Columbia Engineering
The Fu Foundation School of Engineering and Applied Science

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

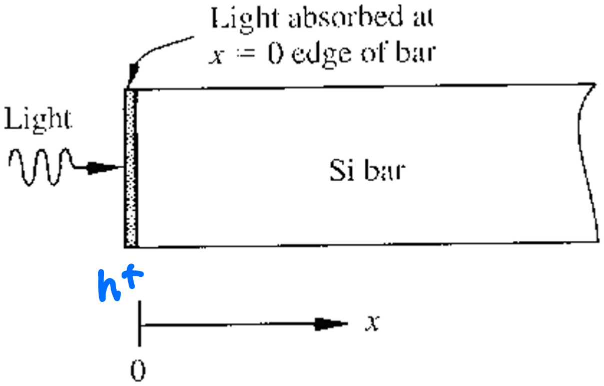
Homework 3 due Friday Sept 26th by 5pm

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 $\delta\rho(x = 0) = \Delta p$
- Injected holes diffuse along the bar, recombining with lifetime, τ_p
- For this problem, the solution to the steady state diffusion equation for holes has the form:

$$\frac{d^2 \delta p(x)}{dx^2} = \frac{\delta p(x)}{L_p^2}$$



2nd order D.E. solution

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

ignore first term

- C_1 and C_2 are the boundary conditions
- Excess holes decay to zero as $x \to \infty$: C_1 goes to 0
- At $x = 0$, C_2 will be Δp

Sources: Textbook

Steady-State Injection: Solution

- So, the solution becomes

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

- The injected excess h+ concentration dies out exponentially in x due to recombination

- What does the diffusion length, L_p, physically represent?
  - The distance at which the excess h+ distribution is reduced to 1/e of its value at the injection point (x=0)
  - We can show that L_p is the average distance a hole diffuses before recombining (see textbook)

Light

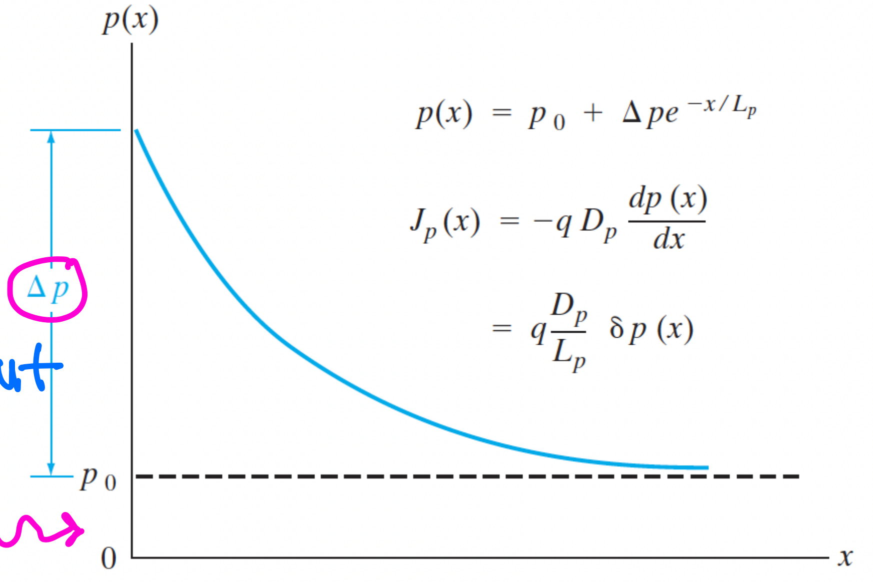
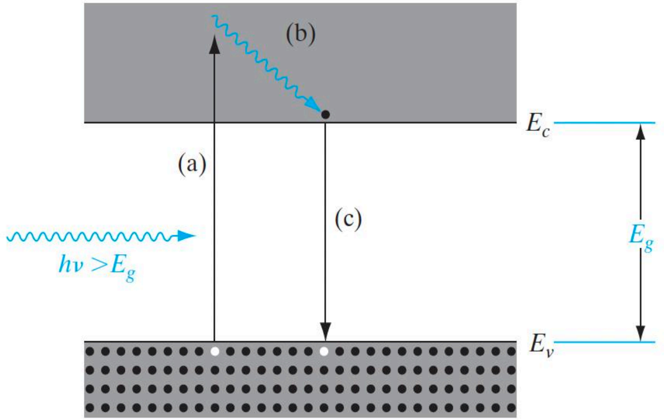


Figure 4–17
Injection of holes at $x = 0$, giving a steady state hole distribution $p(x)$ and a resulting diffusion current density $J_p(x)$.

Sources: Textbook

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)
  - $E = h\nu = \frac{hc}{\lambda}$ ← c = speed of light ← wavelength
  - Eg can be determined from the minimum energy ($h\nu$) of photons that are absorbed by the semiconductor
  - If $E_{photon} <$ Eg, 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…)

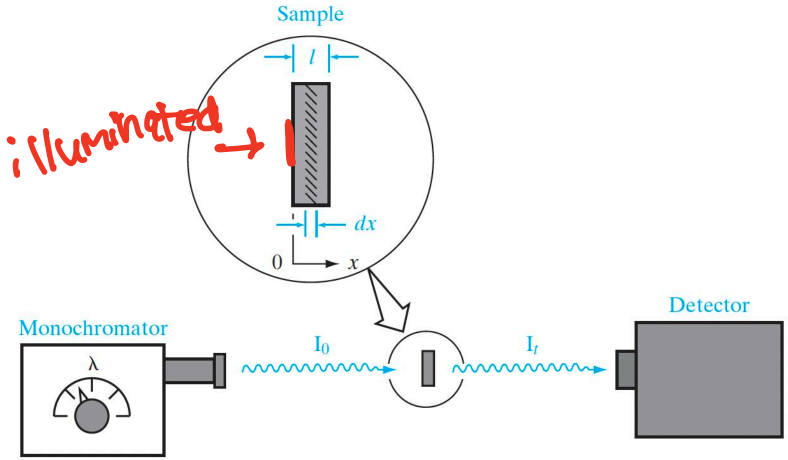
Absorption Coefficient

- 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/cm^2-s)

- Intensity at a distance *x* from the surface can be found:
  - $I(x) = I_0 e^{-\alpha t}$ ← t is thickness (l in this case)
- So what's the intensity transmitted through the sample?

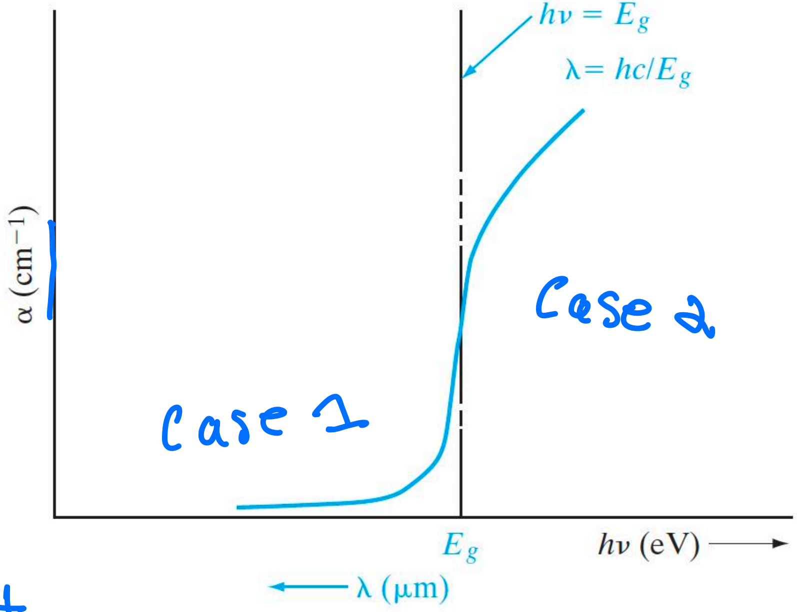
$$I(x=l) = I_t = I_0 e^{-\alpha l}$$

- There is some predictable amount of absorption (material dependent)
- Called the **absorption coefficient**, α
  - Units: cm^{-1}



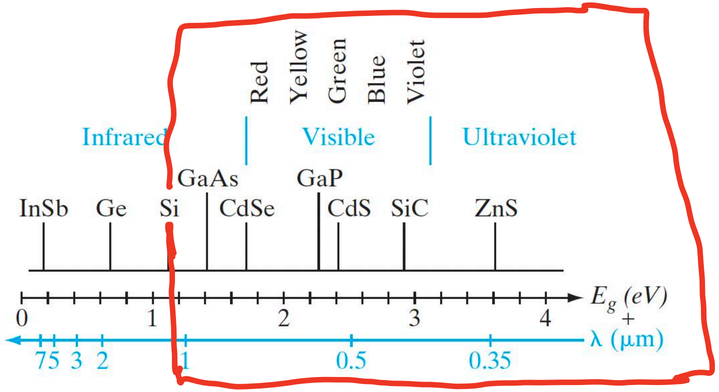
Absorption Dependence on Photon Energy

- α will vary with ___λ___ and ___material___
- At small E (long λ): $E_{ph} < E_g$
  - Absorption is ___negligible___ : case 1
- At large E (short λ): $E_{ph} \geq E_g$
  - Absorption is ___considerable___ : case 2
- 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

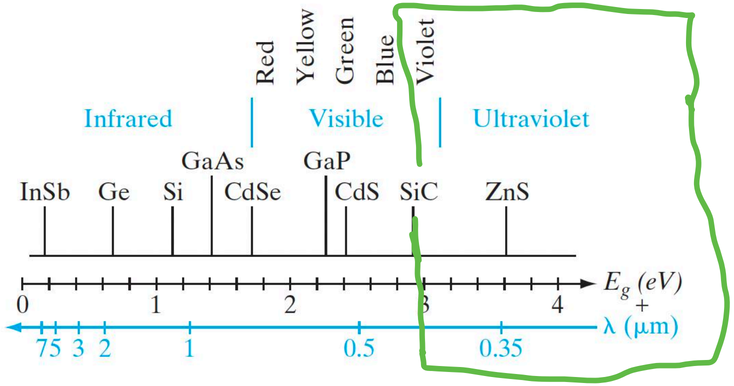
- Once again: semiconductors absorb photons with energies equal to the band gap, or larger.



- What wavelength light can Si absorb?

$E_g = 1.1$ eV

$E_{ph} \geq 1.1$ eV

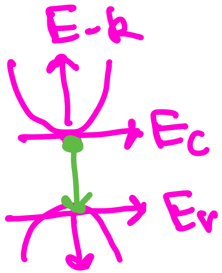


- How about SiC?

E_g (SiC) ≈ 3 eV

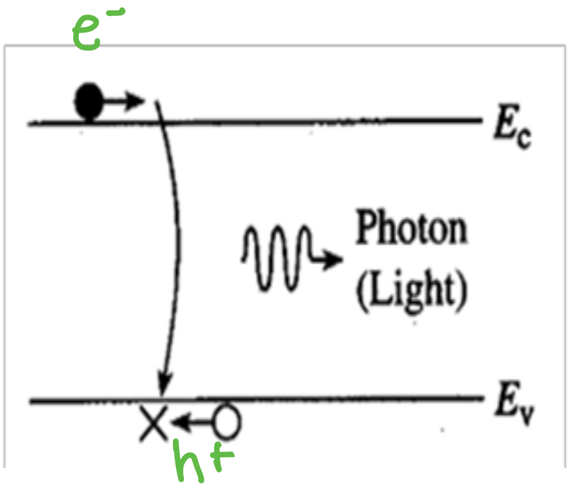
$E_{ph} \geq 3$ eV

Direct Recombination (Radiative)



Direct

- 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!
- Direction 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 E_g
- This happens spontaneously, meaning the rate of recombination is constant in time
- Given by the recombination constant, α_r
  - Units: cm^3/s



Not to be confused optical absorption coefficient, α!

Indirect Recombination

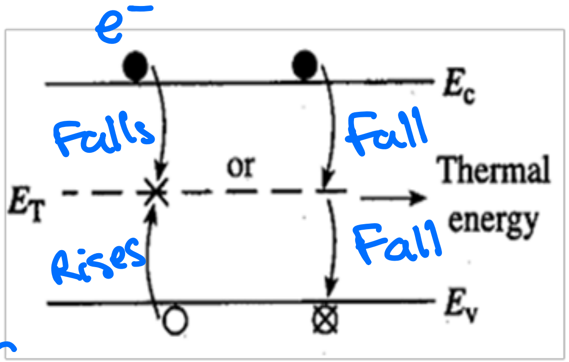
E_c ∪ E_v ∩ × indirect

- Multiple steps for EHP to recombine
- R-G center (trap-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 E_T
  - 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 (non-radiative)
  - It is instead transferred to another carrier
- In general, is indirect or direct recombination to be faster? Direct, no secondary step

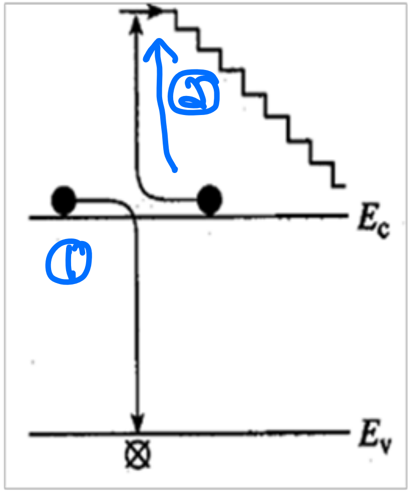
R-G Center

gen.

recomb.



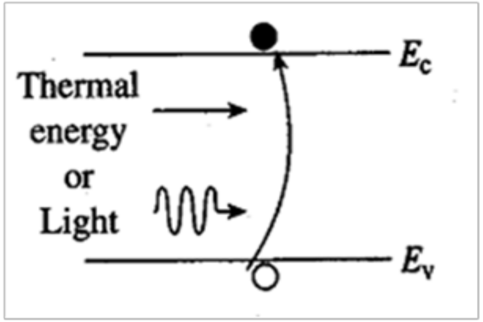
Auger



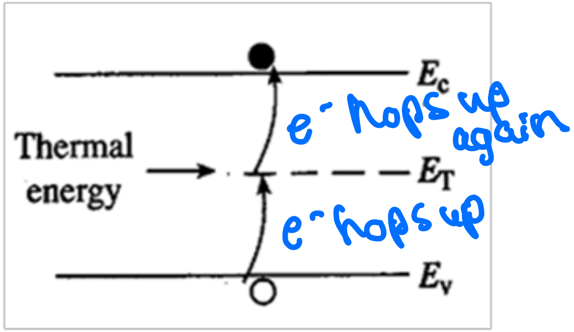
What about Generation Processes?

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

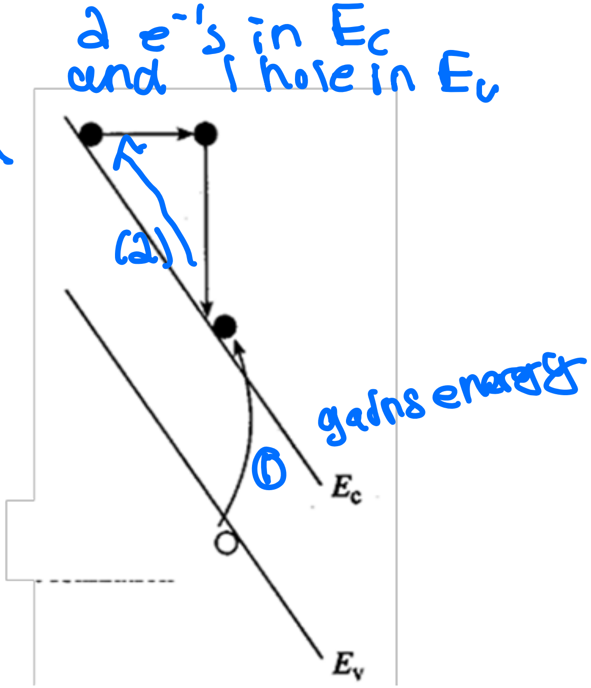
Band-to-Band



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)

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

- How do excess EHPs decay?
  - Assume n-type sample ($n_0 >> p_0$) so holes are in minority
  - Will majority carriers (electrons) be disturbed much? no, n_0 is already large
  - What about minority carriers (holes)? Yes, p_0 is small!

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 Δp (at x=0) and t=0,
$$\delta p(t) = \Delta p e^{-\alpha_r n_0 t} = \Delta p e^{-t/\tau_p}$$
- If the material is p-type ($p_0 >> n_0$), the minority carrier concentration similarly becomes,
$$\delta n(t) = \Delta n e^{-\alpha_r p_0 t} = \Delta n e^{-t/\tau_n}$$

Recall:

- What is α_r?
  - Recombination coefficient
  - Units: cm^3/s
- What is τ?
  - Recombination lifetime $\tau_{Si} = 10^{-8}$ s
  - Units: s

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

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

$\delta n = \delta p$

Low-Level Injection

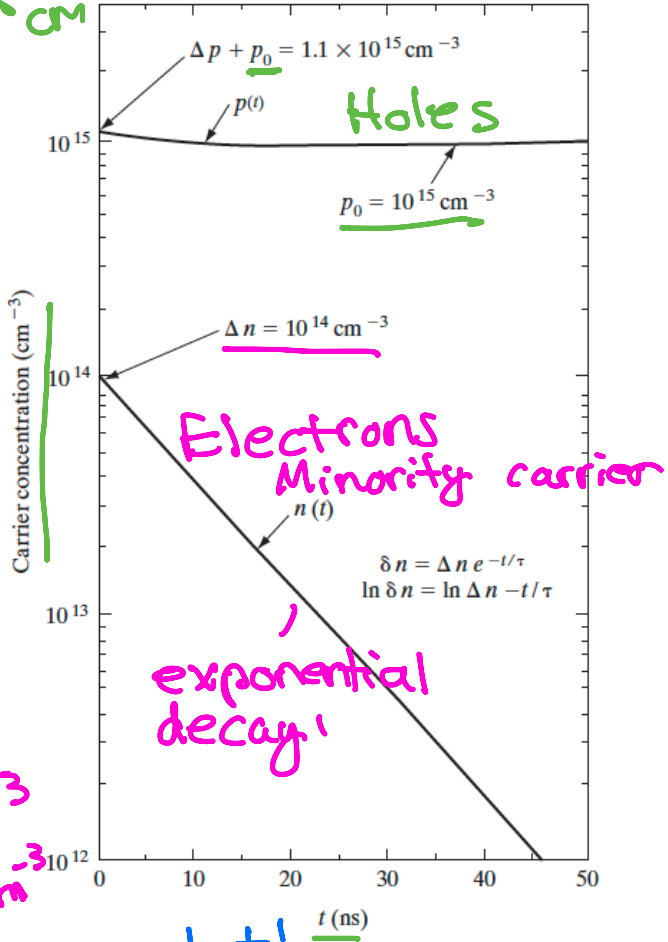
p-type sample

- More generally, we can write:

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

$p_0 = 10^{15}\ cm^{-3}$

$\Delta p = \Delta n = 10^{14}\ cm^{-3}$



- 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

$n_0 = 10^{12}\ cm^{-3}$

$\Delta n = 10^{14}\ cm^{-3}$

* High level injection is when maj. and min. carrier concentrations both increase a lot!

Steady-State Carrier Generation

- Recall,
  - Thermal equilibrium: generation = recombination
  - Steady-state: all time derivatives ($\partial/\partial t$) = 0

$$g(T) = \alpha_r n_i^2 = \alpha_r n_0 p_0$$

- If a **steady** light is shone on the sample, an optical generation rate g_{op} and assuming no trapping, $\Delta n = \Delta p$, (Recall e^- and h^+ generated as pairs)

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

gen. in equilibrium

gen. due to optical excitation

- Assuming low level injection, we can rewrite this,

majority carrier conc. not significantly impacted

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

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

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

Problem: Optical Generation and Recombination

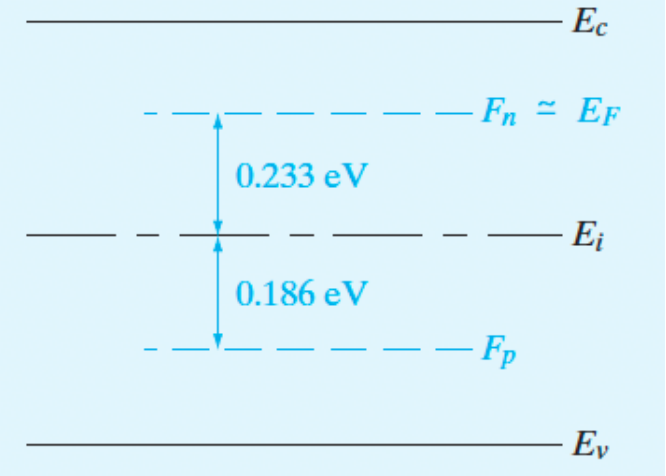
- GaAs doped with 2×10^{15} donors/cm^3 and having 4×10^{14} EHP/cm^3 created uniformly at t = 0. Assume that $\tau_p = \tau_p = 5\ \mu s$. Calculate the recombination coefficient α_r for this low-level excitation. Assume that this value of α_r applies when the GaAs sample is uniformly exposed to a steady state optical generation rate g_{op} = 10^{19} EHP/cm^3-s. Find the steady state excess carrier concentration $\Delta n = \Delta p$.
- First, we find the equilibrium hole concentration,
- $p_0 = \frac{n_i^2}{n_0} = \frac{(2\times10^6)^2}{2\times10^{15}} = 2 \times 10^{-3}\ cm^{-3}$
- Next, we find the recombination coefficient (rearranging eq. on previous slide)
- $\alpha_r = \frac{1}{\tau_n(n_0+p_0)} = \frac{1}{(5\times10^{-6})(2\times10^{15}+2\times10^{-3})} = 10^{-10}\ cm^3/s$
- $\Delta n = \Delta p = g_{op}\tau_p = \left(10^{19}\frac{cm^{-3}}{s}\right)(5 \times 10^{-6}\ s) = 5\times10^{13}\ cm^{-3}$

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,***
  - ___F_n___ for ___e^-___
  - ___F_p___ for ___h^+___
- 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

low-level injection!

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



$$\boxed{\begin{aligned} n &= n_i e^{(F_n - E_i)/kT} \\ p &= n_i e^{(E_i - F_p)/kT} \end{aligned}}$$

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 $N_a = 10^{17}$ cm^{-3}, we inject holes such that the steady state excess hole concentration is 5×10^{16} cm^{-3} at x = 0. What is the steady state separation between F_p and E_c at x = 1000 Å? What is the hole current there? *Assume that* $\mu_p = 500\ cm^2/(V \cdot s)$ *and* $\tau_p = 10^{-10}\ s. =$

- $D_p = \frac{kT}{q}\mu_p = 0.026(500) = 12.95\ \frac{cm^2}{s}$
- $L_p = \sqrt{D_p \tau_p} = \sqrt{(12.95)(10^{-10})} = 3.6 \times 10^{-5}\ cm$
- $p = p_0 + \delta p(x) = p_0 + \Delta p e^{-\frac{x}{L_p}} = 10^{17} + (5 \times 10^{16}) e^{-\frac{1000 \times 10^{-8}}{3.6 \times 10^{-5}}} = 1.379 \times 10^{17}\ cm^{-3}$
- Now, we can solve the carrier concentration equation,
- $p = n_i e^{\frac{E_i - F_p}{kT}} \rightarrow E_i - F_p = \ln\left(\frac{p}{n_i}\right) kT = \ln\left(\frac{1.379 \times 10^{17}}{1.5 \times 10^{10}}\right) 0.026 = 0.415\ eV$
- $E_c - F_p = (E_c - E_i) + (E_i - F_p) = \frac{1.1\ eV}{2} + 0.415\ eV = 0.965\ eV$
- $I_p = A J_p(x) A \frac{qD_p}{L_p} \delta p(x) = A \frac{qD_p}{L_p} \Delta p e^{-\frac{x}{L_p}} = (0.5) \frac{(1.6 \times 10^{-19})(12.96)}{3.6 \times 10^{-5}} (5 \times 10^{16}) e^{-\frac{1000 \times 10^{-8}}{3.6 \times 10^{-5}}}$

$$I_p = 1.09 \times 10^3\ A$$

Photoconductivity

- Last but not least, we have excess carriers with the lights ON. Will the conductivity (resistivity change)?

- Recall: σ = $q(\mu_n n_0 + \mu_p p_0)$
- 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:

Steady-state: $n = n_0 + \delta n \qquad p = p_0 + \delta p$

Not steady-state: $n(t) = n_0 + \delta n(t) \qquad p(t) = p_0 + \delta p(t)$

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

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