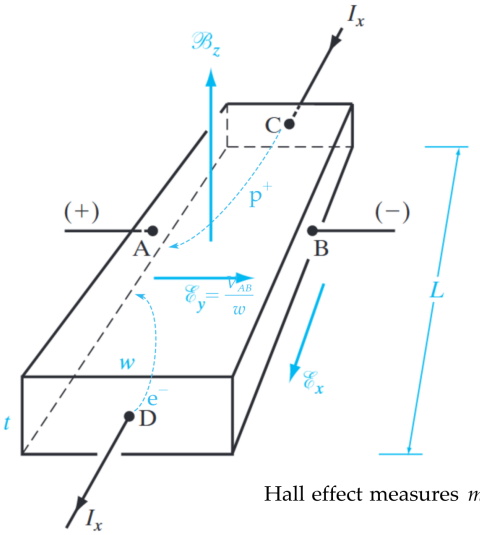
mean free time $\bar{t}$
mobility μ_n, μ_p
drift current density J_x
conductivity σ

electric force accelerates $\frac{\mathrm{d}p_x}{\mathrm{d}t} = -nq\mathscr{E}_x$

$$J_x = q(n\mu_n + p\mu_p)\mathscr{E}_x = \sigma\mathscr{E}_x$$

$$R = \frac{L}{wt}\rho = \frac{L}{wt}\frac{1}{\sigma}$$

collision decelerates $\frac{\mathrm{d}p_x}{\mathrm{d}t} = -\frac{p_x}{\bar{t}}$



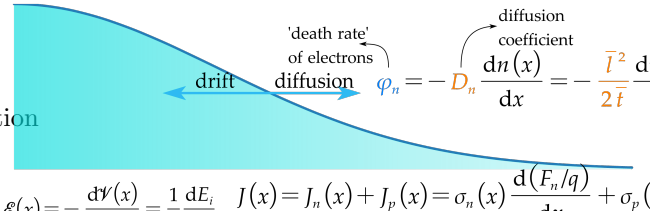
at steady state

$$\mathscr{E}_y = v_x\mathscr{B}_z = \frac{1}{qp_0}J_x\mathscr{B}_z = R_H J_x\mathscr{B}_z$$

using Hall effect to determine:
$V_{AB} < 0$, n − type; $V_{AB} > 0$, p − type
using Hall effect to measure:

$$p_0 = \frac{1}{qR_H} = \frac{1}{q}\frac{\mathscr{B}_z J_x}{\mathscr{E}_y} = \frac{I_x\mathscr{B}_z}{qtV_{AB}}$$
$$\rho = \frac{Rwt}{L} = \frac{V_{CD}wt}{I_x L}$$
$$\mu_p = \frac{\sigma}{qp_0} = \frac{R_H}{\rho}$$

Hall effect measures *majority* carrier mobility



Einstein relation:

$$\frac{D}{\mu} = \frac{kT}{q} \simeq 0.026\,\text{V}$$

for n/p type at equilibrium

$$\mathscr{E}(x) = -\frac{\mathrm{d}\mathscr{V}(x)}{\mathrm{d}x} = \frac{1}{q}\frac{\mathrm{d}E_i}{\mathrm{d}x}$$

$$J(x) = J_n(x) + J_p(x) = \sigma_n(x)\frac{\mathrm{d}(F_n/q)}{\mathrm{d}x} + \sigma_p(x)\frac{\mathrm{d}(F_p/q)}{\mathrm{d}x}$$
$$= \text{drift}(\mathscr{E}) + \text{diffusion}(\nabla n/p)$$
$$= q\mu_n n\mathscr{E} + qD_n\frac{\mathrm{d}n}{\mathrm{d}x} + q\mu_p p\mathscr{E} - qD_p\frac{\mathrm{d}p}{\mathrm{d}x}$$

minority carrier diffusion currents can be significant

diffusion + drift

$$\varphi_p = -D_p\frac{\mathrm{d}p(x)}{\mathrm{d}x} = -\frac{\bar{l}^2}{2\bar{t}}\frac{\mathrm{d}p(x)}{\mathrm{d}x}$$

doping (N_d/N_a) or putting together different semiconductors

gradient of $n/p, E_i$

built − in field $\mathscr{E}(x)$