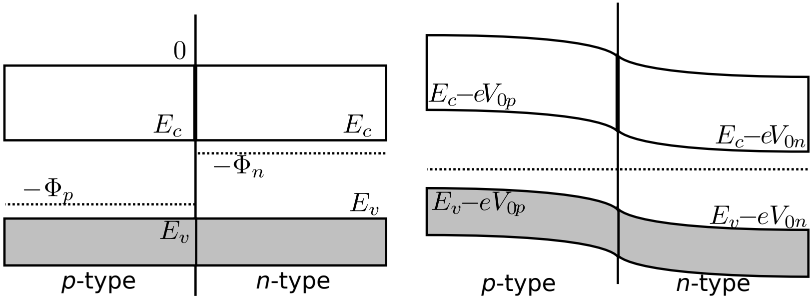
MTLE-6120: Advanced Electronic Properties of Materials

Semiconductor p-n junction diodes

Reading:

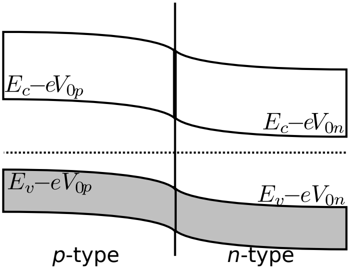
- Kasap 6.1 - 6.5, 6.9 - 6.12

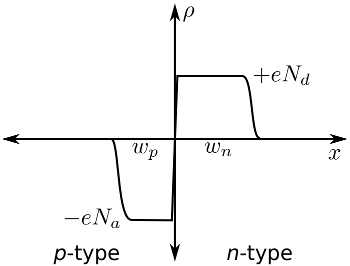
Metal-semiconductor contact potential



- Same semiconductor on both sides, different doping
- Bands line up perfectly, but Fermi level does not
- Bands bend to line up Fermi level
- Equal doping $N_a = N_d \Rightarrow$ symmetric bending
- In general, contact potential shared between both sides
- Extreme limits: one side $p+$ or $n+$, $\sim$ Schottky junction

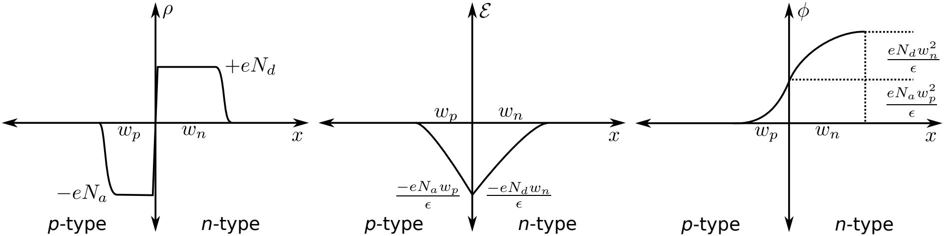
Depletion region charge





- Far from junction, $E_F = E_{F0} \quad \Rightarrow \quad \rho = 0$
- Approaching junction, E_F first deviates $\sim k_B T$ from E_{F0}:
  Small deviation from neutral $\Rightarrow$ Debye screening regime
- Once E_F more than few $k_B T$ away from E_{F0} (towards center of gap):
  $n \ll N_d$ (or $p \ll N_a$) $\Rightarrow$ depletion; they were equal in neutral case
- Across junction, E_F has to cross almost entire gap $\gg k_B T$
- Therefore, depleted width $\gg$ width where Debye screening applicable
- Assume $\rho = +eN_d$ for width w_n on n-side,
  $-eN_a$ for width w_p on p-side, and 0 elsewhere

Depletion region field and potential



- Neutrality of junction $\Rightarrow \quad N_a w_p = N_d w_n$
- Solve for electric filed using $\nabla \cdot \vec{\mathcal{E}} = \mathcal{E}'(x) = \rho(x)/\epsilon$
- Solving from left, $\mathcal{E}(x) = -eN_a(w_p + x)/\epsilon$ for $x > -w_p$ (0 otherwise)
- Solving from right, $\mathcal{E}(x) = -eN_d(w_n - x)/\epsilon$ for $x < w_n$ (0 otherwise)
- Peak field $\mathcal{E}(0) = -eN_a w_p/\epsilon = -eN_d w_n/\epsilon$
- Solve for potential using $\nabla\phi = \phi'(x)\hat{x} = -\mathcal{E}(x)\hat{x}$ to get:

$$\phi(x) = \begin{cases} \frac{eN_a(x+w_p)^2}{2\epsilon}, & -w_p \le x \le 0 \\ \frac{eN_a w_p^2}{2\epsilon} + \frac{eN_a(2xw_n - x^2)}{2\epsilon}, & 0 \le x \le w_n \end{cases}$$

Depletion region width

- Total width $w_0 \equiv w_p + w_n$; $N_a w_p = N_d w_n \Rightarrow w_p = \frac{w_0 N_d}{N_a+N_d}$, $w_n = \frac{w_0 N_a}{N_a+N_d}$
- Total potential across region:

$$V_0 = \frac{eN_a w_p^2}{2\epsilon} + \frac{eN_a(2w_n^2)}{2\epsilon} = \frac{eN_a N_d w_0^2}{2\epsilon(N_a + N_d)}$$

- But total potential is the contact potential:

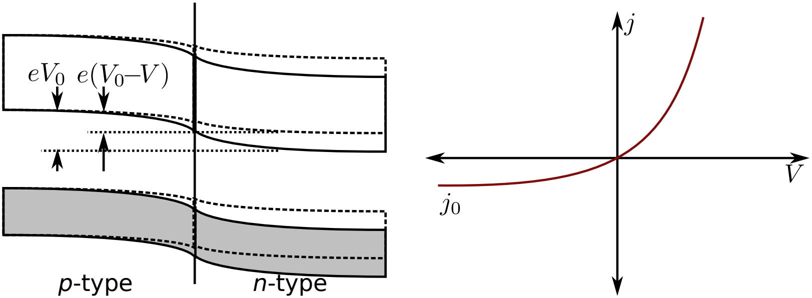
$$eV_0 = \underbrace{\left(E_{F0} + k_B T \ln \frac{N_d}{n_i}\right)}_{E_{Fn}} - \underbrace{\left(E_{F0} - k_B T \ln \frac{N_a}{n_i}\right)}_{E_{Fp}} = k_B T \ln \frac{N_d N_a}{n_i^2}$$

- Therefore depletion region width:

$$w_0 = \sqrt{\frac{2\epsilon(N_a + N_d)V_0}{eN_a N_d}} = \sqrt{\frac{2\epsilon(N_a + N_d)k_B T}{e^2 N_a N_d} \ln \frac{N_d N_a}{n_i^2}}$$

- When will depletion region width be set by λ_D?

Applied bias



- Barriers for e^- from $n \to p$ and holes from $p \to n$: $e(V_0 - V)$
- Corresponding 'diffusion' current: $j_2 \exp \frac{-e(V_0 - V)}{k_B T}$
- Junction field drives 'drift current': j_1
- Must be balanced at $V = 0 \Rightarrow j_1 = j_2 \exp \frac{-eV_0}{k_B T} \equiv j_0$
- Therefore $j = j_0 \left(\exp \frac{eV}{k_B T} - 1 \right)$

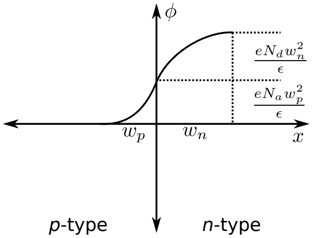
Magnitude of current

- So far IV-characteristics exactly like Schottky diode
- For Schottky diode, we found $j_0 \propto \exp \frac{-\Phi_B}{k_B T}$
  i.e. significant current when $eV \gtrsim \Phi_B$
- For pn-junction diode at zero bias: equal drift and diffusion currents $= j_0$
- Minority carrier diffusion current driven by concentration gradient
- In uniform n-semiconductor $\dot{p} = -(p - p_0)/\tau_h$ (minority carrier lifetime τ_h)
- In non-uniform semiconductor: $\dot{p} = -D_h \nabla^2 p$ (diffusion)
- Therefore in steady-state: $D_h \nabla^2 p = (p - p_0)/\tau \Rightarrow$
  p decays exponentially towards p_0 with length scale $L_h = \sqrt{D_h \tau_h}$
- Diffusion current $j_h = -eD_h p'(x) \sim \frac{eD_h p_0}{L_h} = \frac{eD_h n_i^2}{L_h N_d}$
- Total minority diffusion current

$$j_0 = \frac{eD_h n_i^2}{L_h N_d} + \frac{eD_e n_i^2}{L_e N_a} = eN_c N_v \left[\frac{D_h}{L_h N_d} + \frac{D_e}{L_e N_a} \right] \exp \frac{-E_g}{k_B T}$$

- Therefore current significant for $V > E_g/e$

Minority carrier concentration in depletion region



- In n-depletion region, potential changes from neutral value by $(V_0 - V)N_a/(N_a + N_d)$ (maximum at junction)
- Assume symmetric doping, potential changes by $(V_0 - V)/2$
- Hole concentration at junction

$$p_M \sim N_a \exp \frac{-e(V_0 - V)}{2k_B T} \sim n_i \exp \frac{eV}{2k_B T}$$

- Hole recombination rate $\sim \frac{p_M}{\tau_h} \cdot \frac{w_n}{2}$ (averaged over region)

Recombination current

- Current due to recombination of both e and h:

$$j_r = en_i\left(\frac{w_n}{\tau_h} + \frac{w_p}{\tau_e}\right)\exp\frac{eV}{2k_BT}$$

- Previous IV accounted for e and h transport separately, but not this recombination (except that it is needed for equilibrium)
- Net current density therefore:

$$j(V) = j_{dd0}\left(\frac{eV}{k_BT} - 1\right) + j_{r0}\left(\frac{eV}{2k_BT} - 1\right)$$

- Frequently approximated as

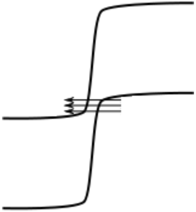
$$j(V) = j_0\left(\frac{eV}{\eta k_BT} - 1\right)$$

with ideality factor η expected to be between 1 and 2

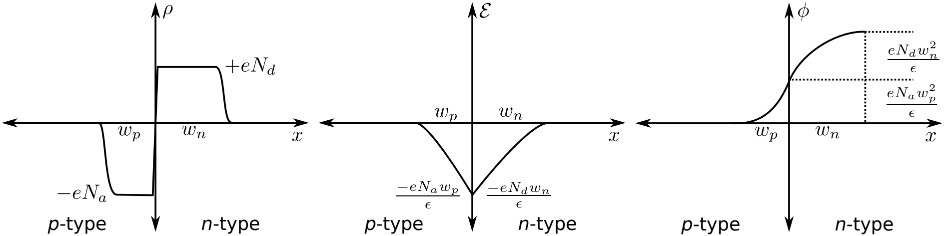
- Ideal diode: no recombination $\Rightarrow \eta = 1$

Additional effects in reverse bias

- Space charge layer generation
  - Reverse bias increases junction potential
  - Higher field in space charge layer (depletion region)
  - e and h in equilibrium: thermal generation vs recombination
  - Field sweeps carriers away before they recombine $\Rightarrow$ current
  - Linearly increasing reverse current instead of saturated $-j_0$
- Avalanche breakdown
  - Depletion region: large field, few carriers
  - If $e\mathcal{E}\lambda > E_g$, carriers can excite additional e-h pairs
  - Cascade process leading to sudden increase in current
- Zener breakdown
  - Highly doped junctions $\Rightarrow$ narrow depletion regions
  - Potential larger than E_g: direct band-to-band tunneling
  - Design sharp breakdown at specific potential (Zener diodes)



Depletion layer capacitance



- Charge stored $= eN_a w_p = eN_d w_n = ew_0 N_a N_d / (Na + N_d)$ (per unit area)
- Substituting for width of depletion region:

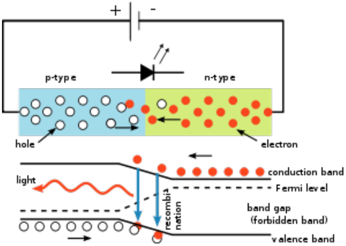
$$\frac{q}{A} = \frac{eN_a N_d}{Na + N_d} \cdot \sqrt{\frac{2\epsilon(N_a + N_d)(V_0 - V)}{eN_a N_d}} = \sqrt{\frac{2\epsilon e N_a N_d (V_0 - V)}{(N_a + N_d)}}$$

- Therefore differential capacitance:

$$\frac{C_d}{A} \equiv \frac{\partial q}{A \partial V} = \sqrt{\frac{\epsilon e N_a N_d}{2(V_0 - V)(N_a + N_d)}}$$

- Typical value for Si, $N_a = N_d = 10^{17}$ cm^3, $C \sim 0.1$ μF/cm^2

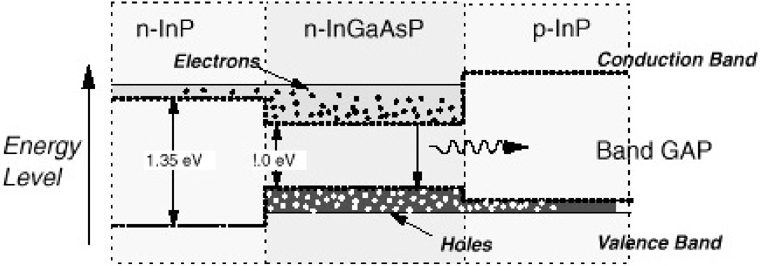
Light-emitting diode



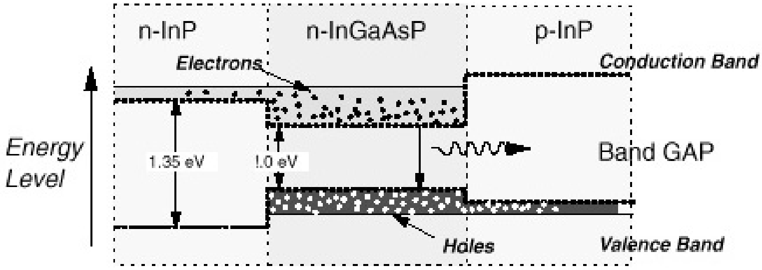
- Basic design: just a p-n junction, but in direct band-gap material
- Current density $\rightarrow$ recombination near junction
- Fraction of recombination is radiative $\Rightarrow$ light
- Spontaneous emission: light is incoherent and in random direction
- Efficiency: $\eta = P_{\text{light}}/(IV)$ (can be $> 10\%$ for direct semiconductors)
- Typically use asymmetric junctions: pn^+ or np^+: why?

LED: light spectrum

- Minimum photon energy: E_g
- Peak photon energy $\sim E_g + k_B T$
- Spectral width $\sim 3k_B T$
- Due to distribution of both hole and electron energies
- For GaAs, $E_g = 1.42$ eV, $\lambda = 870$ nm (IR)
- $\Delta(hc/\lambda) \sim 0.08$ eV $\Rightarrow \Delta\lambda \sim 50$ nm
- Light emitted by LED can be absorbed by semiconductor
- Circumvent in hetero-junction LEDs



Semiconductor laser



- Very similar to LED at the junction level
- Key difference: optical cavity using reflecting surfaces
- Start with spontaneous emission, sharpened by cavity resonance
- Stimulated emission builds up intensity in specific mode
- Require population inversion: e-h pairs waiting to recombine
- Population inversion achieved by bias: electrical pumping!
- Cavity resonance + laser amplification, $\Delta\lambda \sim 0.1$ nm $\ll k_B T$

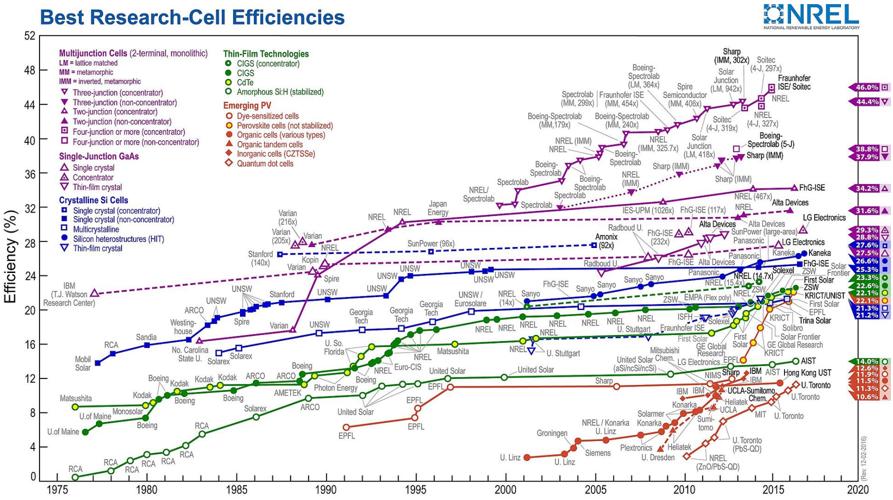
Photodiodes and solar cells

- LED in reverse?
- Not quite, can use indirect band gap materials
- Absorption still occurs right at band gap (how?)
- eh-pairs created in depletion region swept across by field
- Loss: recombination (radiative or non-radiative)
- Modified device characteristic

$$j(V) = -j_{\mathrm{ph}} + j_0 \left[\exp \frac{eV}{\eta k_B T} - 1 \right]$$

- Why non-zero current at $V = 0$ if it is in equilibrium?
- Photodiode: operated in reverse bias: why?

Photovoltaic efficiencies



Single junction efficiency limited by band-gap;
circumvent using multi-junction devices

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