# Introduction to Semiconductor Devices
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## Lecture - 07
## Electron Hole Pair Generation

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Hello, everyone, welcome back to Introduction to Semiconductor Devices. This is lecture 3 of first week of the course.

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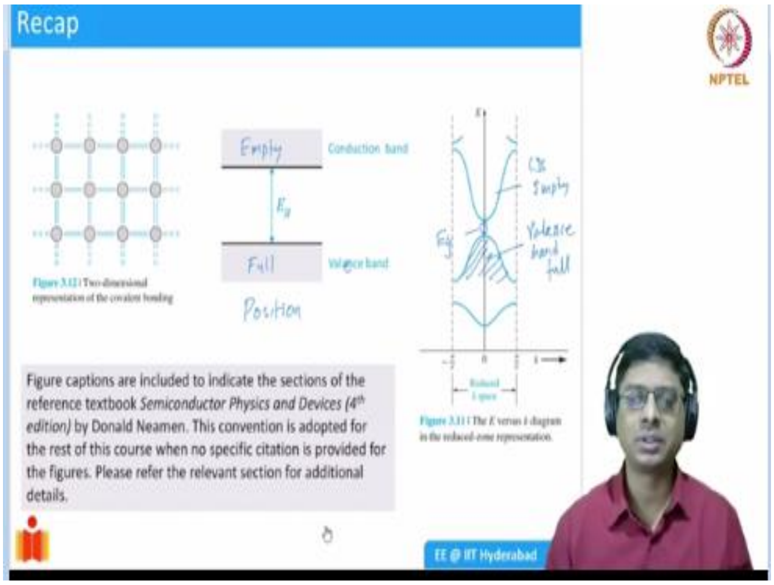

Recap

Figure 3.12 | Two-dimensional representation of the covalent bonding

Figure 3.11 | The E versus k diagram in the reduced-zone representation

Figure captions are included to indicate the sections of the reference textbook *Semiconductor Physics and Devices (4th edition)* by Donald Neamen. This convention is adopted for the rest of this course when no specific citation is provided for the figures. Please refer the relevant section for additional details.

So, in the last lecture, we were talking about the 2D visualisation model for bonding in silicon. We said that every silicon atom is bonded to 4 different nearest neighbours, which are silicon atoms. And then there is a covalent bond between these atoms. And so, you have essentially 8 electrons surrounding each silicon atom; 4 from the original silicon atom and 4 from the neighbouring atoms.

So, that is how we satisfy the valence requirements and then we have the bonding happen. And because of that, we saw that there are energy bands found and we saw 2 different forms of energy band representation; one is energy bands in space, you know, where we will simply know, this could be a position. And you have the band splitting up into valence band and the conduction band. This is valence.

So, you have the valence band, which is completely full and conduction band which is empty. So, all the electrons are occupying the lower band and there is a band gap Eg. So, this is one representation, which we will commonly use whenever we draw band diagrams for p-n junctions or MOSFETs and so on. And then the other form is what is known as the E-k relation. This is essentially the band diagram in the Fourier space; k is wave vector.

So, energy versus k diagram, E-k diagram we call it. So, here it essentially shows you the various states that are available, you know, we saw the dispersion for a free electron. E-k diagram for a semiconductor is similar to that. So, for a Kronig Penny model, we just showed you; we did not solve it; we showed you that E-k diagram will look something like this wherein you have the lower bands and then you have the valence band which is full. This is full of electrons.

And then the conduction band is one which is straight about that. And this is conduction band. And this is empty. So, it has lots of states available for electrons to fill up. And the gap between them is basically Eg. This is simply another representation of it. And this is useful for distinguishing between direct and indirect band gap semiconductors that we will do towards the end of today’s lecture.

So, that is why we want to look at E-k relation. And also, it is useful in explaining a few concepts like mobility and things like that. Other than that, we will use most of the time, the energy bands with respect to position. And there is one more aspect, I wanted to just emphasise one more time, which is, I am leaving the figure captions on the, you know slides. I am putting the captions deliberately.

Whenever you see this, this means that have taken that particular figure from the appropriate section in the textbook, the textbook, basically semiconductor physics and devices by Donald Neaman, the 4th edition of it, I have taken. So, if you have any doubts or if you would like to learn more about it, you could go back and look at the textbook. Otherwise, if you are able to follow along with the lecture, that should be sufficient.

And by the way, the textbook is actually having a lot more details. So, if you try to read the textbook from beginning to end, I think it will be a lot of material for you for this course. So, I am picking sections from the textbook and if you are able to follow along with it, that should be sufficient for the purposes of this course. Alright, let us get started.

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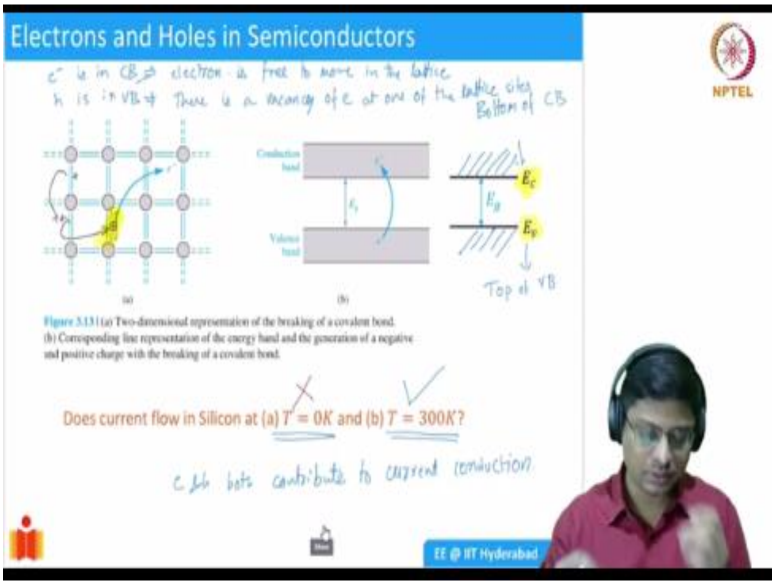

Electrons and Holes in Semiconductors

$e^-$ is in CB ⇒ electron is free to move in the lattice

h is in VB ⇒ There is a vacancy of e at one of the lattice sites

Figure 3.13 | (a) Two-dimensional representation of the breaking of a covalent bond. (b) Corresponding line representation of the energy band and the generation of a negative and positive charge with the breaking of a covalent bond.

Does current flow in Silicon at (a) $T = 0K$ and (b) $T = 300K$?

e & h both contribute to current conduction

So, today, we would like to talk about electrons and holes in semiconductors. And this is one of the fundamental concepts and understanding electrons and holes, how they behave is one of the fundamental aspects. So, we talked about this 2D-bonding model, we said that there are this bonds and the bond, the line represents an electron. What happens is one of the bond breaks.

If the bond breaks that means the electron is simply breaking and going away from the location, physical location of the bond. Then essentially you have this electron which is moving around and that can go anywhere it wants, unless it is you know, captured by another lattice side. So, whenever this happens, physically, this is a picture on the left. You can also represent it in an energy band diagram by showing an electron which is going from the valence band to the conduction band by the arrow.

That means the electron has this, this particular arrow, this particular transition is telling you that the bond have, between the electron and the silicon atoms has been broken, it requires of course, some energy. We have to supply that energy. Otherwise, this bond cannot break. So, the amount of energy you need to supply is basically Eg. When you do that, it goes into the upper state.

Upper state has a lot of empty states like conduction we saw, is completely empty. So, then this can happen. So, this process which we saw is represented and of course, you know, we find it difficult to, you know, draw all these grey shades and all that. So, many times we simply represent the band diagrams in the form of these 2 lines, the upper line Ec. This represents Ec. This represents the bottom of conduction band, bottom of CB.

Similarly, this represents top of VB valence band. And between them, we have a forbidden gap that means there are no states available for the electron to be there alright. So, we will adopt the simple line. If you draw a line like this, it implies that there are of course many states available here and of course, there are many states available here. That is an implication which is take it as a convention from now onwards alright.

So, we have created these electrons and holes. Are they able to carry current? What does it physically mean? One more time, what does it physically mean that electron is in conduction band? Physically it means that electron is free to move, free to move in the lattice. And what does it mean that electron is in valence band or hole is in a valence band? Well, we will talk about it, hole in valence band.

So, before we do that, can the semiconductor carry current? Look at it. Let us first assume that the temperature is 0 degrees Kelvin. Can the semiconductor carry current? If you look at it, you might be inclined to say yes, because you know, you have so many electrons available. Each silicon atom has 4 electrons, and then there are $10^{22}$ silicon atoms per $cm^3$.

So, you have a huge number of electrons. And if you have so many electrons, why cannot it carry current? Of course, it can, but then it turns out that at 0 degrees Kelvin, it cannot carry current. The reason for that is, even though there are like this $10^{22}$ electrons or the order of $10^{22}$, they are all bonded to the lattice, they are not free to move. That is why at 0 degrees Kelvin, semiconductor cannot carry current.

Now, what happens if I increase the temperature, I will make it room temperature. If you make it room temperature, essentially, you are heating the material. Your material is now at a slightly higher temperature than 0 Kelvin. So, when you do this process, you are supplying energy and some of this energy is used in breaking the bonds, breaking some of these covenant bonds, which are binding electrons to the lattice side.

So, when you break this bond, the electron becomes free to move and that you know the electron goes into the conduction band. So, when the electron goes into conduction band, it can help in current conduction. So, when you go to higher temperatures, you will have current conduction which is possible. So, when an electron goes into the conduction band, what happens to the valence band because these atoms are electrically neutral.

They are only sharing electrons, but electron is not being removed by the from the silicon atoms. So, what happens if you electron becomes free and then it is able to move around, then of course, it is going to live a positive charge behind. And this positive charge, we are showing it as that we call it as a hole. You know, simply say, to say that there is a deficiency of an electron. Hole is simply lack of electron.

So, now, the question is, there is a hole in the valence band, why do we say it is in the valence band? Because the hole is part of the lattice, you know, it is the location of; the physical location of the hole is basically where the lattice, where the bond was broken. So, whenever we say conduction band, we say that it is the carrier anywhere in the lattice you want, but the hole is basically located to the specific region, not the inter-atomic distances, not those regions, but only with the, in between 2 of the silicon atoms.

So, hole is in valence band that is the physical picture. Now, can a hole conduct? I am saying that the hole is captured, you know, it is located at 1 between 2 atoms. Then will hole conduct electricity? You should think about it. You can pause a moment and think about it if you would like. But it turns out that it can conduct the electricity. Though you might think that it is fixed, so it cannot, but then it is actually conducting because what can happen is; there is nothing secret about this particular location for a hole.

You could always have an electron from the neighbouring side. For example, here can jump into this? When electron jumps, the hole is filled up, but then a new hole is created at a different location. Then you can have one more electron jumping from somewhere else and the new hole is created. So, the original hole was filled up, I mean in sense, when you say hole is filled up, essentially the bond is satisfied; the valence requirement is satisfied.

So, there are 2 electrons shared between those 2 atoms that is all. So, it is not a physical you know, hole in the silicon. So, now, you are able to move this you know, the hole is actually able to move through the lattice. It is something similar to what happens in a if you have a bubble of air in water. What happens? You know, the bubble moves, it is not actually the bubble moving but it is the water which is moving like the background water is moving and because of that the bubble appears to move.

Similarly, even though when we say the motion of a hole, it is in fact electrons which are moving but then it appears as if the vacant state is moving. So, please remember this. So, basically whenever you see a hole is in a valence band, it means that the bond, basically there is a vacancy of electron at one of the lattice sides that is a hole in valence bands. Alright good.

So, now, because of that, what do we conclude? We conclude that electrons and holes both contribute to current conduction. If you have a metal, you will only think of electrons but in semiconductors, you can have both is contributing to current conduction. Alright. So now, how do we; you know, we talked of electron going into the conduction band and leaving behind a hole in the valence band. So, it appears that these things are forming in pairs.

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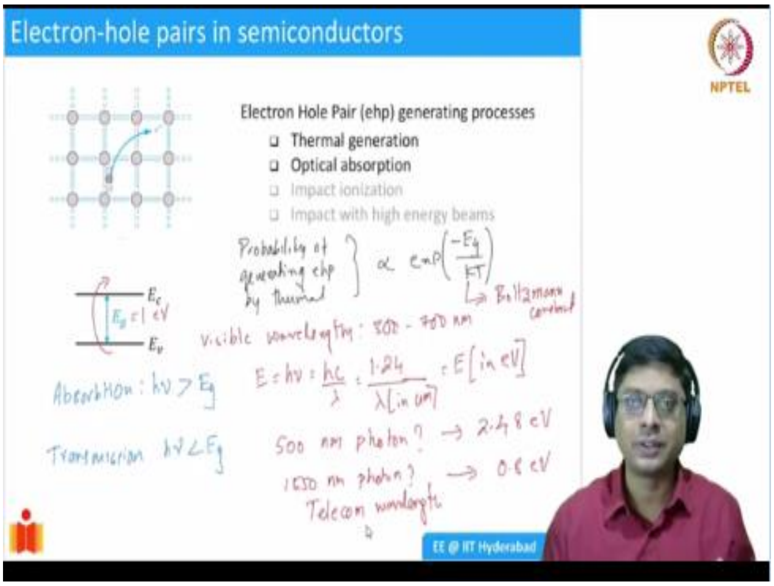

Electron-hole pairs in semiconductors

Electron Hole Pair (ehp) generating processes
- ☐ Thermal generation
- ☐ Optical absorption
- ☐ Impact ionization
- ☐ Impact with high energy beams

Probability of generating ehp by thermal } $\propto \exp\left(\frac{-E_g}{kT}\right)$ ↳ Boltzmann constant

Visible wavelength : 500 - 700 nm

$E = h\nu = \frac{hc}{\lambda} = \frac{1.24}{\lambda[\text{in } \mu m]} = E[\text{in eV}]$

Absorption : $h\nu > E_g$

Transmission $h\nu < E_g$

500 nm photon? → 2.48 eV

1550 nm photon? → 0.8 eV

Telecom wavelength

So, we actually give them in it. We call it as electron hole pair EHP. So, electron hole pairs by this process at least, it is produced in pairs. So, what are the various electron hole pair producing processes in semiconductors? One of them is heating. We already talked about it. When you heat a semiconductor, it produces electron hole pairs and it turns out that the probability of a generating you know, electron hole pair by the thermal process.

Probability of generating EHP by thermal process, this turns out to be dependent on as

$$probability\ of\ generating\ EHP\ by\ thermal\ \propto exp\left(-\frac{E_g}{KT}\right)$$

So, if we increase the temperature, you are essentially supplying more and more energy. So, the fraction in the exponential reduces and you get higher probability. So that is how at higher temperatures you are able to have more electron hole pairs.

What happens if you have higher band gap? Well, band gap is the energy that has to be overcome to produce electron hole pairs. Unless you give that amount of energy to the electron, it cannot go into the conduction band. So, that goes into the numerator as band gap increases, the probability of electron hole pair generation reduces. So, this is one of the processes, thermal process.

And the second process is basically optical absorption. When I say optical, I am essentially referring to visible wavelengths. So, what are the visible? By the way, I am sorry, I did not; this scale, you please make note, this is not know your wave vector that we were talking about. But this is basically Boltzmann constant. Sorry, I should have mentioned that anyway. Coming back to optical absorption, we are talking about visible wavelengths.

When we have visible wavelengths, what are the range visible wavelengths? It is basically 300 to 700 nano-meters, I mean, you could even say 750 nano-meters, but this is a broad range. When you have a photon of this wavelength incident on a semiconductor, what happens? For that, we have to analyse what is energy of a photon. So, the energy of a photon is you know, we will like to know use it, we calculate, we use it frequently. So, we will actually give you a simple formula to calculate.

So, we know that

$$E = h\nu = \frac{hc}{\lambda} = \frac{1.24}{\lambda[in\ microns]}$$

and this can be computed and we say that this is basically equal to 1.24 by lambda in micron. If you calculate this, you get basically E in eV directly. This is a simple formula that you should I think, remember, it is very useful and it is very accurate for visible wavelength , even others.

So, now, what is a; let us consider the green light, which is the centre of the visible range we can say. Because it is 500 nano-meters. 532 is one of the famous peaks of green but let us take 500 nano-meters. So, if you had a 500 nano-meter light or photon, what is its energy? It turns out, it is basically 2.48 eV. So, now let us say at 2.4 eV or 2.5 eV photon is incident on the semiconductor which has a band gap of, let us say 1 eV.

What happens? Well, the energy is higher. The photon supplies the energy to the electron in the valence band and the electron makes a transition into the conduction band because there is sufficient energy in the photon to make this happen. And of course, you are never I mean, traditionally you are never going to put only one photon; you put lots of photons or more, electron hole pairs generated alright.

So, what happens if you use let us say 1500 nano- meter 1500 whatever, let us say 1550 nano-meter photon. This is a famous wavelengths or telecommunications you know, all your optical fibres you use IR needed, which is basically telecommunications wavelengths we call it. What happens if you shine this photon? Will it, you know what is energy we calculate? It turns out to be 0.8 eV.

If you shine a photon of 0.8 eV on piece of material which has a band gap 1 eV. Of course, it cannot produce electron hole pairs because its energy is not sufficient. The energy that supplying the electron is not sufficient to make it go to the higher state. You might argue that when 2 photons can simultaneously you know, contribute energy to one electron and then it can make the transition happen.

Well, it is possible. It is called multi photon absorption, but then the probability of that happening is very, very small. So, we will neglect it you know for purposes of this course, alright. So, basically the optical absorption process has been; we can summarise that you know absorption whenever, know when $h\nu > Eg$ , transmission. So, transmission $h\nu < Eg$ . why do I say transmission?

Let us say I take a thin piece of silicon, I shine this photon, when the electron makes a transition from the conduction band into the valence, sorry from the valence band into the conduction band, then it is getting absorbed, the photon is destroyed. But if this transition does not happen, the electron stays in the valence band, then the photon can simply go through it. That is where we say that the photon gets transmitted.

So, this is optical absorption process, one of the ways of creating a electron hole pairs. So, I listed a couple of more processes here. And those are basically impact ionisation.

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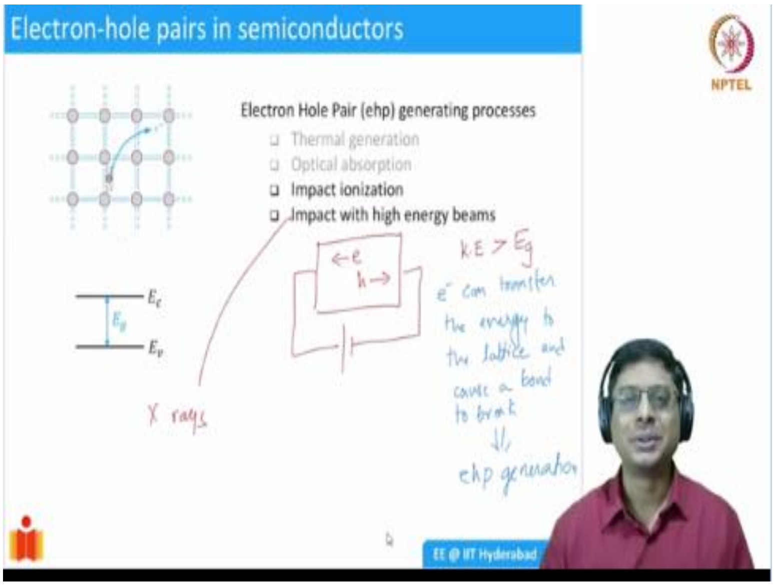

Electron-hole pairs in semiconductors

Electron Hole Pair (ehp) generating processes

- ☐ Thermal generation
- ☐ Optical absorption
- ☐ Impact ionization
- ☐ Impact with high energy beams

K.E > $E_g$

$e^-$ can transfer the energy to the lattice and cause a bond to break

⇓

ehp generation

X rays

When we say impact ionisation, what we mean is let us if you consider this piece of silicon let us say and you apply voltage. If you apply a voltage, what happens? It assumes that it is at room temperature. Then electrons will go towards the positive terminal; holes will go to the negative terminal. So, the battery is causing the electrons to move and they acquire kinetic energy. Kinetic energy is basically proportional to velocity.

So, now, as they move if the kinetic energy is greater than Eg, what happens? If the electron has acquired a large enough kinetic energy that it is above Eg, the band gap; if that happens, electron can transfer the energy to the lattice and cause a bond to break. This implies you have EHP generation. Whenever bond breaks, you have EHP generation by the way, you know.

So, now, this is one of the processes. And when will it be significant? When you have large amounts of energy, if you put a large voltage, then you have this huge amount of energy that is transferred to the electrons from the external battery or whatever. And that gets that leads to more and more broken bonds. You can think of it like you know, highway you know, a car is travelling on the highway.

If the velocity of the car is, the speed of the car is large, the if by chance, even there is no damage itself, when there is an accident, it is fine. But if by chance there is an accident, then the damage, amount of damage it causes is proportional to its energy. Similarly, you can think of the electron as a moving car and then it is actually colliding with the lattice. And there is a lot of damage to the lattice if the energy of the electron is large.

So, this process is not as impact ionisation because essentially, you have an electron making you know, impact with the lattice side. Well, I am talking as if the electron is a particle, but you know, we already saw that you could call it, you could also think of it like a wave. Electron has a probability and then probability wave it travels, the same, it still holds. It is not, we are not negating that you could either talk in terms of wave packets or you know, electrons.

So, this is a one process and you also have another process which is basically impact ionisation sorry, high energy beams. If you have X rays, these are high energy beams. If you have x ray shining on a semiconductor, the energy of X ray, the wavelength of X ray is very, very small in one nano-meter also, then X ray energy will be very large, when the energy is large, it is going to cause electron hole pair generation. Same process.

I mean, like optical absorption, what happens but it is actually even more high energy. And this sort of, you know, impact with high energy beams is very significant in space. On Earth, the atmosphere protects all the high energy radiations; it blocks all of it and so we are safe, but the moment you send a satellite into orbit, there is a lot of high energy radiation and that causes a lot of electron hole pairs in the electronics in the satellites.

So, you have to do something special to make sure that the electronic still works. This is a branch of semiconductors that you know, I am sure so and others are interested.