Recombination: Depletion Region, Bulk, Radiative, Auger, and Tunnelling

Ch 140

Lecture Notes #13

Prepared by David Gleason

Review of Depletion Region Recombination

- We assume:
  - Flat Quantum Fermi Levels
    - Requires that the fastest recombination rate is slow with respect to diffusion
  - $k_n \approx k_p = \sigma\nu$
    - There are an even distribution of traps where σ does not depend on x
  - $\int_0^{w'} U(x)dx \approx \int_0^{\infty} U(x)dx$

This leads to: $$U_{total} = \frac{\pi kTw}{q(V_{bi} + V_{app})} U_{\max}$$

Review of Depletion Region Recombination (cont.)

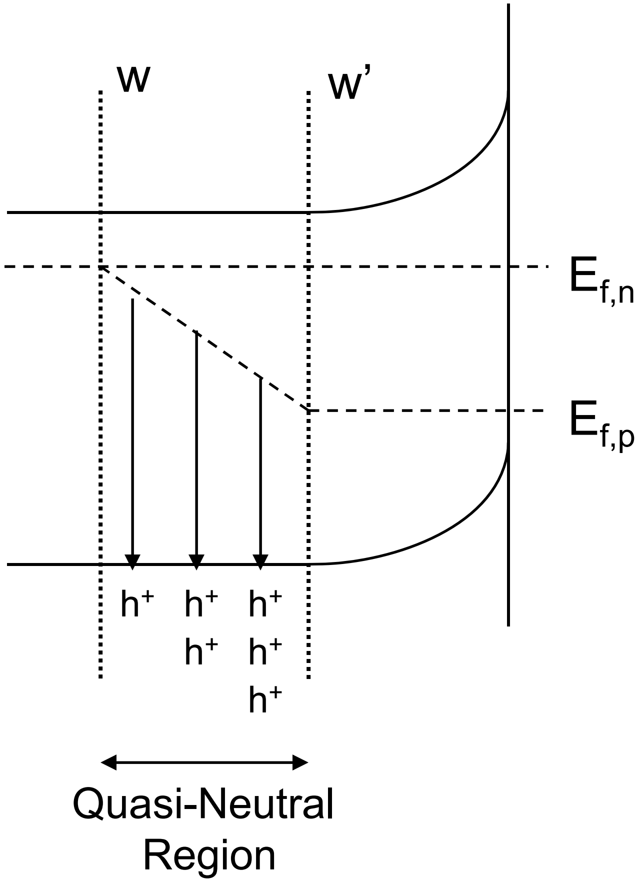
We also have $U_{\max} = \tfrac{1}{2} N_T \sigma v n_i \exp(-qV_{app}/2kT)$

and $J_{D/R} = qU_{total}$

So $J_{DR} = \dfrac{\pi kTw}{4(V_{bi} + V_{app})} N_T \sigma v n_i \exp(-qV_{app}/2kT)$

Quasi-Neutral Region

- The Quasi-neutral region is defined as a region of the semiconductor with an uneven distribution of carriers in a region of flat bands
- As pictured, the holes will diffuse away from w' into the bulk where they will recombine



Bulk Recombination

At steady state $$\frac{\delta p(x)}{\delta t} = R(\Delta x) - D(\Delta x) = 0$$

using Fick's 1st Law $$\text{Flux } = D_o \frac{\delta C_o(x,t)}{\delta(x)}$$

and Fick's 2nd Law $$\frac{\delta C_o}{\delta t} = D_o \nabla^2 C_o(x,t) = D_o \frac{\delta^2 C_o(x,t)}{\delta x^2}$$

We have $$\frac{\delta p(x)}{\delta t} = 0 = \frac{p(x) - p_o(x)}{\tau_p} - D_p \frac{\delta^2 p(x)}{\delta x^2}$$

Bulk Recombination (cont.)

To solve this we must first establish some boundary conditions

1. $p(w') = p_o \exp(-qV_{app}/kT)$

2. $n(w')\,p(w) = n_i^2 \exp(-qV_{app}/kT)$

3. $p(\infty) = p_o$

Solving for p(x) yields

$$p(x) = p_o + p_o\left[\exp(-qV_{app}/kT) - 1\right]\exp\left\lfloor -\frac{x-w}{L_p} \right\rfloor$$

Where $L_p = \sqrt{D_p \tau_p}$ is the diffusion length

The bulk recombination current can be determined by

$$J_{BR} = q \text{ flux}$$

where the flux here is for all carriers at any point in the flat band region

This is solved easiest at w' since there there is no electron movement to consider. At other values of x

$$J_{BR}=-q \text{ flux}_{holes}+q \text{ flux}_{electrons}$$

At x=w' this simplifies to $J_{BR} = -qflux_{holes} = -qD_p \frac{\delta p(x)}{\delta x}$

Solving this and evaluating at x=w' recognizing that the last term simplifies

$$\exp\left(-\frac{(x-w')}{L_p}\right) \rightarrow 1$$

We have $$J_{BR} = \frac{qD_p p_o}{L_p}\left\lfloor \exp\left(\frac{-qV_{app}}{kT}\right) - 1\right\rfloor$$

From
$$J_{BR} = \frac{qD_p p_o}{L_p}\left\lfloor \exp\left(\frac{-qV_{app}}{kT}\right) - 1 \right\rfloor$$

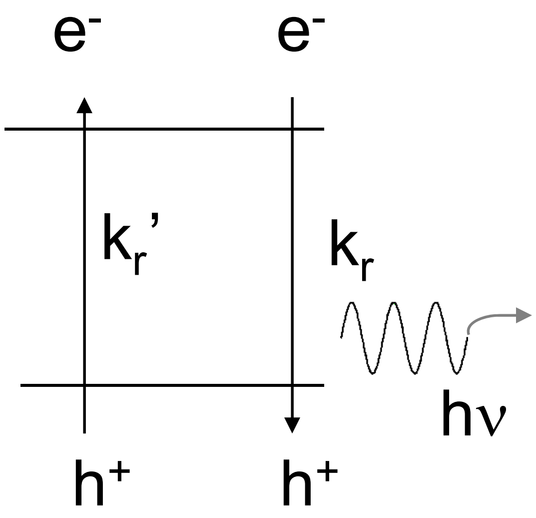
We can substitute
$$n_o p_p = n_i^{\,2} \rightarrow p_o = \frac{n_i^{\,2}}{n_o} \approx \frac{n_i^{\,2}}{N_D}$$

To get
$$J_{BR} = \frac{qD_p n_i^{\,2}}{L_p N_D}\left[\exp\left(\frac{-qV_{app}}{kT}\right) - 1 \right]$$

This is the bulk region recombination

Radiative Recombination

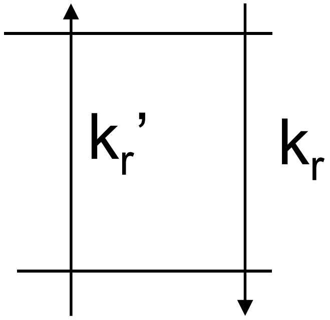
- Assume a perfect semiconductor crystal
  - No surface state recombination
  - No depletion region recombination (σ is very small)
  - No bulk recombination (L_p is very big)
- Generate carriers through light absorption or thermal excitation
  - Carriers diffuse until finally they recombine in the inverse of the absorption reaction
  - Light is emitted with $h\nu = E_g$



Radiative Recombination (cont.)

- This process has been ignored until now because for indirect band gap semiconductors the carrier lifetime due to radiative recombination is **really** long.
  - – 99.9% of bulk recombination in Si and Ge will occur across trap states
- For direct gap semiconductors, including GaAs and porous Si, radiative recombination is more competitive
  - – Leads to LEDs, lasers, ect.

Radiative Recombination Current



Rate of electron recombination given by

$$-\frac{\delta n}{\delta t} = npk_r - k_r'$$

At equilibrium $0 = n_o p_o k_r - k_r' \rightarrow k_r' = n_i^2 k_r$

This expression can be plugged into the rate equation away from equilibrium to give

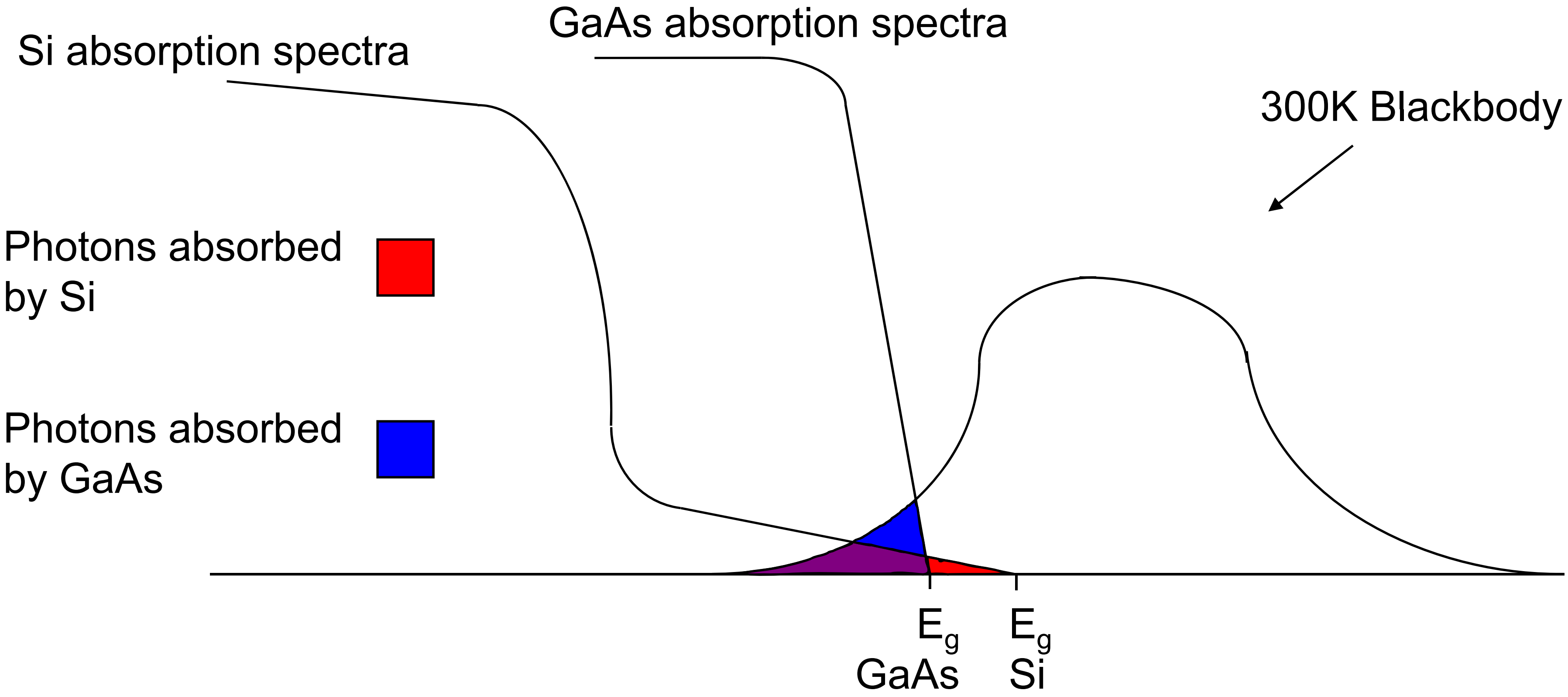
$$-\frac{\delta n}{\delta t} = k_r\left(np - n_i^2\right)$$

And finally $J_r = qk_r\left(np - n_i^2\right)$

Determination of k_r from the absorption spectra

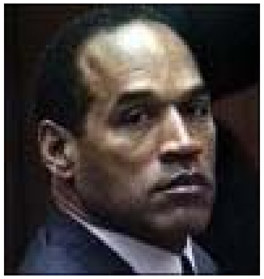
- Indirect semiconductors can not be made pure enough to emit, so k_r must be calculated from the absorption spectra
  - At equilibrium in a perfect sample, the rate of thermal absorption must equal the rate of radiative recombination because they are inverse processes
  - The thermal absorption is given by the overlap between the blackbody curve at temperature T and the absorption spectra at temperature T

Determination of k_r from the absorption spectra



Note that even though Si has a lower E_g than GaAs, less light is absorbed due to the shape of the absorption spectra caused by the indirect band gap of Si.
At equilibrium, the amount absorbed is equal to that emitted through radiative recombination, so we can calculate k_r, which is sometimes called B, and has units of cm^4s^{-1}.

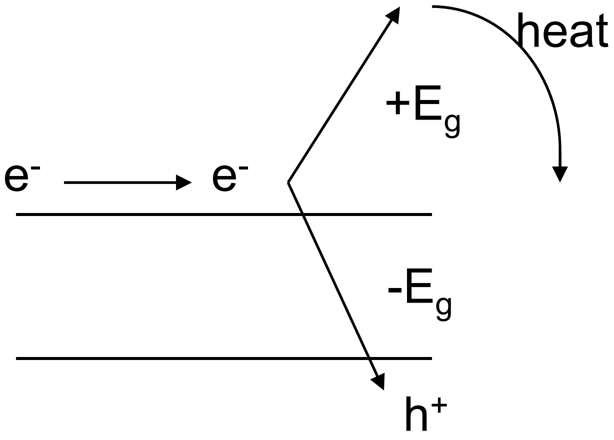
Auger Recombination

- Pronounced  or 

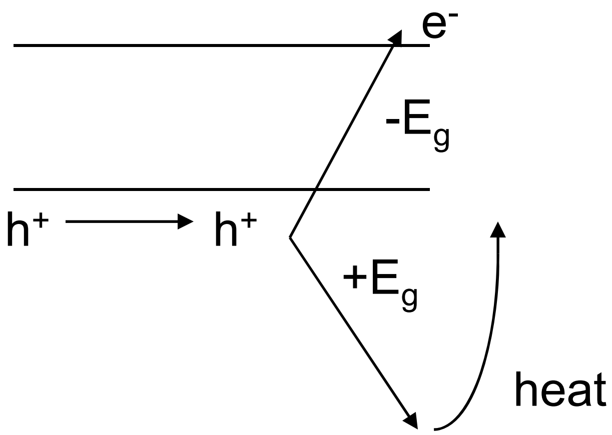
- Occurs at very high injection or doping conditions
  - This is a 3 body process whereby two majority carriers collide
    - One looses energy E_g and combines with a minority carrier
    - The other gains energy E_g, which it subsequently looses through thermalization

Auger Recombination (cont.)

- For n-type
  - Auger lifetime $$\tau_A = \frac{1}{G_n n^2}$$
  - G_n = recombination rate



- For p-type
  - Auger lifetime $$\tau_A = \frac{1}{G_p p^2}$$
  - G_p = recombination rate
    - $G_p \approx 2 \times 10^{-31}$ cm^6/s for Si at room temperature
- The dependence is on n or p, and therefore depends on the doping or excitation level



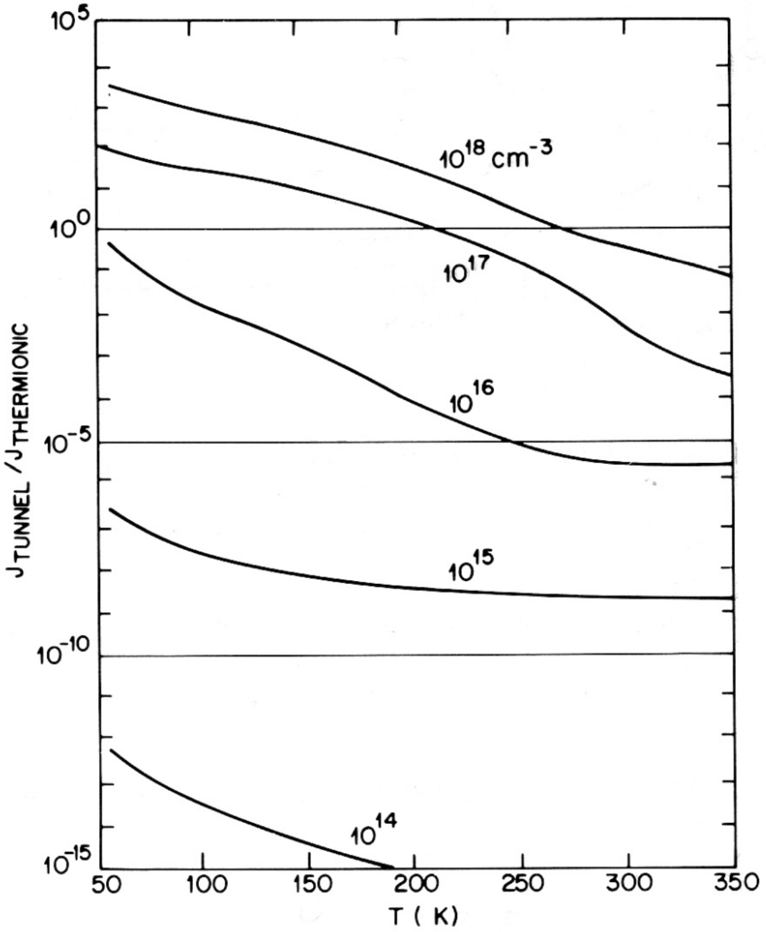
Tunneling Current

- Tunneling is only important at high high dopant densities and low temperatures
- The tunneling probability is given by

$$T_{tun} = \exp\left\{-\frac{8\pi w}{3h}\left[2qm_e^*\left(\left|V_{bi}\right| + V\right)\right]^{\frac{1}{2}}\right\}$$

where $w \propto \sqrt{\frac{1}{N_D}}$

- The tunneling probability is temperature independent, and since most other currents (thermionic emission) are highly temperature dependent it is only seen at low temps



Ratio of tunneling current to thermionic current for Si-Au barrier taken from Sze p. 264

Summary of Recombination

- Bulk $J_{BR} = \frac{qD_p n_i^{\;2}}{L_p N_D}\left[\exp\left(\frac{-qV_{app}}{kT}\right) - 1\right]$
- Depletion Region $J_{DR} = \frac{\pi kTw}{4(V_{bi} + V_{app})} N_T \sigma v n_i \exp(-qV_{app}/2kT)$
- Thermionic $J_{th} = A^* T^2 \exp\left(\frac{-q\phi_b}{kT}\right)\left[\exp\left(\frac{-qV_{app}}{kT}\right) - 1\right]$
- Radiative $J_r = qk_r\left(np - n_i^2\right)$
- Auger $\tau_A = \frac{1}{G_n n^2}$
- Tunneling $J_T \propto \exp\left(-\alpha\phi_b/\sqrt{N_D}\right)$

Summary of Recombination (cont.)

- Bulk
  - A=1, depends N_D
  - J_o proportional to $\exp(-E_g/kT)$
- Depletion Region
  - A=2
- Thermionic
  - A=1, does not depend on N_D
  - J_o proportional to $\exp(-q\phi_b/kT)$
- Radiative
  - Insignificant for indirect gap semiconductors,
  - Strictly depends on excess carriers
- Auger
  - Only at really high carrier concentrations
- Tunneling
  - Only significant at low T and high N_D or N_A
  - Constant with temperature