Semiconductor Devices and Circuits

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Lecture – 14
Recombination and Generation

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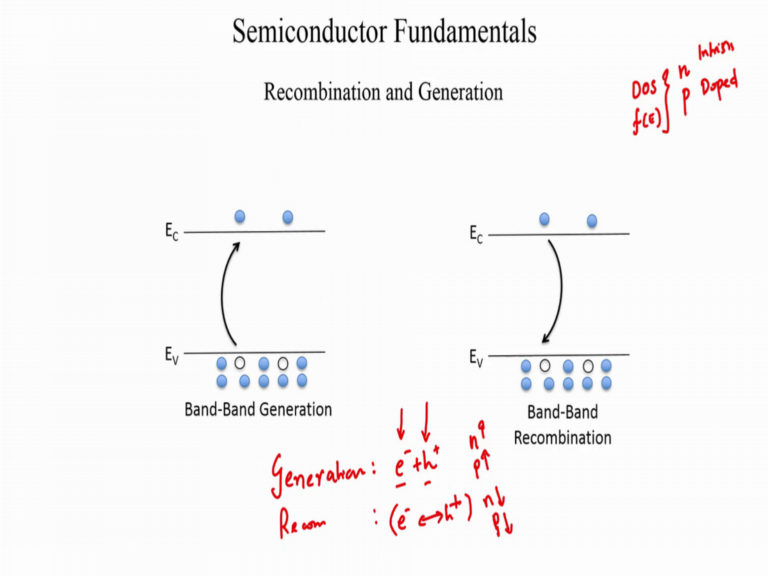

Semiconductor Fundamentals

Recombination and Generation

Generation : $e^- + h^+$ n↑ p↑

Recom : $(e^- \leftrightarrow h^+)$ n↓ p↓

We will now look at a very important concept with regards to semiconductors which is the mechanism of recombination and generation of carriers. So, far we have been able to establish a carrier count by while considering the semiconductor to be an thermal equilibrium. So, we kept the semiconductor in the dark where the electrons had only the ambient temperatures the source of energy. And we could calculate the density of states in the semiconductor we established something called as the Fermi function which gave us the probability that an electron occupy these states. And these two quantities we could measure the number of electrons and the number of holes in both an intrinsic semiconductor as well as in a doped semiconductor.

Now, what we are interested in this topic is to look at what happens when the semiconductor is taken out of equilibrium. You know what is the dynamics of the change in carrier count when the semiconductor shifted out of equilibrium. And even in equilibrium what are the mechanics or the mechanisms of you know of generation of carriers, and the recombination of carriers.

So, firstly, what do we mean by generation and recombination? So, by definition generation implies the mechanism by which electron hole pairs are created. So, you have a neutral specie and I you know it gets excited maybe through a photon, and you create an electron hole pair. And recombination is the process by which electron hole pairs are and highlighted. So, which means the electron and the hole they sort of meet each other, and they recombine. And they basically the electron essentially occupies the vacancy and there is no more free l that is no longer a free electron and a hole. So, we are you know as we mentioned before we are interested in the electrons in the conduction band and the holes in the valence band.

So, generation essentially increases n and p because you have increased you have created an additional electron and a hole in the conduction and valence bands respectively. Whereas, recombination lowers and n p because you are now taking carriers that were free, and now you are recombining them to form a neutral species, and therefore loop, the therefore, you are losing then you are in fact, dropping down in the carrier count. So, let us look at some of the basic mechanisms of carrier generation and recombination.

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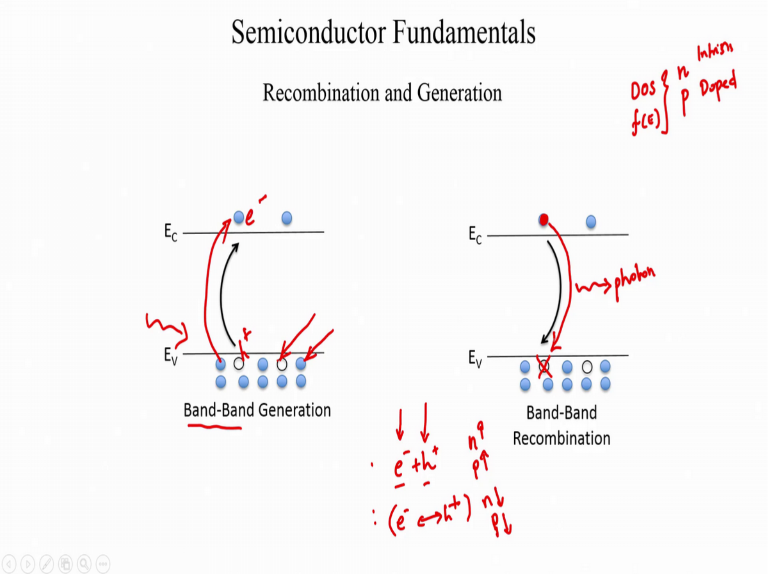

Semiconductor Fundamentals

Recombination and Generation

The first is something called as band to band generation and recombination. So, what does this mean? Band to band simply implies that you have your valence band, you have electrons here. So, I represent the electrons by these blue circles and I represent holes by these hollow circles. So, you have electrons here which are bound to the silicon atom.

And you have these electrons get some energy because of either thermal energy or perhaps a photon you know interacted with these electrons. And this electron is now excited and has enough energy to get into the conduction band, so that is something called as the band to band generation. So, you have created an electron in the conduction band and this electron has left behind a hole in the valence band.

Now, what is band to band recombination? It is the exactly opposite process. So, you have an electron in the conduction band and this electron most free I mean it was it was contributing to any current. But now due to some reason this electron has now dropped its lost energy and it has dropped down into the valence band and it has recombined with this hole. And this process this loss of energy typically results in some radiation. So, probably this electro might release a photon when it loses this energy. So, this mechanism is called as a recombination, and it is the band to band recombination. So, it is directly from the conduction band to the valence band.

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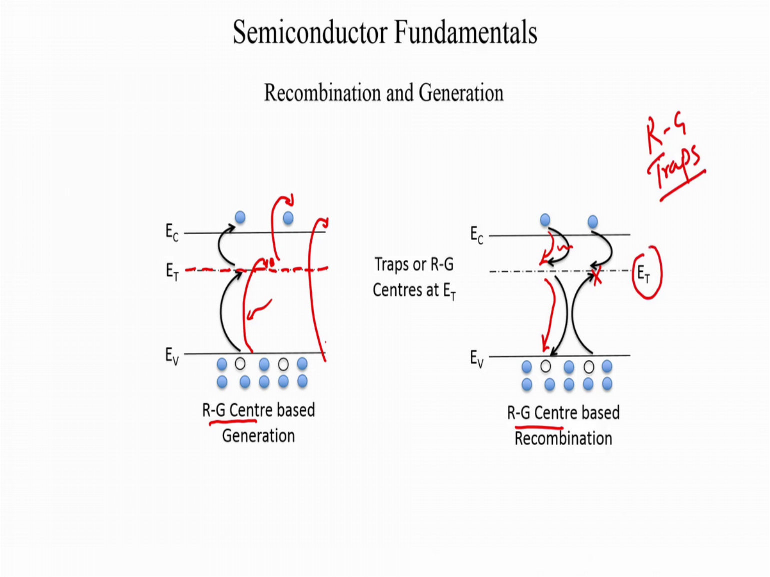

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Recombination and Generation

So, the next mechanism is something called as R-G center based generation and recombination. So, this mechanism is quite important from the point of view of this topic. And we will look at this mechanism in a bit of detail, but what this essentially states is that you have certain trap states located inside your band gap. So, these trap states we already looked at creating traps by doping a semiconductor, and those traps were you know the donor level traps or the acceptor level traps in the conduct created very close to the bandages. But one could in principle create trap states deeper inside the gap by probably doping it at some other specie or by or by just having defects in the semiconductor.

So, these trap states E it as a stepping stone or it is like a ladder for the recombination and generation processes. So, therefore, an electron in the valence band can first climb on to this state, can first occupy this state and then get excited into the conduction band. So, this may this two step process need not happen at the same time. And this is very strong because the energy needed for this jump is much smaller than the energy needed for a direct band to band generation. Therefore, this could lead to a significant increase in carrier count.

The R-G center based recombination mechanism is the exact opposite. So, you have an electron in the conduction band. And this electron falls into this trap state releases a small amount of energy, and then it drops down into the valence band or it could simply recombine at the location of the trap state. So, these are the generation and recombination mechanisms involving a R-G centre. So, R-G centres are simply recombination generation centres or we can also call them as traps. So, and we these traps are all sitting at this energy level E T.

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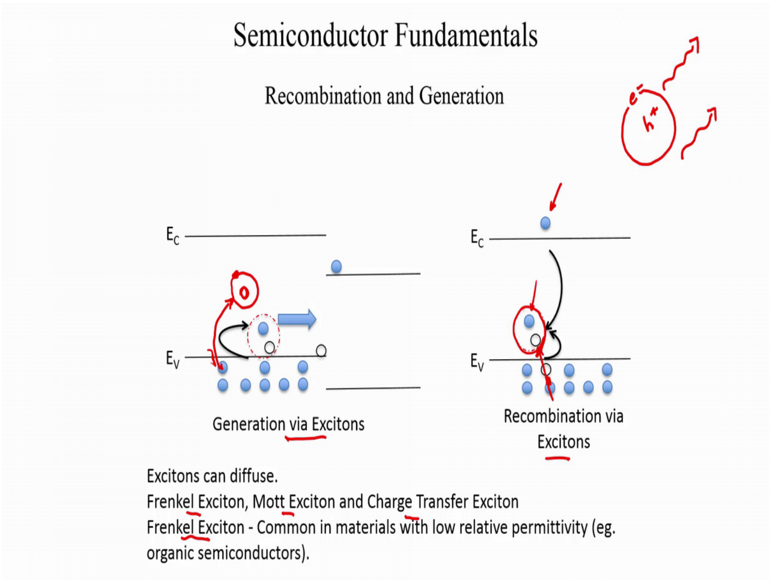

Semiconductor Fundamentals

Recombination and Generation

Generation via Excitons

Recombination via Excitons

Excitons can diffuse.

Frenkel Exciton, Mott Exciton and Charge Transfer Exciton

Frenkel Exciton - Common in materials with low relative permittivity (eg. organic semiconductors).

The next mechanism of recombination generation is something is a process that uses an entity called as an exciton. So, we say generation via excitons; and generation and recombination via excitons. So, what does the generation via excitons mean? So, an exciton is an entity there in you do have an electron that is free you do have a whole, but this electron and hole are sort of coupled to each other. So, you can think of it as a you know in the very hand wavy manner you can think of it as a hydrogen atom all right. So, you have this electron and hole that are bound to each other. So, they are not completely free from each other that is it, but this species such can actually diffuse through the medium it can actually move through the semiconductor.

So, excitons are quite common in materials that have got a very low relative permittivity for example, say organic semiconductors. So, excitons are quite common and they are not so common in probably materials that have got very high permittivity except under certain circumstances. So, you have different kinds of excitons you have the Frenkel exciton you have, the Mott exciton and you have something called as a charge transfect exciton. And what is common in organic semiconductors are due to their low relative permittivity is something called as the Frenkel exciton. It is a, very tight, it is a very tightly bound electron hole pair with a very small radii.

So, the generation via exciton so simply a mechanism wherein the electrons in the valence band where excited because of some energy they received. And they did become free from the clutch of the atoms in the lattice, but then they are still bound to the whole, and this species called as the exciton. And this exciton can be sort of energized or you know it can be it can lead to a pure electron hole pair separation probably due to this due to in the presence of an electric field.

The other mechanism is recombination via excitons, wherein you have a free electron hole pair and this electron hole pair they recombine, but do not recombine fully they instead form an exciton state. So, you they are no longer a completely free electron hole pair, they instead form an exciton. So, the exciton does not have any charge. So, although it can move it does not have any charge. So, therefore, this is an effective loss in terms of charge carriers.

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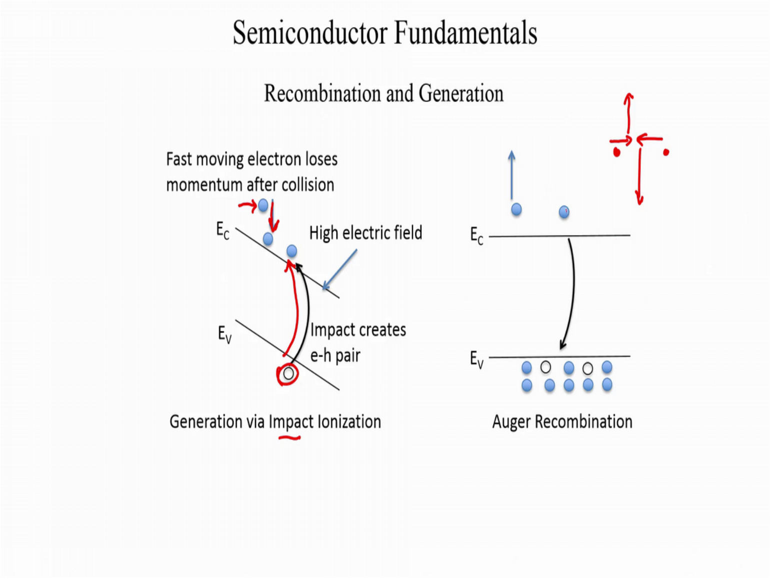
Semiconductor Fundamentals

Recombination and Generation

The next mechanism of generation and recombination is via something called is impact ionization. So, what is the impact ionization means you have a very fast moving electron and this electron collides with the atom in the lattice and that collision is so powerful that the atom gives up an electron and it not electron leaves behind a hole. So, here you have a high velocity electron, it is got a high velocity probably because of the presence of a very high electric field. And this high velocity electron loses energy after collision and that collision leads to the formation of a new electron and a whole pair.

Now, the exact opposite process is responsible for recombination. So, s, this is something called as Auger recombination. And what happens here is you have 2 electrons in the conduction band, and let us say they have a momentum exchange. So, they collide, and one of the electrons gains energy the other loses energy and recombines. So, one of the electrons gains energy it goes up to higher energy levels, whereas the other one loses energy and falls down to the valence band and recombines with the hole. So, this is something called as the Auger recombination process.

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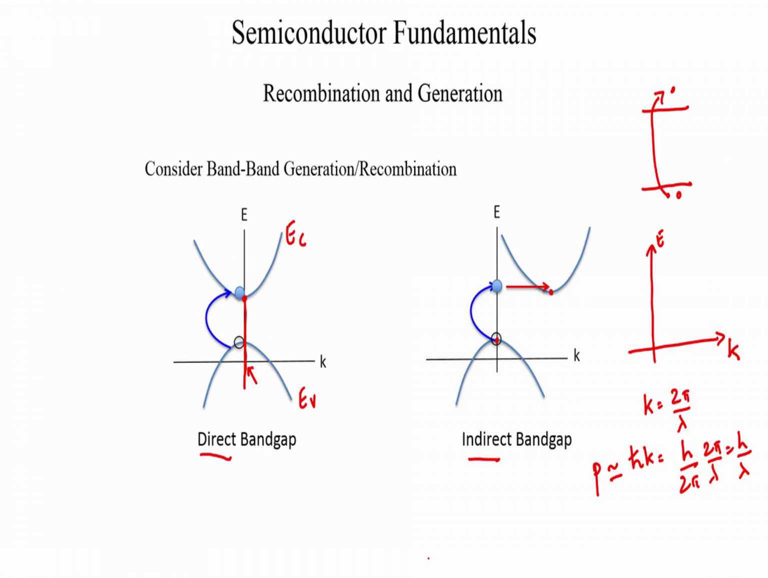

Semiconductor Fundamentals

Recombination and Generation

Consider Band-Band Generation/Recombination

$k = \frac{2\pi}{\lambda}$

$p \approx \hbar k = \frac{h}{2\pi}\frac{2\pi}{\lambda} = \frac{h}{\lambda}$

Now, so these are the you know I would say the basic generation recombination mechanisms. Now, let us consider band to band generation recombination. So, band to band implies you need to have a direct transition of an electron from the valence band into the conduction band thereby leaving a hole behind. Now, the efficiency of a band to band generation mechanism strongly depends upon the kind of semiconductor used.

And what we specifically mean by that is if we look at the E k diagram of the semiconductors what will what is the E k diagram, it is the energy versus wave vector diagram. Essentially the E k diagram is also energy momentum diagram because k is the wave vector which is 2 pi by lambda. And h bar k is nothing but h by 2 pi into 2 pi by lambda which is h by lambda which is the De-Broglie equation for momentum. So, p essentially relates to k.

So, what we are looking at is an energy momentum diagram. And you can have two kinds of semiconductors. So, you could have a semiconductor where if this is the conduction band edge and that is the valence band edge, the maximum of the valence band and the minima of the conduction band lie at the same value of k. So, they both lie at the same value of k, and these semiconductors are called as direct band gap semiconductors, you could also have a semiconductor wherein the maxima of the valence band and the minima of the conduction band lie at different values of k. And these are called as indirect band gap semiconductors. Now, how does a semiconductor being direct or indirect effect the generation process?

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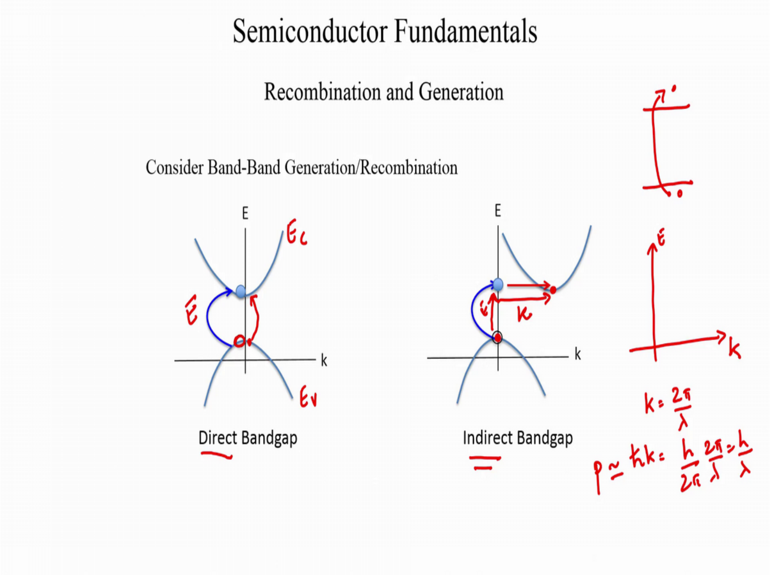

Semiconductor Fundamentals

Recombination and Generation

Consider Band-Band Generation/Recombination

So, in the case of a direct bandgap semiconductor for an electron sitting in the valence band to be excited into the conduction band via band to band generation, all that is needed is an increase in energy. If the energy of the electron increases, you have you have a generation process. On the other hand, if I have an indirect bandgap semiconductor for the electron to go from the valence band to the state in the conduction band, we not only need an increase in energy, but we also need a change in momentum. So, it is both E and k have to change and the mechanisms or the species involved in providing a change in energy and change in momentum are quite different. So, we need to have both the photon and phonon interaction for in an indirect band gap semiconductor for a generation process, whereas for a direct band gap semiconductor we need to have only a photon interaction. So, why do we say photon and phonon.

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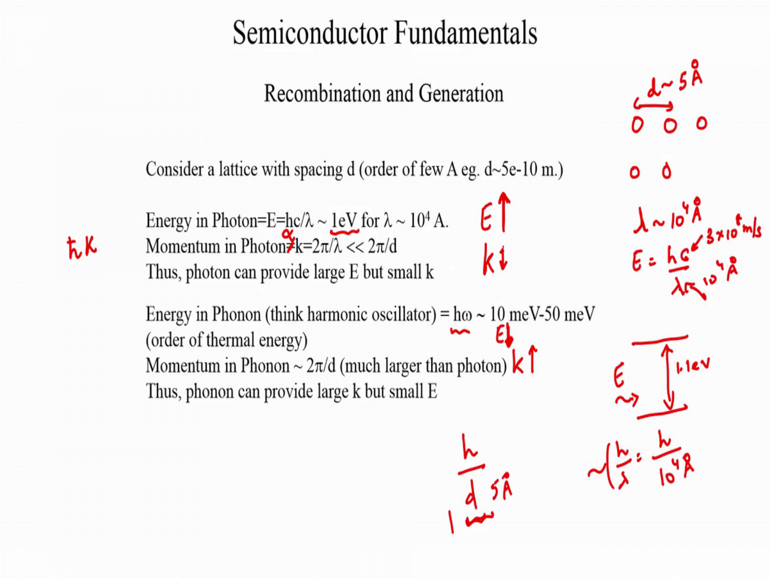

Semiconductor Fundamentals

Recombination and Generation

Consider a lattice with spacing d (order of few A eg. d~5e-10 m.)

Energy in Photon=E=hc/λ ~ 1eV for λ ~ 10^4 A.
Momentum in Photon=k=2π/λ << 2π/d
Thus, photon can provide large E but small k

Energy in Phonon (think harmonic oscillator) = hω ~ 10 meV-50 meV
(order of thermal energy)
Momentum in Phonon ~ 2π/d (much larger than photon)
Thus, phonon can provide large k but small E

So, let us look at these two species. So, if you take a typical lattice. So, let us say you have all these atoms in the lattice and the typical spacing between these atoms is given by d which is a few angstroms and which for the sake of argument we will just say 5 angstroms. Now, let us take a photon. So, let us consider a full photon that is that is got an energy sort of less than the visible band. So, let us say lambda is 10 power 4 angstrom.

So, what is the energy of the photon? The energy the photon is head c by lambda where c is the velocity of light. So, let us say c is the order of 3 into 10 power 8 meters per second, and your lambda is 10 power 4 angstrom. And for this particular wavelength, the energy turns out to be about 1 electron would. And considering the fact that silicon has got a band gap above band gap of about 1.1 electron volt, the energy provided by the photon of this particular wavelength is of the order of the band gap of silicon.

But what is the momentum in a photon, the momentum in a photon is h by lambda, which is h by 10 power 4 angstroms. So, although I have to used to symbol equal to we should just say that it scales or it is proportional, because k is not the momentum k is the wave vector. And as we state the momentum is related to k by the Planck's constant, so that is that is a little typo there. So, we have we have the photon having a momentum that is h by 10 power 4 Angstroms. So, the that order but what is the momentum that we are talking about when we look at this generation process.

So, when we want a shift in k what is the order of that, it is the order of h by d where d is the spacing between the lattice. So, we need something that is equivalent to your lattice vibration or you know of phonons or momentum. So, therefore, since d is just 5 angstrom as compared to lambda being 10 power 4 angstrom the momentum provided by a photon is very very small it is extremely small, it is about 1000 times less.

Therefore, a photon can provide good E, it can provide a large amount of energy, but a very small shift in k, very very small. But let us think about a phonon next a photon is the unit of your vibration right, it is the energy carrier for vibrations. So, if you think about the energy of a phonon if you look if you remember the harmonic oscillator the energy is the order of h omega which is about say 10 to 50 milli electron volts, and that is the order of the thermal energy that is what is responsible for your lattice vibrations.

So, the energy in a phonon is very very small compared to a photon. The energy in a phonon is about 1000 times less than the energy in a photon. So, the energy is very small. But the momentum is of the order of 2 pi binding into h by 2 pi, so that is the momentum. So, the momentum is quite large. So, this is the momentum of a the momentum of phonon is of this order, whereas the momentum provided by a photon is very small. So, therefore, a phonon interaction can give a large shift in k and a small shift in E, whereas an interaction with the photon can give you a large shift in E, but a small shift in k.

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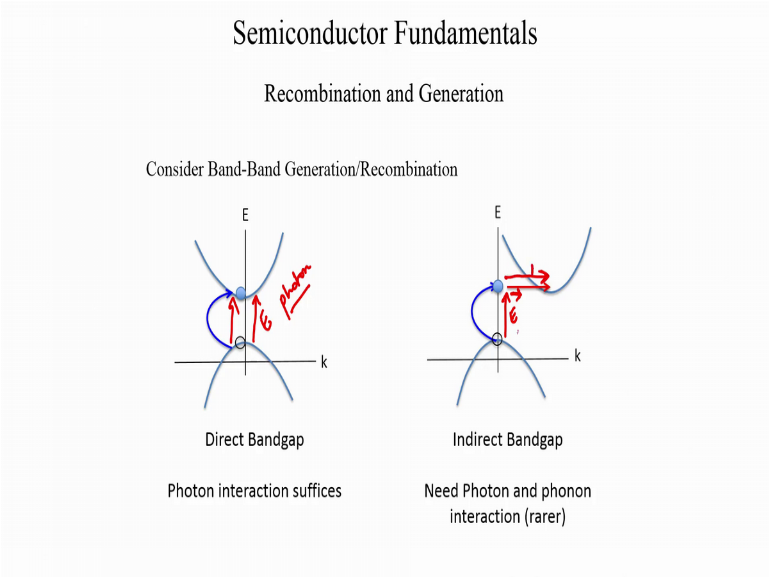

Semiconductor Fundamentals

Recombination and Generation

Consider Band-Band Generation/Recombination

Direct Bandgap

Photon interaction suffices

Indirect Bandgap

Need Photon and phonon interaction (rarer)

So, going to this picture what this means is that in order for us to take the electron from the top of the valence band to the conduction band, we need an increase in E which comes through an interaction with the photon. So, just one interaction with the photon is sufficient to push this carry out. But here we need interaction with two different species you need an interaction of the photon to push the carrier up in E, but a photon interaction cannot give you too much of shift in k; instead we need a interaction with the phonon to give you a shift in k and interaction of the phonon cannot give you too much of a shift in E.

So, we need to have both, you need to have an interaction with the photon and a phonon for us to generate a carrier. And this is a much rarer process as compared to carrier generation in a direct band gap semiconductor.

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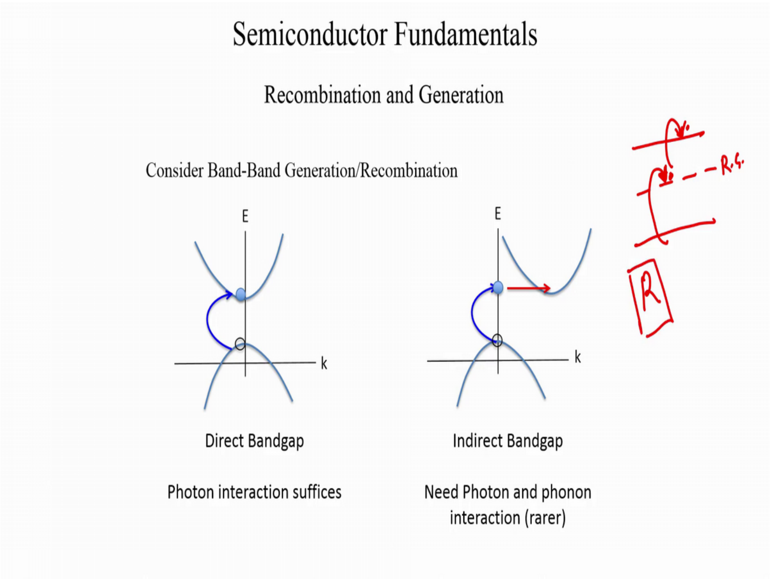

Semiconductor Fundamentals

Recombination and Generation

Consider Band-Band Generation/Recombination

Direct Bandgap

Photon interaction suffices

Indirect Bandgap

Need Photon and phonon interaction (rarer)

Therefore, when we talk about indirect band gap semiconductors, for example, silicon, the R-G center based recombination generation mechanisms are quite important they are the ones that are going to create enough carriers. So, you need so that was the we look at band to band recombination generation and we also looked at R-G center based recombination generation. It is the R-G center based recombination generation that is going to lead to a significant change in electron and hole count.

So, what we are going to do from this point on is we are going to get involved with some amount of calculation and some amount of mathematics that would sort of enable us to understand in a more analytical, and a more quantitative manner the impact of R-G center based generation and recombination. And in particular, we are trying to calculate the end goal is to calculate the recombination rate; the rate at which excess carriers recombine in a semiconductor because that is going to be of use to us further down the road. So, from this point on we are going involve a bit of mathematics, but we will just go through all this, and try to understand the key ideas behind the different concepts.

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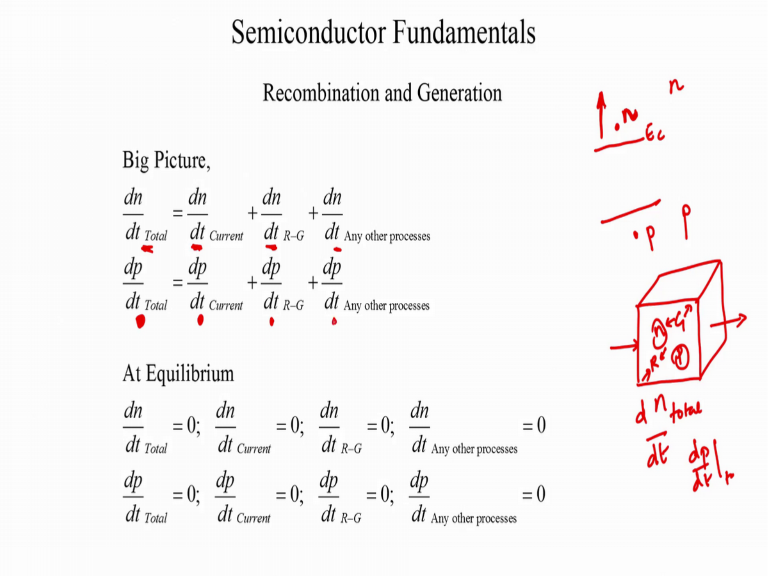

Semiconductor Fundamentals

Recombination and Generation

Big Picture,

$$\frac{dn}{dt}_{Total} = \frac{dn}{dt}_{Current} + \frac{dn}{dt}_{R-G} + \frac{dn}{dt}_{\text{Any other processes}}$$

$$\frac{dp}{dt}_{Total} = \frac{dp}{dt}_{Current} + \frac{dp}{dt}_{R-G} + \frac{dp}{dt}_{\text{Any other processes}}$$

At Equilibrium

$$\frac{dn}{dt}_{Total} = 0; \quad \frac{dn}{dt}_{Current} = 0; \quad \frac{dn}{dt}_{R-G} = 0; \quad \frac{dn}{dt}_{\text{Any other processes}} = 0$$

$$\frac{dp}{dt}_{Total} = 0; \quad \frac{dp}{dt}_{Current} = 0; \quad \frac{dp}{dt}_{R-G} = 0; \quad \frac{dp}{dt}_{\text{Any other processes}} = 0$$

Now, if you look at the electron and hole count, if you look at the total number of free carriers, so which are n the electrons in the conduction band and the holes in the valence band. So, what we mean by n is the electron concentration, and the hole concentration is p. So, if you look at the total count and you know we are now interested in trying to play around with this count, we are trying to create a dynamics, we are trying to study the dynamics of the change in n and p via generation and recombination mechanisms.

So, the if you take any little volume in a semiconductor, and you look at the n and p values in that, how are these n and p values affected. They are affected by any currents coming in or going out of the semiconductor. And they are affected by any mechanisms of generation inside the semiconductor or they are affected by recombination mechanisms in these semiconductor. So, and that could be say other processes depending on the specific case that affects the population count.

So, the d n by d t, the effective total variation of free electrons, the free electron concentration and the hole concentration is dependent on the rate of change the electron concentration due to currents due to the R-G mechanisms and due to any other processes. And similarly for p for the hole count, it is dependent the total the effective variation is dependent on any currents that are coming in and going out, it depends upon any R-G mechanisms and any other processes.

And at equilibrium conditions when you say equilibrium what that means is each one of these mechanisms is balanced out, which means that each one of these derivatives are 0. So, you have at equilibrium you have no changes due to current, you have no changes due to R-G mechanisms, you have no changes due to any other process processes and you have no change in the total effective count.

So, each one of these terms is equal to 0. So, everything is balanced out, internally this is something called as detailed balance. And when we move out of equilibrium, these parameters need not be 0. So, when you start throwing light on a semiconductor and start creating a method of generation or you apply a voltage and start establishing currents through a semiconductor. These rates need not be 0, they can then shift away from 0 and we are no longer in equilibrium. Now, it could be that we are not in equilibrium, but we are in steady state. So, this is the condition for equilibrium.

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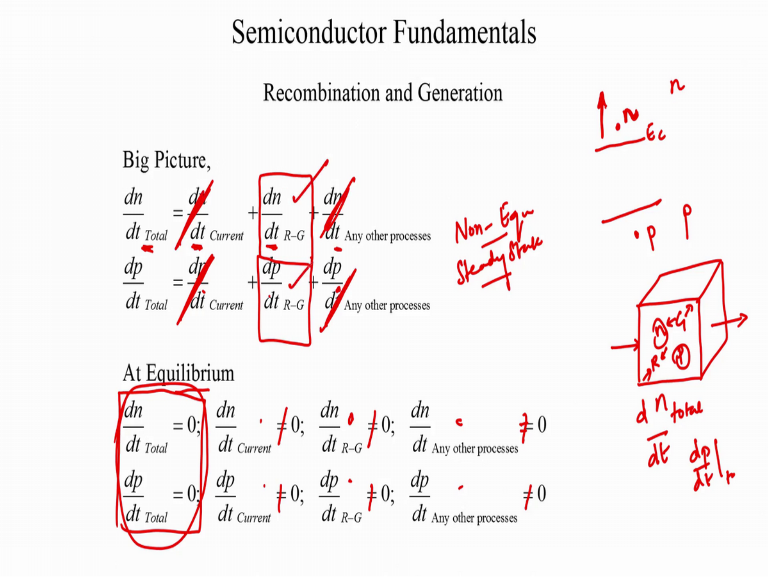

Semiconductor Fundamentals

Recombination and Generation

Big Picture,

$$\frac{dn}{dt}_{Total} = \cancel{\frac{dn}{dt}}_{Current} + \boxed{\frac{dn}{dt}_{R-G}} + \cancel{\frac{dn}{dt}}_{Any\ other\ processes}$$

$$\frac{dp}{dt}_{Total} = \cancel{\frac{dp}{dt}}_{Current} + \boxed{\frac{dp}{dt}_{R-G}} + \cancel{\frac{dp}{dt}}_{Any\ other\ processes}$$

Non-Equ

Steady State

At Equilibrium

$$\boxed{\frac{dn}{dt}_{Total} = 0;} \quad \frac{dn}{dt}_{Current} \neq 0; \quad \frac{dn}{dt}_{R-G} \neq 0; \quad \frac{dn}{dt}_{Any\ other\ processes} \neq 0$$

$$\boxed{\frac{dp}{dt}_{Total} = 0;} \quad \frac{dp}{dt}_{Current} \neq 0; \quad \frac{dp}{dt}_{R-G} \neq 0; \quad \frac{dp}{dt}_{Any\ other\ processes} \neq 0$$

$\frac{dn_{total}}{dt}$ $\frac{dp}{dt}\Big|_{r}$

Now, suppose we are in non equilibrium, we have gone out of equilibrium which means that this is not 0, this need not be 0, all these need not be 0, but we have reached steady state condition. So, when we say we are not in equilibrium, but we are in steady state what we imply is that these two parameters the total effective variations are all 0, whereas, these internal variations need not be 0. So, these are just some fine definitions that could you know help us understand all the analysis a bit more clear.

So, we could be an equilibrium where each and every one of these processes 0, and we could be in non equilibrium where these individual processes move out of 0, but we could be in non-equilibrium steady state at the same time wherein this effective count does not change with time while although these individual rates are all nonzero. So, there is balance between the processes.

So, using these ideas, so this is the big picture; so using these ideas, we will now focus only on the recombination generation rates. We will not worry about any other processes, we are not worried about currents, we are not worried about anything else that is going on, we are only interested in the recombination generation mechanisms, so that is going to be the focus of the next few slides that is just this. So, this is of importance to us.