ECE 340
Lecture 14: Carrier R-G I

Class Outline:

• Direct Recombination
• Steady State Carrier Generation

Things you should know when you leave...

Key Questions

• What are the major mechanisms for recombination?
• What are the major mechanisms for generation?
• What is trapping?
• How do I describe the carrier concentrations out of equilibrium?

Direct Recombination

If a beam of photons hits a semiconductor, there should be some predictable amount of absorption.

This should depend on materials parameters:

- Thickness
- Energy of photons

A beam of photons (photons/cm²*s) is directed at the sample of thickness, l, where the beam only contains photons of wavelength, λ.

The intensity of the transmitted beam can be calculated by considering the absorption in any increment dx.

Since the photon has no memory of how far it has travelled, the probability of absorption is constant.

\[ \frac{dI(x)}{dx} = \alpha I(x) \]

Degradation of intensity is proportional to the intensity remaining at x.

\[ I(x) = I_0 e^{-\alpha x} \]

- \( \alpha \) is the absorption coefficient and has units of cm⁻¹.
- There is negligible absorption at long wavelengths (hv small) and considerable absorption of photons with energies greater than \( E_g \).
Let's visualize this decay of carriers...

1. This sample is doped with $10^{15}$ cm$^{-3}$ acceptor atoms.
2. The intrinsic carrier concentration is about $10^{6}$ cm$^{-3}$ in GaAs.
3. Minority carrier concentration is $\sim 10^3$ cm$^{-3}$.
4. $10^{14}$ cm$^{-3}$ EHP are added to the system.
5. Figure shows the decay lifetime of the excess populations for a carrier recombination lifetime of 10 ns.

**Steady State Carrier Generation**

We have been discussing carrier recombination.

Type 1: Direct recombination
- Electron and hole drift into the same vicinity and recombine.
- They can give off light if the semiconductor has a direct bandgap.
- Create states in the band gap.
- Electrons see a potential well and get trapped losing energy. Holes are attracted to the electron and annihilates it giving off heat to the lattice.

Type 2: R-G Center recombination
- R-G centers may be impurity atoms or lattice defects.
- EHP are added to the system.
- Excess majority carriers decay at same rate as minority carriers.
- There is a large change in the minority carrier concentration, but a small one in the majority carrier concentration.

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Type 3: Auger recombination
- Collision between two like carriers.
- Energy released by recombination is given to the surviving carrier.
- Surviving electron then loses excess energy through lattice collisions.
Steady State Carrier Generation

But where there is recombination, there is generation…

Type 1: Band-band generation
- Electron is excited directly from the valence band to the conduction band.
- Either thermal energy or light can provide the energy required for the transition.

Type 2: R-G Center generation
- Create states in the band gap as in the case of recombination.
- Electrons absorb phonons and are excited from the valence band to the impurity band. A second phonon interaction promotes the electron into the conduction band.

Type 3: Impact ionization generation
- Occurs in high electric field regions.
- Electrons gain enough energy that when they collide with the lattice they ionize and electron and create an electron-hole pair.
- Created electrons are then accelerated and the process repeats.

In the steady state...

- The generation rate must be balanced by the recombination rate.
- Further, this equality maintains the equilibrium carrier concentrations and must include all possible generation mechanisms.

Thermal generation rate

Now let's shine light on the situation...

We must now add an additional generation rate \( g_{op} \) to the generation process...

- Carrier concentrations \( n \) and \( p \) will increase to new steady state values.
- We can express the balance between carrier recombination and generation in terms of the equilibrium carrier concentrations and the departures from equilibrium.

What are we neglecting?

- Probability of direct electron-hole recombination in group IV materials is very small.
- Recombination events occur through traps.
- Energy given off as heat rather than light.
Steady State Carrier Generation

So we ignore trapping.

For steady state recombination $\delta_n = \delta_p$, so we now have...

$$g(T) + g_{op} = \frac{\alpha_e n_0 p_0}{\tau_e} + \frac{\alpha_p (n_0 + p_0) \delta n + \delta n^2}{\tau_e}$$

**Thermal generation rate**

Assume again that we have low-level injection so we can neglect the $\delta n^2$ term...

$$g_{th} = \frac{\alpha_e (n_0 + p_0) \delta n}{\tau_e}$$

And the excess carrier concentration may be written as...

$$\delta n = \delta p = g_{op} \tau_p$$

Caution: when trapping is present these rates for electrons and holes are not equal.

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**Steady State Carrier Generation**

But we're not in equilibrium, so what happens now??

When we were in equilibrium...

$$n = \frac{e^{qE_F/kT} - 1}{e^{qE_F/kT} + 1}$$

$$p = \frac{e^{qE_F/kT} + 1}{e^{qE_F/kT} - 1}$$

Carrier concentrations have a one-one correspondence with the Fermi level.

Consider the following situation: a uniformly donor doped silicon wafer maintained at room temperature is suddenly illuminated with light at time $t = 0$. Assuming $N_D = 10^{15}$ cm$^{-3}$, $\tau_p = 10^{-6}$ sec and a light induced creation of $10^{17}$ electrons and holes per cm$^3$-sec throughout the semiconductor.

How do we describe the bands, carrier concentrations?

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**Steady State Carrier Generation**

How do we get the carrier concentrations from the quasi-fermi levels?

**Electron quasi-fermi level:**

$$E_n = E_F - kT \ln \left( \frac{n}{n_0} \right)$$

**Hole quasi-fermi level:**

$$E_p = E_F - kT \ln \left( \frac{p}{p_0} \right)$$

- We can now use the same formalism to determine the carrier concentrations out of equilibrium.
- The above equations are assuming that the semiconductor is non-degenerate.
- Notice that $E_n$ and $E_p$ are simply conceptual constructs determined by prior knowledge of $n$ and $p$.
- The quasi-fermi levels are chosen so that if the system relaxes back to equilibrium then normal carrier concentration equations are recovered.

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Old Band Diagram

*The electron concentration is unperturbed but the hole concentration has increased many orders of magnitude.
*The old band diagram no longer adequately represents the situation in the semiconductor as the Fermi level is only defined for a system in equilibrium.
*To deduce the carrier concentrations, we introduce the quasi-fermi levels.