

ELEN E3106/4106 Lecture 7

Optical Absorption, Luminescence, Carrier Lifetime and Photoconductivity Outline

- Absorption
- Photo/electroluminescence
- Recombination (direct vs. indirect)
- Diffusion with recombination
- Quasi-Fermi levels
- Photoconductive devices

Assignments:

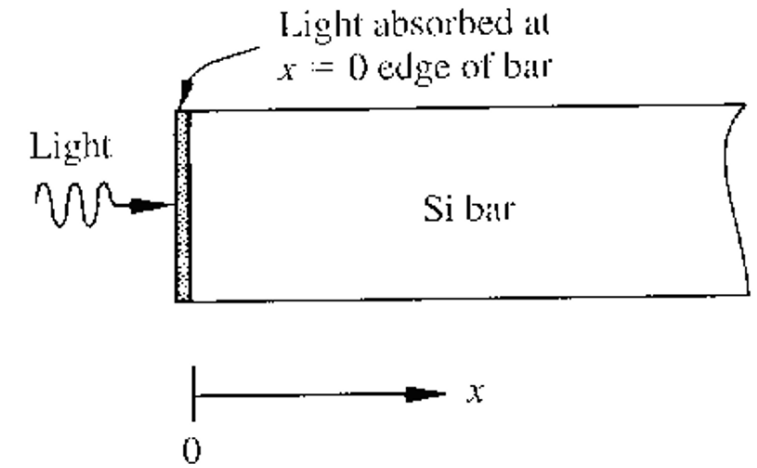
Reading: Streetman and Banerjee §4.1-4.3

Homework 3 due Friday Sept 26th by 5pm

Exam 1 on Tuesday Sept 30th

Steady-State Injection of Carriers

- Imagine that excess h^+ are somehow injected into a semi-infinite semiconductor bar at $x = 0$,
- Injection maintains a constant excess hole concentration at the injection point $\delta p(x = 0) = \Delta p$
- Injected holes diffuse along the bar, recombining with lifetime, _____
- For this problem, the solution to the steady state diffusion equation for holes has the form:
- C_1 and C_2 are the _____ -
- Excess holes decay to zero as $x \rightarrow \infty$: C_1 goes to _____
- At $x = 0$, C_2 will be _____



$$\delta p(x) = C_1 e^{x/L_p} + C_2 e^{-x/L_p}$$

Steady-State Injection: Solution

- So, the solution becomes

$$\delta p(x) = \Delta p e^{-x/L_p}$$

- The injected excess h⁺ concentration dies _____ in x due to _____
- What does the diffusion length, _____, physically represent?
 - The distance at which the excess h⁺ distribution is reduced to 1/e of its value at the injection point
 - We can show that L_p is the average distance a hole diffuses before recombining (see textbook)

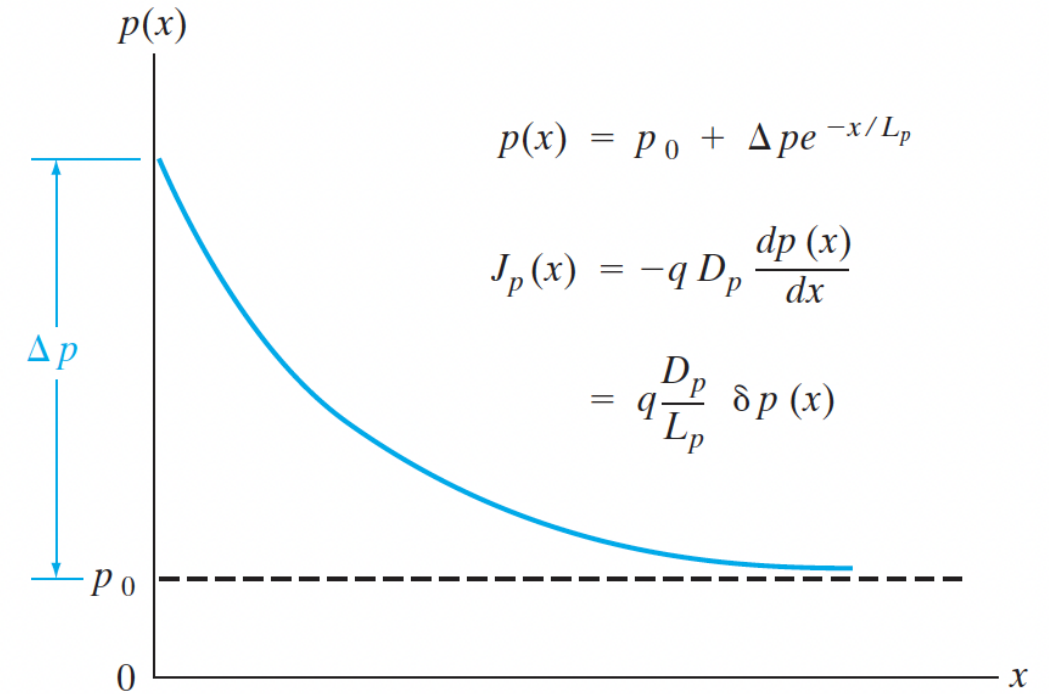
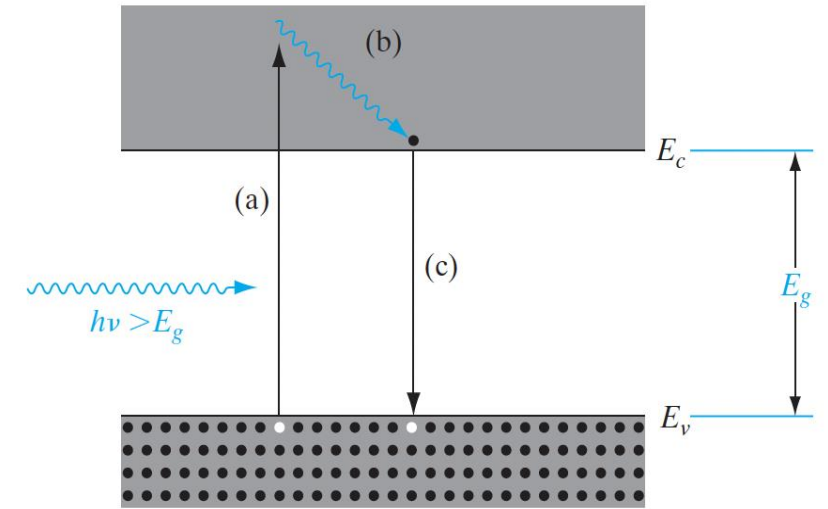


Figure 4-17
Injection of holes at $x = 0$, giving a steady state hole distribution $p(x)$ and a resulting diffusion current density $J_p(x)$.

Semiconductors Under Illumination

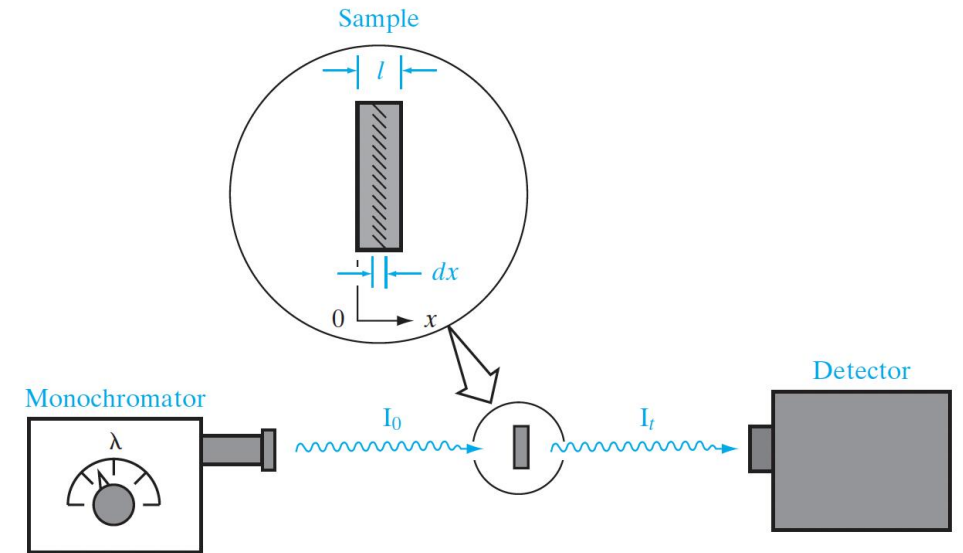
- So far, we have assumed our semiconductors are in the dark. # of carriers is determined by thermal EHP generation and doping
- What happens when we turn the lights on?
 - We create excess carriers!
- Recall: We saw an example of this already
 - Internal photoelectric effect (Lecture 3)
 - $E = h\nu = \frac{hc}{\lambda}$
 - _____ can be determined from the minimum energy ($h\nu$) of photons that are absorbed by the semiconductor
 - If $E_{\text{photon}} < \text{_____}$, light will not be absorbed and material will behave as transparent



(a) EHP is created during photon absorption; (b) the excited e^- gives up energy to the lattice by scattering; (c) e^- recombines with h^+ (more on this later...)

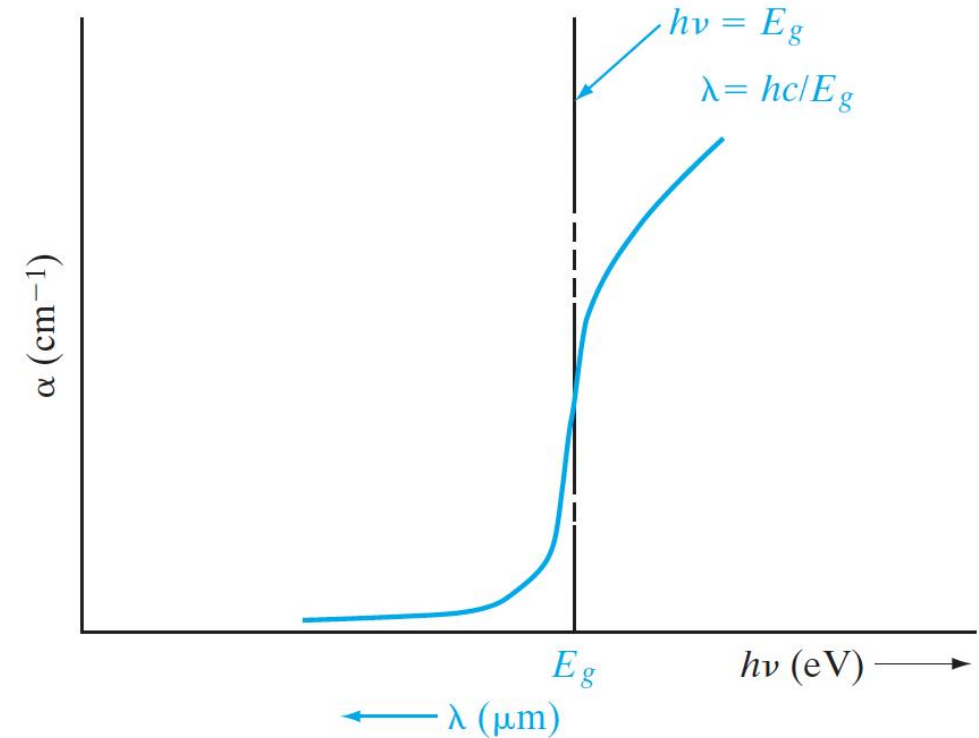
Absorption Coefficient

- Let's say we have a beam of photons shining on sample of thickness l
 - Assume $h\nu > E_g$ and only one λ
 - Intensity is I_0 (photons/cm²-s)
- Intensity at a distance x from the surface can be found:
 - $I(x) = I_0 e^{-\alpha x}$
- So what's the intensity transmitted through the sample?
- There is some predictable amount of absorption (_____ dependent)
- Called the **absorption coefficient**, _____
 - Units: cm⁻¹



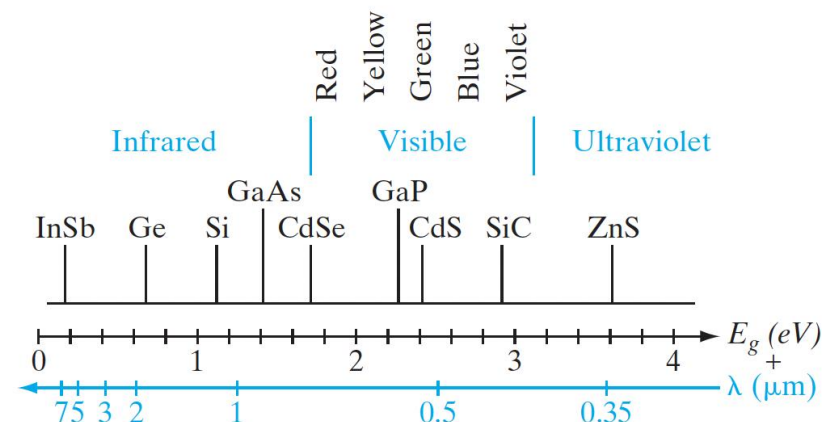
Absorption Dependence on Photon Energy

- α will vary with _____ and _____
- At small E (long λ):
 - Absorption is _____
- At large E (short λ):
 - Absorption is _____
- Semiconductors absorb photons much more efficiently at energies greater than the band gap
- Note: this means the ratio of transmitted to incident light intensity depends on the photon wavelength and the thickness of the sample.

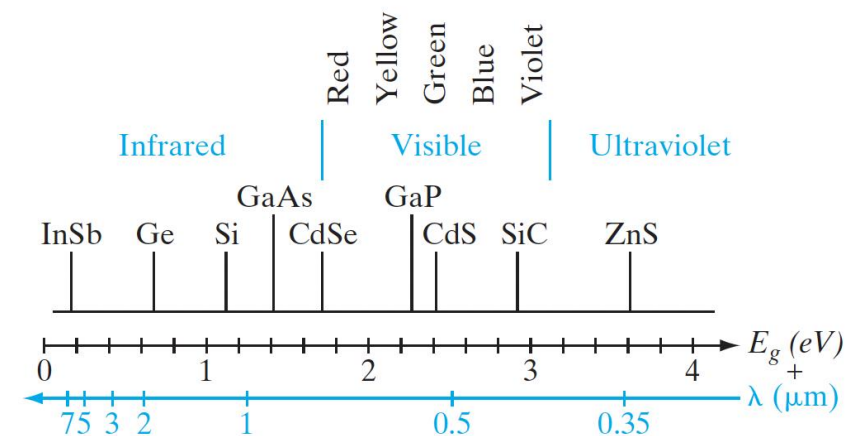


Absorption in Common Semiconductors

- Once again: semiconductors absorb photons with energies equal to the band gap, or larger.
- What wavelength light can Si absorb?



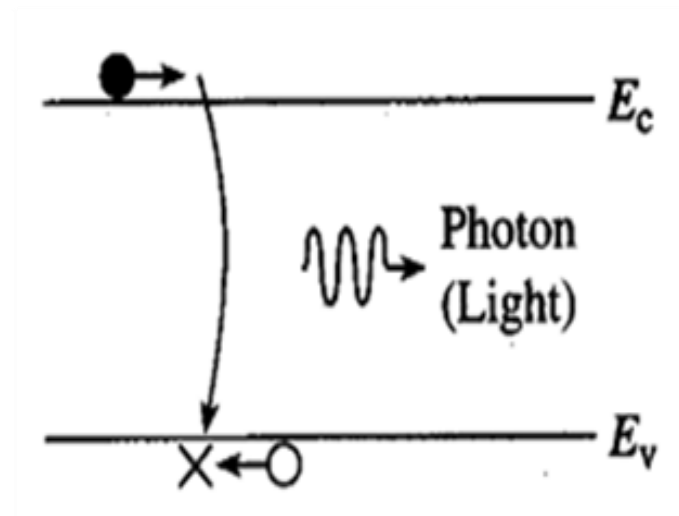
- How about SiC?



Direct Recombination

- Remember, recombination is when EHPs annihilate one another (e- occupy the empty state of the hole)
- This can take place through one or multiple steps!
- Direct recombination (Band-to-Band)
 - e- falls from its conduction band state into the empty valence band state associated with the hole
 - Emits a photon with energy equal to _____
- This happens spontaneously, meaning the rate of recombination is constant in time
- Given by the recombination constant, _____
 - Units: cm^3/s

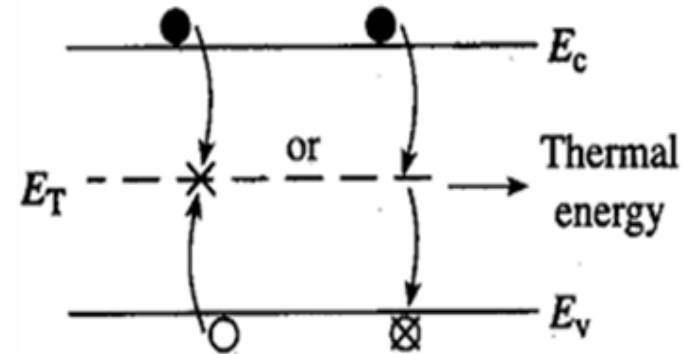
Direct



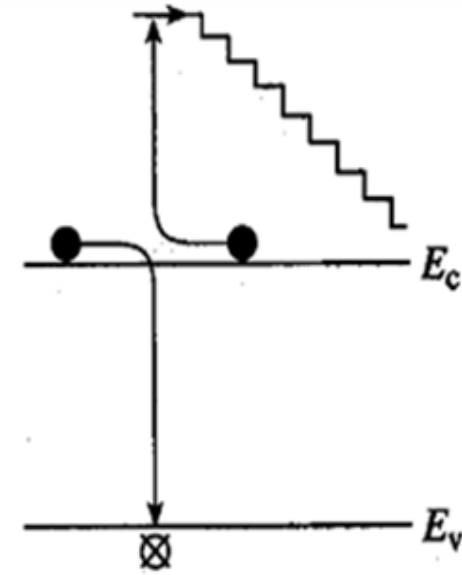
Indirect Recombination

- Multiple steps for EHP to recombine
- R-G center (_____-assisted recombination)
 - e- falls into a “trap” (energy level within the bandgap caused by an impurity or structural defect)
 - Captured e- is at the impurity level _____
 - Then, it falls into the empty valence band state (hole)
- Auger recombination
 - EHP recombine in band-to-band transition
 - But, the resulting energy is not given off as photon
 - It is instead transferred to _____
- In general, is indirect or direct recombination to be faster?

R-G Center



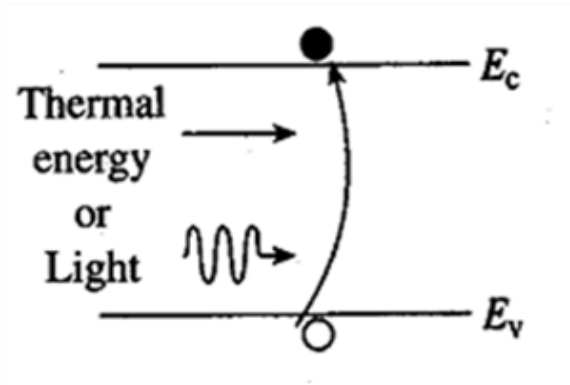
Auger



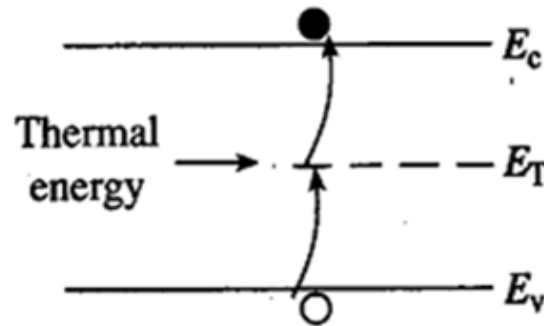
What about Generation Processes?

- We can generate EHP through one or multiple step processes, too
- Some are the counterpart of a recombination process

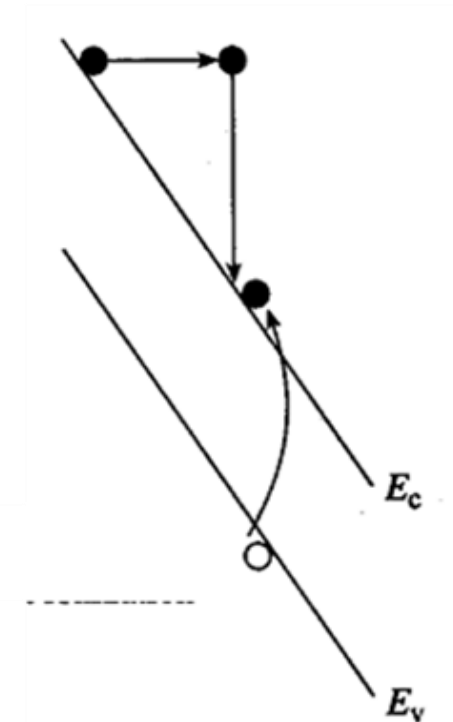
Band-to-Band



R-G Center



Impact Ionization



Recombination Effects on Excess Carrier Concentrations

- Excess carrier notation:
 - $\delta n(t) = \delta p(t)$ instantaneous excess EHPs at time t
 - $\Delta n = \delta n(t=0)$ initial excess EHPs at time $t = 0$, right after initial excitation (e.g. light flash)

$$n = n_0 + \delta n$$

$$p = p_0 + \delta p$$

- How do excess EHPs decay?
 - Assume n-type sample ($n_0 \gg p_0$) so holes are in minority
 - Will majority carriers (electrons) be disturbed much?
 - What about minority carriers (holes)?

Recombination Effects on Excess Carrier Concentrations

- Excess minority carriers will recombine with already existing majority e-: $\frac{d}{dt}\delta p(t) \approx -\alpha_r n_0 \delta p(t)$

- And the solution is an exponential decay from the original excess carrier concentration _____,

$$\delta p(t) = \Delta p e^{-\alpha_r n_0 t} = \Delta p e^{-t/\tau_p}$$

- If the material is p-type ($n_0 \gg p_0$), the minority carrier concentration similarly becomes,

$$\delta n(t) = \Delta n e^{-\alpha_r p_0 t} = \Delta n e^{-t/\tau_n}$$

- What is α_r ?

- _____
- Units: cm/s

- What is τ ?

- _____
- Units: s

$$\tau_n = (\alpha_r p_0)^{-1}, \quad \tau_p = (\alpha_r n_0)^{-1}$$

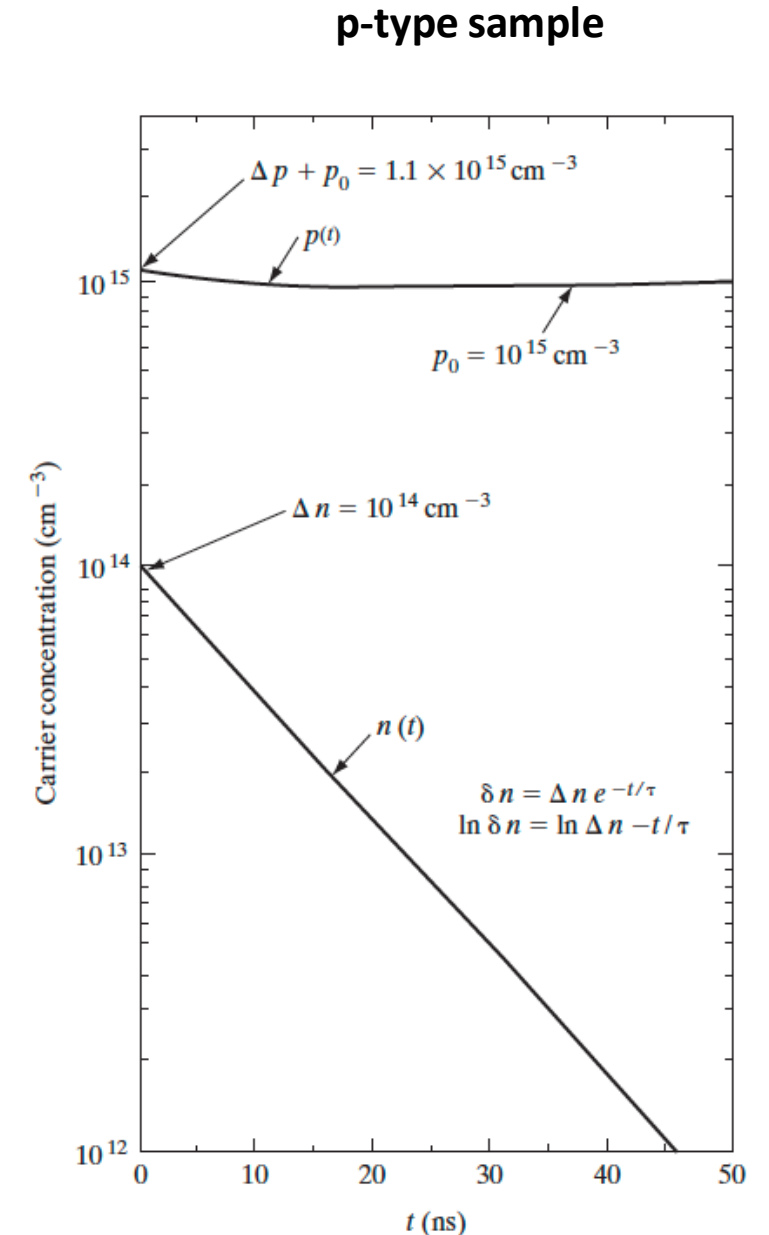
- Calculations made in terms of minority carriers!
- In the case of direct recombination, δn decay at same rate as δp

Low-Level Injection

- More generally, we can write:

$$\tau_n = \frac{1}{\alpha_r(n_0 + p_0)}$$

- This is valid for n- or p-type material if the injection level is low
- What does “low-level” mean?
 - The excess carrier concentration is much less than the majority carrier concentration



Steady-State Carrier Generation

- Recall,
 - Thermal equilibrium: generation = recombination $g(T) = \alpha_r n_i^2 = \alpha_r n_0 p_0$
 - Steady-state: all time derivatives $(\partial/\partial t) = 0$
- If a **steady** light is shone on the sample, an optical generation rate _____ and assuming no trapping, $\Delta n = \underline{\hspace{2cm}}$,

$$g(T) + g_{\text{op}} = \alpha_r n_0 p_0 + \alpha_r [(n_0 + p_0)\delta n + \delta n^2]$$

- Assuming low level injection, we can rewrite this,

$$g_{\text{op}} = \alpha_r (n_0 + p_0)\delta n = \frac{\delta n}{\tau_n}$$

- Why is this important? Now we can write our excess carrier concentrations,

$$\delta n = \tau_n g_{\text{op}} \quad \text{and} \quad \delta p = \tau_p g_{\text{op}}$$

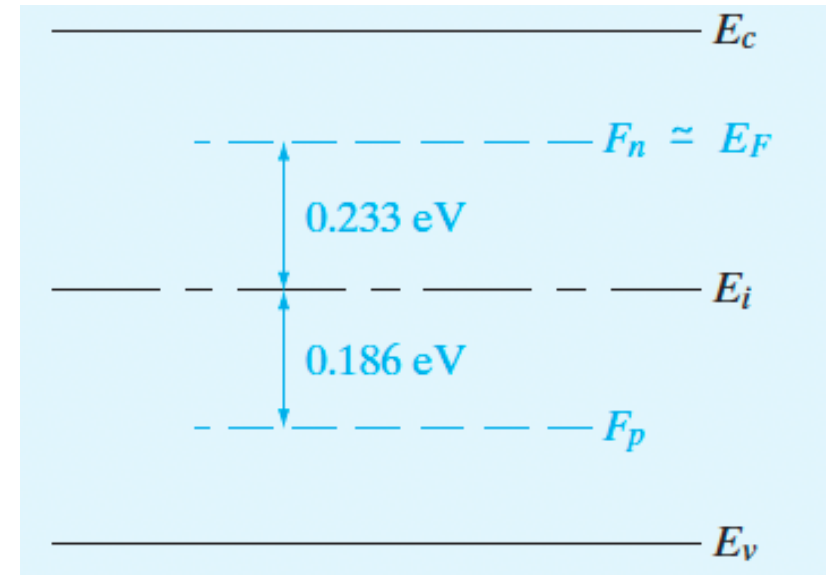
Problem: Optical Generation and Recombination

- GaAs doped with 2×10^{15} donors/cm³ and having 4×10^{14} EHP/cm³ created uniformly at $t = 0$. Assume that $\tau_p = \tau_p = 5 \mu\text{s}$. Calculate the recombination coefficient α_r for this low-level excitation. Assume that this value of α_r applies when the GaAs sample is uniformly exposed to a steady state optical generation rate $g_{op} = 10^{19}$ EHP/cm³-s. Find the steady state excess carrier concentration $\Delta n = \Delta p$.
- First, we find the equilibrium hole concentration,
- $p_0 = \frac{n_i^2}{n_0} = \frac{(2 \times 10^6)^2}{2 \times 10^{15}} = 2 \times 10^{-3} \text{ cm}^{-3}$
- Next, we find the recombination coefficient (rearranging eq. on previous slide)
- $\alpha_r = \frac{1}{\tau_n(n_0 + p_0)} = \frac{1}{(5 \times 10^{-6})(2 \times 10^{15} + 2 \times 10^{-3})} = \text{cm}^3/\text{s}$
- $\Delta n = \Delta p = \frac{g_{op}}{\alpha_r} = \left(10^{19} \frac{\text{cm}^{-3}}{\text{s}}\right) (5 \times 10^{-6} \text{ s}) = \text{cm}^{-3}$

Quasi-Fermi Levels

- Often times we want to write expressions for steady-state carrier concentrations in terms of our Fermi level
- But the Fermi level is only meaningful without excess carriers
- So in the case of excess carriers, we define ***quasi-Fermi levels***,
 - _____ for _____
 - _____ for _____
- Why are these (visually) useful? So we can demonstrate the deviation from equilibrium caused by excitation, like a light
 - Minority carrier quasi-Fermi level will be greatly displaced!
- $F_n - F_p$ is a direct measure of the deviation from equilibrium

n-type Si sample. The % change in n is small (quasi-Fermi level hardly moves), while # change in p is large --> quasi-Fermi level is far from equilibrium Fermi-level



$$n = n_i e^{(F_n - E_i)/kT}$$
$$p = n_i e^{(E_i - F_p)/kT}$$

Problem: Quasi Fermi Level under Steady-State Injection

In a very long p-type Si bar with cross-sectional area = 0.5 cm^2 and $N_a = 10^{17} \text{ cm}^{-3}$, we inject holes such that the steady state excess hole concentration is $5 \times 10^{16} \text{ cm}^{-3}$ at $x = 0$. What is the steady state separation between F_p and E_c at $x = 1000 \text{ \AA}$? What is the hole current there? Assume that $\mu_p = 500 \text{ cm}^2/(\text{V} \cdot \text{s})$ and $\tau_p = 10^{-10} \text{ s}$. =

- $D_p = \text{_____} = 0.026(500) = 12.95 \frac{\text{cm}^2}{\text{s}}$
- $L_p = \text{_____} = \sqrt{(12.95)(10^{-10})} = 3.6 \times 10^{-5} \text{ cm}$
- $p = p_0 + \delta p(x) = p_0 + \Delta p e^{-\frac{x}{L_p}} = \text{_____} + (5 \times 10^{16}) e^{-\frac{1000 \times 10^{-8}}{3.6 \times 10^{-5}}} = 1.379 \times 10^{17} \text{ cm}^{-3}$
- Now, we can solve the carrier concentration equation,
- $p = n_i e^{\frac{E_i - F_p}{kT}} \rightarrow E_i - F_p = \ln\left(\frac{p}{n_i}\right) kT = \ln\left(\frac{1.379 \times 10^{17}}{\text{_____}}\right) 0.026 = 0.415 \text{ eV}$
- $E_c - F_p = (E_c - E_i) + (E_i - F_p) = \frac{1.1 \text{ eV}}{2} + 0.415 \text{ eV} = 0.965 \text{ eV}$
- $I_p = A J_p(x) A \frac{q D_p}{L_p} \delta p(x) = A \frac{q D_p}{L_p} \Delta p e^{-\frac{x}{L_p}} = (\text{_____}) \frac{(1.6 \times 10^{-19})(12.96)}{3.6 \times 10^{-5}} (5 \times 10^{16}) e^{-\frac{1000 \times 10^{-8}}{3.6 \times 10^{-5}}}$
 $I_p = 1.09 \times 10^3 \text{ A}$

Photoconductivity

- Last but not least, we have excess carriers with the lights ON. Will the conductivity (resistivity change)?
- Recall: $\sigma =$ _____
- Before, we were neglecting the term associated with minority carriers for n- or p-type samples
- But with excess carriers, δn and δp from the light, n and p are affected:

$$n = n_0 + \delta n \quad p = p_0 + \delta p$$

- The increase in conductivity caused by excess carriers (EHPs) from lights being turned on:

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