EE 116 Lectures 16-17

Optical Absorption; Recombination; Quasi-Fermi levels

- We continue studying semiconductors with light ON
  - **Read 2.8 to 2.8.2, 2.8.6 and 2.11.5 in BVZ online book**

- But first, recall that with the lights OFF, the number of "free" carriers in a sample are just given by:

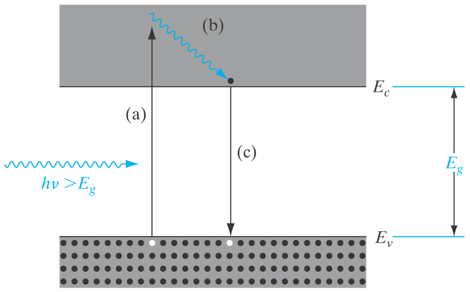
  1) Thermal generation = recombination:

  2) Charge neutrality:

  [two equations with two unknowns;
  a little nicer when $N_D >> N_A$ or $N_A >> N_D$]

- When we turn light on, we can generate electron-hole pairs (EHPs), depending on the light frequency (energy)

- What is the condition for light absorption?
- Plot intensity of transmitted light vs. incident photon energy:

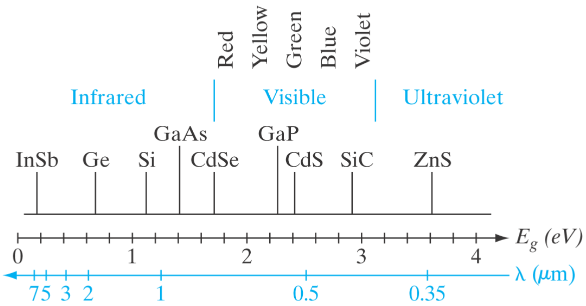


- Assume $\hbar\omega > E_G$ and sample of thickness L
- The intensity of transmitted photons is:

- Where $\alpha =$

- Plot the absorption coefficient vs. photon energy:

- Keep in mind some of the material band gaps:



- Semiconductors absorb photons much more efficiently at energies greater than the band gap ($\hbar\omega > E_G$)

- Light absorbed created excess EHPs

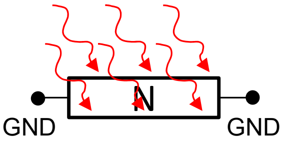
- How long do excess EHPs “live” before they recombine?

- Direct EHP recombination occurs spontaneously, emitting a photon of energy ______________

- Excess carrier notation:
  - δn(t) = δp(t) instantaneous excess EHPs at time t
  - Δn = δn(t=0) initial excess EHPs at time t = 0, right after initial excitation (e.g. light flash)

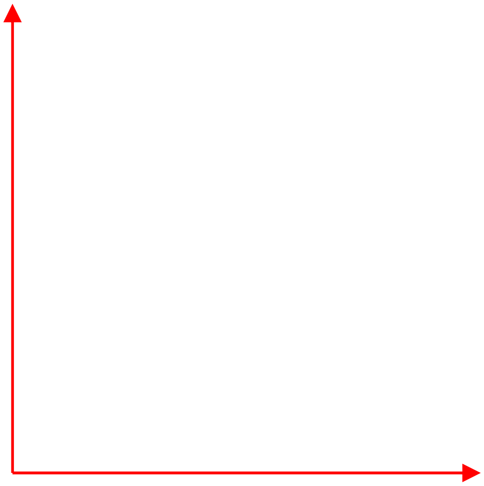
$$n = n_0 + \delta n \qquad\qquad p = p_0 + \delta p$$

- How do excess EHPs evolve <u>in time</u>?
  - **Assume <u>uniform</u> illumination and generation ($d^2/dx^2 = 0$)**
  - Assume n-type sample ($n_0 >> p_0$) so holes are in minority
  - Will <u>majority</u> carriers (electrons) be disturbed much?
  - What about <u>minority</u> carriers (holes)?

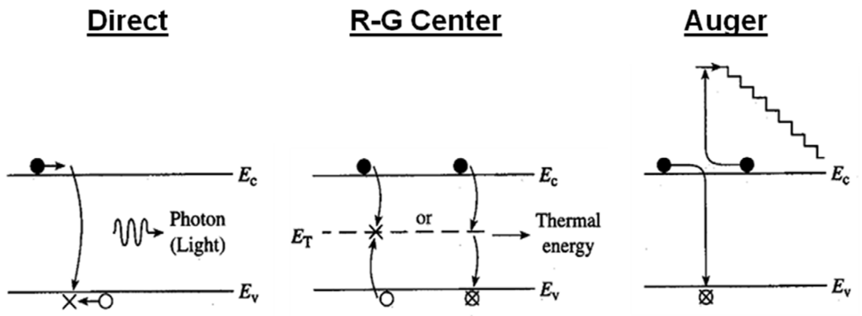


- Excess minority holes will recombine with already existing majority electrons: $\frac{d}{dt}\delta p(t) \approx -\alpha_r n_0 \delta p(t)$
- Solution is a simple exponential: $\delta p(t) = \Delta p e^{-\alpha_r n_0 t} = \Delta p e^{-t/\tau_p}$
- Typical EHP recombination in Si are $\tau \sim$
- Direct recombination → δn decay at same rate as δp

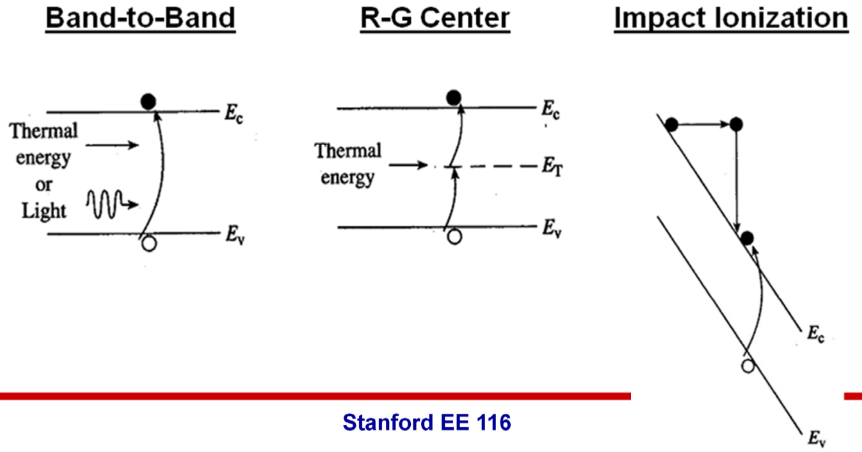
- <u>Ex:</u> p-doped GaAs sample with 10^{15} cm^{-3} acceptors. Flash light (on/off) to produce $\Delta n = \Delta p = 10^{14}$ EHPs/cm^3 at t=0 <u>uniformly</u>. Recombination lifetime τ = 10 ns. How do p(t) and n(t) evolve with time?



- Recombination processes (more generally):



- Generation processes:



- Revisit some definitions:
  - Thermal equilibrium: generation = recombination, no current, constant T
  - Steady-state: all time derivatives ($\partial/\partial t$) = 0

- <u>Ex:</u> A sample of Si doped with $N_A = 10^{16}$ cm^{-3}, with recombination lifetime τ = 1 μs. It is exposed *continuously* to light, such that electron-hole pairs are generated throughout the sample at the rate of 10^{20} per cm^3 per second, *i.e.* the generation rate $G_L = 10^{20}$/cm^3/s.

  a) What are equilibrium n_0 and p_0 (before light is on)?

  b) How many extra δn and δp are there with light on?

c) What are total carrier concentrations with light on?

d) What is the *n·p* product?

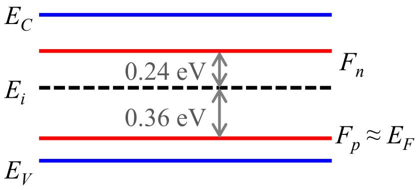
- Note: so far, Fermi level (E_F) has only been defined in *thermal equilibrium*, giving us n and p like:

- Q: What does Fermi level look like when we have excess carriers (from light) and hence non-equilibrium?
- A:

- But we like similar (easy) equations so we define *quasi-Fermi* levels F_n and F_p:

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

- Ex: Calculate and draw quasi-Fermi levels from the previous example.



- Last but not least. We have all these excess carriers with the lights ON. Does the conductivity (resistivity) change?

- Remember: $\sigma = q(\mu_n n_0 + \mu_p p_0)$
- Often before, with lights off, we could neglect the minority carriers if the sample was doped n- or p-type
- But with lights ON, we have extra carriers δn and δp such that n and p are affected:

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

- Photoconductivity = change in conductivity due to excess carriers (EHPs) from lights being turned on:

$$\delta\sigma = q(\mu_n \delta n + \mu_p \delta p)$$

Some common midterm issues (from 2017)

- Do not mix v_T (thermal) with v_d (drift)
- Metals are not n-type (but they can have "high" or "low" workfunction, corresponding similar to p-type or n-type semiconductors)
- Heated n-type device can become intrinsic, not p-type
- Check v_d for v_{sat} at high field (I is not linear in V at high voltage)
- Impurity scattering is limited by N_D+N_A (not N_D or N_A alone)
- Open circuit means E_F flat and $J_{TOT}=0$
- Cannot ignore majority carrier diffusion with light illumination
- In devices much longer than diffusion length ($L \gg L_{p,n}$) surface diffusion currents go to zero "far" away where n, p gradients flatten out

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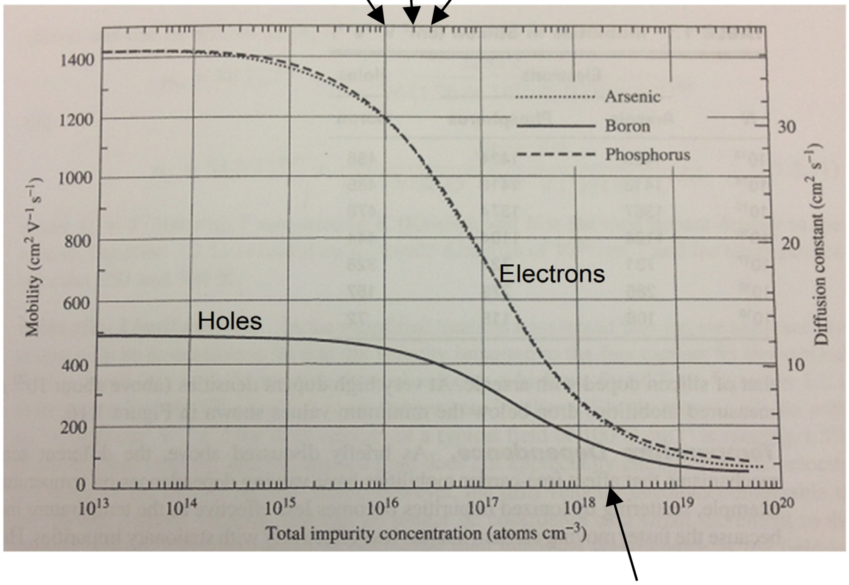
More common midterm issues (from 2018)

- 1 Å = 0.1 nm = 10^{-8} cm = 10^{-10} m
- Be careful when converting cm^3 to m^3, there is a 10^6 factor
- Mobility changes with doping... see plot on page 1 of exam

- Draw complete energy band diagram, including E_C, E_V, E_i, E_F
- Electrons drift (move) against $\mathcal{E}$-field, but $J_{drift,n}$ is in $\mathcal{E}$-field direction
- Diffusion (net motion of electrons & holes) from high (n, p, T) to low (n, p, T)

- Be careful when reading log-scale graphs
- Electron-hole recombination lifetime (μs-ms) is NOT the scattering time (ps)
- If you get unreasonable numerical value (e.g. 10^{-12} cm diffusion length, or 50,000 mobility in Si) please STOP and think whether this makes sense

10^{16} $2\text{x}10^{16}$ $3\text{x}10^{16}$



$2\text{x}10^{18}$