Recombination of Electrons Lesson

Lesson Topic: Recombination of Electrons

Objective of Lesson: To learn about recombination of electrons and holes in semiconductors.

Reading Assignment: Sections 3.3.1, 3.3.2, 3.3.4

Discussion Questions:

   1. What are the differences among the three mechanisms of recombination in semiconductors?
   2. What is the same for all three mechanisms of recombination in semiconductors?

Homework: Derive the last equation of this lesson.

What do you need to know for the exam?:

   1. You must be able to recognize the recombination mechanisms.
   2. You must know where the energy goes after the transition.
   3. You must be able to recognize the equations for the recombination rates for each mechanism.
   4. You must be able to simplify the rate equations for low injection conditions.

Summary
There are three mechanisms for the recombination of electron-hole pairs in the bulk of a semiconductor, Shockley-Read-Hall (or thermal recombination), radiative recombination, and Auger recombination. The three have similarities and differences, but once we get quantitative, the recombination rate equations for all three can be expressed in identical fashion. Topics such as low level injection and excess carriers are also explained.

Recombination of Electrons and Holes
Recall that electrons tend to move to lower energies (we like to say, unscientifically, that they "prefer" lower energy states). When this transfer occurs from band to band, we call it recombination.

The mechanisms of recombination are illustrated in the text and below. Each mechanism shows the loss of an electron and a hole and each involves the transfer of the potential energy of the electron to another entity. By "recombination mechanism" we are talking about a way that we can lose electrons from the conduction band and holes from the valence band. Each of the three most important recombination mechanisms is present in EVERY semiconductor, but they are not equally important in each semiconductor. In fact there is usually one mechanism that is dominant—one that is much more efficient than the others at causing the loss of electrons and/or holes under the conditions present in the semiconductor.

The three mechanisms of recombination are Auger recombination, radiative recombination, and Shockley-Read-Hall recombination (or SRH recombination or thermal recombination), and they are depicted below.
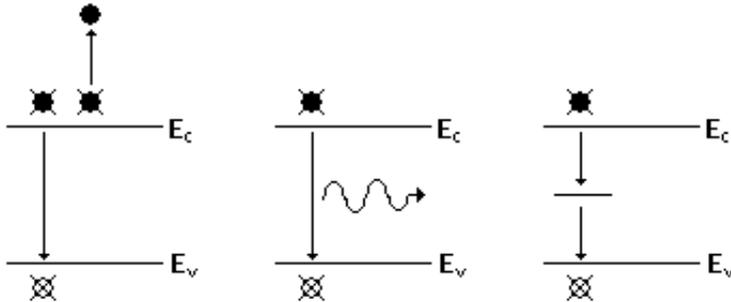
The table below lists the recombination mechanism and the corresponding receiver of the energy.

SRH	energy lost to lattice in form of phonons
Radiative	energy lost to photon
Auger	energy lost to other carrier—other electron or hole, but not both for one event

The rates of recombination for each mechanism are,

$$R_{rad} = B(pn - n_i^2)$$

$$R_{SRH} = \frac{pn - n_i^2}{\tau_n(p + n_i) + \tau_p(n + n_i)}$$

$$R_{Auger} = C_n n(pn - n_i^2) + C_p p(pn - n_i^2)$$

Let's focus on the SRH recombination first. The equation looks pretty complicated (there are already several assumptions built into the derivation of this equation, including low-level injection and that the traps are very near the middle of the bandgap), but for most situations, the equation is easily simplified. Assume we are dealing with an n-type semiconductor with a typical doping concentration, and that we are in low injection—whoops! What is low injection?

Before we talk about low injection we first we need to define the excess carrier concentrations, Dn and Dp,

$$\Delta n \equiv n - n_o$$
$$\Delta p \equiv p - p_o$$

Dn and Dp, in other words, represent how much the respective carrier concentrations have changed from equilibrium—equilibrium becomes our reference point for non-equilibrium situations. Dn and Dp can both be negative as they are changes in carrier concentrations, and the change can be negative if you have extracted/removed carriers.

Back to low injection. In words low injection means the semiconductor is out of equilibrium, but that the majority carrier concentration has not been perturbed (changed). In equations we write it as Δp or $\Delta n \ll n_o$ for an n-type semiconductor and Δp or $\Delta n \ll p_o$ for a p-type semiconductor.

Comparing these conditions to the definitions above means that the majority carrier concentration is not changed significantly in low injection. More on low injection will appear in the next lesson.

Now back to trying to simplify the equation for the SRH recombination rate.

Let's assume we are talking about an n-type semiconductor in low injection again.

Replace all the n's with N_D because $n = n_o = N_D$ — because of low injection and because it is n-type, respectively, and replace $p = p_o + D_p$. The equation becomes,

$$R_{SRH} = \frac{p_o * N_D + \Delta p * N_D - n_i^2}{\tau_n(p_o + \Delta p + n_i) + \tau_p(N_D + n_i)}$$

.

Note that $p_o * N_D - n_i^2 = 0$ because that is essentially $p_o n_o = n_i^2$. Also note that $N_D \gg n_i$. Now we have,

$$R_{SRH} = \frac{\Delta p * N_D}{\tau_n(p_o + \Delta p + n_i) + \tau_p(N_D)}$$

.

One last assumption is that τ_n ? τ_p. Not so much that they have nearly the same value, but that

they are of similar orders of magnitude. If that is the case, then τ_{p_ND} will be much larger than any other term in the denominator. Further simplification results in,

$$R_{SRH} = \frac{\Delta p}{\tau_p}$$

.

What a nice and simple equation! The SRH recombination rate in an n-type semiconductor is dependent on the number of excess holes and on the time constant, τ_p, which is called the minority carrier lifetime. Let's look at this from another perspective. Recall the figure above illustrating SRH recombination; it shows it as a two-step process, and we associate τ_n with the first step in the process, the capturing of a free electron, and $?_p$ with the second step of the process, the annihilation of a hole. Now let's add a Fermi level indicating an n-type semiconductor. This is what it would look like.

$$\rule{4cm}{0.4pt}\ E_C$$
$$\rule{4cm}{0.4pt}\ E_F$$
$$\quad\quad\blacklozenge$$
$$\rule{4cm}{0.4pt}\ E_V$$

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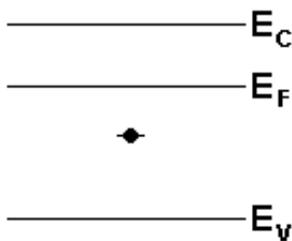
Note the Fermi level above E_i. Recall that we have a rule about the Fermi level that says that any states below the Fermi level are filled—that is why the figure shows the trap state as being filled. At equilibrium that trap state is filled. The first step of the two-step SRH recombination process has already been completed before any non-equilibrium situation is created. This is what the equation above is suggesting—that the SRH recombination rate has nothing to do with τ_n because the first step is already completed.

The same conclusions can be drawn about a p-type semiconductor. In that situation the trap is empty so it easily captures an electron. It will release that electron to the valence band quickly because there are so many empty valence states, and we don't care how long it takes because we are usually looking at minority carriers anyway.

The radiative recombination rate can be recast/simplified as well. Let's assume another n-type semiconductor in low injection, and it is easily shown that,

$$R_{rad} = B(p_oN_D + \Delta pN_D - n_i^2)$$

which simplifies to, $R_{rad} = B\Delta pN_D$

which looks like

$$R_{rad} = \frac{\Delta p}{\tau_p}$$

$$\text{if } \frac{1}{\tau_p} = BN_D$$

B is a constant known as the Einstein coefficient for radiative recombination. The key here is that we can make the simplified radiative recombination rate equation look like the simplified SRH recombination rate equation.

The Auger recombination rate can be simplified to $R_{Auger} = \dfrac{\Delta p}{\tau_p}$

$$\text{if } \frac{1}{\tau_p} = C_p N_D^2$$

.

As all three mechanisms are present in all semiconductors, we can deduce that $\dfrac{1}{\tau_{p_{total}}} = \dfrac{1}{\tau_{p_{rad}}} + \dfrac{1}{\tau_{p_{SRH}}} + \dfrac{1}{\tau_{p_{Auger}}}$

, indicating that the several recombination mechanism rates add together like resistors in parallel—this make sense because they are all paths of varying "resistance" (or conductance!) for electrons to travel from conduction band to valence band.

The equation you will see the most to represent the recombination rate in a semiconductor is $R = \dfrac{\Delta p, n}{\tau_{p,n}}$

for a(n) n-type, p-type semiconductor. Note that what we have done here shows that the lifetime can concurrently represent all recombination mechanisms—still, most texts, including Pierret's, will have in mind the SRH mechanism when that equation is written because the SRH mechanism is the dominant mechanism in silicon and silicon is the dominant semiconductor.

Useful other links
[Electronic transitions in an atom](#)

Definitions:

  Injection: Act of inserting something.

  Recombine: To combine again, to refill a hole with an electron.

  Shockley: A smart guy named Bill (well, William). Lived 1910-1989. He was a British-born, American physicist. He shared a 1956 Nobel Prize for the development of the   electronic

transistor.

   Read: A famous guy (to those of us in the semiconductor field) who developed some of the early semiconductor theory, including recombination.

   Hall: Another famous guy (to those of us in the semiconductor field) who developed some of the early semiconductor theory, including recombination.

   Auger: Yet another famous guy (to those of us in the semiconductor field) who developed some of the early semiconductor theory, including recombination.

   Radiative: Of or having to do with electromagnetic waves.