Introduction to Semiconductor Devices
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Lecture - 2.8
Drift Current and Energy Band Representation of Kinetic Energy of Carriers

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What happens to a semiconductor when you have electric fields applied? Because finally that is what is going to happen in a device, we will take a piece of semiconductor.

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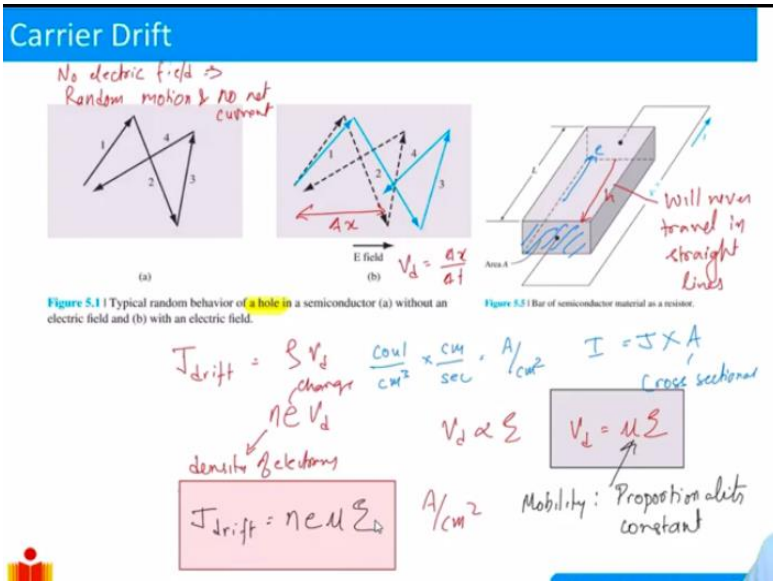

Let us say apply electric field, what happens? So, this schematically, something like that is shown here. So, you have a piece of semiconductor of length l here to which we are applying a voltage on both ends. So, there is a certain voltage applied. Now, what happens? So, this semiconductor, you know, could have electrons and holes. Whatever it is, whatever the doping, it does not matter for us right now. How will the electrons move?

Electrons will move towards the positive terminal. So, in this case, you will have electrons which are going towards this direction, because this is positive terminal. So, they want to go towards the positive terminal. What happens to the holes? So, holes will move in the opposite

direction. Is it that simple? You know, it is not going to be that simple. The reason is we have a lattice full of electrons.

They are never going to travel in will never travel in straight lines. If you go to a crowded railway station, you are never going to go straight in a straight line from your starting point to ending point. We are going to have lot of people you are encountering lot of people. So, you have to change your direction multiple times and finally reach your destination. So, similarly, something similar happens.

If initially, if you consider a situation where you do not have any external field, electrons will simply keep colliding, because there is a certain amount of thermal energy in because there is a finite temperature, let us say room temperature. Electrons will keep moving in some random directions in such a way that let us say, here, this is actually for a hole, but the exact same thing will be applicable for electron as well.

So, consider a hole which is starting out at let us say, this point, it gets scattered, it goes in one direction. It gets scattered again, it will go in the other direction, back scattered, so again, back. So, basically, it starts out at this point and kind of ends up in the same point on an average. This is never going to be for each electron. On an average, electrons will simply scatter undergo multiple scattering processes and end up at the same position.

So, if you do not have any electric field, if you have no electric field, see, then implies random motion and no net current. Current occurs when your charges move. When you do not have a field, there is this random motion. And finally, on an average, there is no net current. But if you introduce a field, so that is what is shown in the blue here. Of course, still there is going to be some random motion.

But on a overall basis, there is going to be average moment of charge. For example, here, electron is now getting scattered in this direction. Again back, again here. So, the net moment is basically going to be you know in this diagram this is a net change in x, Δx, you could say. If you have a field in a certain time, there is going to be a change in Δx. And so essentially, what we are having is a velocity that is being created.

The velocity now this is called as drift velocity. And we will refer to as V_d is going to be

$$V_d = \frac{\Delta x}{\Delta f}$$

If you give a certain duration, how much is a change in the position. So, that is the drift velocity. So, a hole has moved in let us say positive direction here. Electron will move in the opposite direction. And this is what we are referring. Whenever we draw these lines, we are not saying that electrons and holes will move in straight lines.

We understand that intrinsically, they undergo random motion. But overall, whenever you have an electric field, there is a net drift in the carriers. A drift in the electrons and drift in the holes which actually occur in the opposite directions. So, this sort of a drift phenomena, we call it. I know the current due to this, we will just you know is going to be what. We will let us call it J drift just to distinguish that it is a drift current, current density actually in this case.

So, how much is the current that is flowing here? So, the current is going to be how much is the charge density? The charge density is simply let us call it rho(ρ). And then how much with what speed is it moving? This is going to be V_{drift}, V_d we will call it up. So, now this is your net charge density. Sorry, net current density $J_{drift} = \rho V_d$. Is it satisfying the units? Let us look at that. Now, for example, here in this case, your charge density should be coulombs per centimetre cube,

And your velocity is going to be centimetres per second. So, this is giving you coulombs per second will be amperes per centimetre square, which is essentially charge density. So, remember, we are not taking into account the total current. If you want to calculate the total current, we have to you know, if you want to calculate I, the total current, it is going to be J times area. What area? This is a cross sectional area in this face.

$$I = J * A$$

In this face A in perpendicular direction to the current flow or electric field direction you have to take and that you have to multiply to get the net current. So, good. What is the charge density then? Do we know anything about charge density? If you let us take a uniformly doped semiconductor, then the charge density is going to be simply that which is given by n. The charge density is n or it could be p also. p is holes.

If you have a holes let its be p. So, this is going to be this times charge the electron charge of an electron. So, this is going to be this is basically I can call it density of electrons. And of course, you know what is e and then multiplied by V_d.

$$J_{drift} = \rho V_d = neV_d$$

This charge and drift velocity. What is drift velocity? The drift velocity is going to be proportional to the electric field. V_d is going to be proportional to the electric field.

The reason is, when you know you saw that whenever you do not have any external field, your drift velocity is 0. And as you increase up to a point of course, you know, there is a limitation that we will tell you about in the MOSFETs part. But essentially, as electric field increases, V_d increases. So, we will introduce a proportionality constant here, we will call it drift velocity, V_d.

$$V_d = \mu E$$

So, this is an important relation that I want you to remember. So, what this is telling you is that the drift velocity is going to be proportional. And this proportionality constant we will call it us mobility. So, proportionality constant and this is a term mobility we will hear very often in semiconductor devices. So, what happens is we will talk about the proportionality constant in just a moment.

So, what happens is here J_{drift} is going to be,

$$J_{drift} = ne\mu E$$

So, this is going to be this. So, you can verify that it is still electric. You know, what should be the units? This is interesting. What should be the units of μ so that you have J equal to ampere per centimetre square? Please verify, what it is.

Just a moment, you can pause it if you would like. Just make sure that you get the right units. Never forget the units of mobility. So, now, what happens is we talked about only the electron drift, but the hole drift also is going to be analogous to it.

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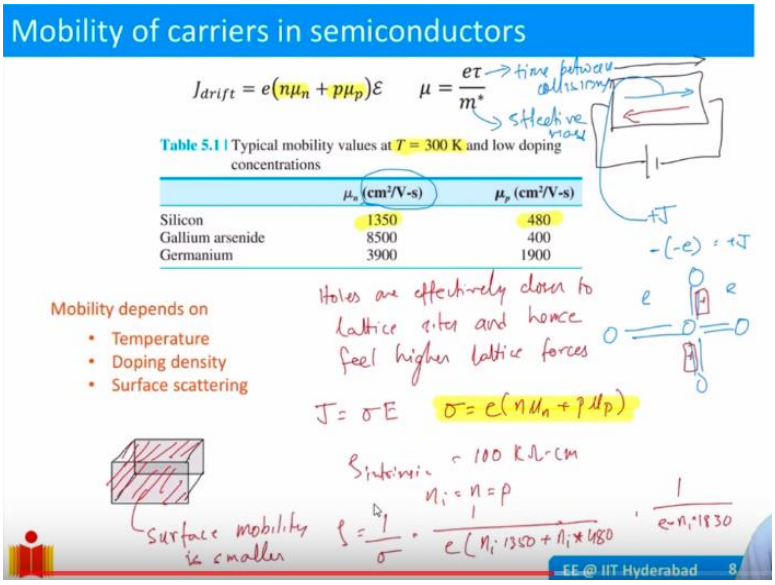

And essentially, what happens in a semiconductor? If you take a piece of semiconductor this way and let us say I apply a field like this positive field like this so positive terminal negative terminal. So, the field in the semiconductor is going to be in this direction. So, electrons are going to move in this direction, holes are going to move in this direction in the positive direction. So, by convention, we can take the direction of flow of the holes as the J.

You know the current density J. You know positive J, plus J. The current is going in that. Now, electrons are moving in the opposite direction, but because electrons have a negative charge, the overall current is going to be in the same direction. So, basically because of drift, whatever current flows, it flows in the direction of the electric field. So, for electrons, there is a minus, and then there is a minus E.

So, basically, overall, it is going to still be plus J, plus positive direction. So, current due to both electrons and holes are going to be in the same direction. So, now, because of that we could generalise the expressions for J_{drift}. I will take the charge of electron out. And so, you have the charge density times the electron density times the mobility of electrons plus the hole density times the mobility of holes.

And so, and this mobility is going to be material dependent. And there are lot of other dependences as well. So, for example, you know mobility is in a way it is measured by how many scatterings are occurring. For example, think of yourself in a busy railway station. If the number of people is more in the railway station, the speed with which you are going to walk is going to be smaller.

So, the mobility of the human being in a crowded railway station is going to be smaller when compared to mobility of a person in the empty field or somewhere. So, that is one measure. So, basically this τ is going to be the time between collisions. And if this is going to be effective mass if your effective mass is high then the mobility will be low and up vice versa. So, these are kind of, you could qualitatively understand what these are.

$$\mu = \frac{e\tau}{m^*}$$

So, now, this mobility is I said is a material parameter. It is going to depend on temperature. It is going to depend on carrier density and many other factors. But here are some numbers which are very commonly accepted at temperature T=300 degrees. The mobility of electrons in silicon are going to be 1350 cm^2/V-s. Please make sure that you got this. I asked you to verify what are the units.

The units of mobility are going to be centimetre square per volt second. So, the mobility of electrons is going to be 1350 and mobility of holes is going to be 480. This is the typical number for electron silicon. Why is the mobility of holes lower than mobility of electrons? One way to qualitatively understand is to go back to the bonding picture. We talked about this silicon lattice.

And then we talked about the bonds surrounding the silicon atoms. And there are these bonds. Where are the electrons moving? And we say electron is in the conduction band. We mean that electron can go wherever it needs to. I mean it is free to move around in the lattice. So, it has high mobility. Electron is basically anywhere. It could be and it is free to move around. So, it has a higher mobility. But, what is the hole?

The hole is simply going to be the deficiency of an electron here. This is basically let us say, positive. You just removed an electron. That is why it is positive. Or, it could be a deficiency of electron here. So, the holes are effectively closer to the lattice sites. Holes are effectively closer to lattice sites. And hence, feel higher crystal interactions. Crystal forces you can say or lattice forces whatever you would want to call.

Let us call it lattice forces because I called lattice cells. And because they feel this higher amount of holes, the impact of the external field is going to be smaller. And after all, the

mobility is essentially capturing the impact of the external field. So, because of that, you could qualitatively understand that the mobility of holes is going to be small. This is true for most of the older generation technologies up to about even 45V, I would say.

But now, with the new technologies, this is no longer true and there are some corrections that are being done. I mean, we have to. Anyway, you will not encounter this in this course. Only if you do research in advanced semiconductor devices, then you have to worry about that. So, we have seen current is like this. So, this also gives us an opportunity to go back and revisit what we talked about in the first lecture.

We talked about the conductivity or resistivity of a semiconductor. So, $J = \sigma E$ if you see this is essentially Ohm's law.

$$J = \sigma E$$

You can write it as $V = IR$ and then you can do some manipulations and you will end up with this. $J = \sigma E$ is essentially Ohm's law in different form. I leave that to you as an exercise. So, from this what it implies is.

$$\sigma = e\left(n\mu_n + p\mu_p\right)$$

This is your conductivity of a material. And so, if you know the doping density you could calculate this. For example, what is the, you know, I mentioned you know resistivity of intrinsic semiconductor intrinsic silicon $\boldsymbol{\rho}_{\text{intrinsic}}$. For silicon was I said it will be hundreds of kilo ohms centimetre i.e,($\boldsymbol{\rho}_{\text{intrinsic}}$=100 K Ω-cm). Verify how much it is? So, for intrinsic semiconductor $n_i = n = p$, and you have the mobility here.

So, if you want to calculate resistivity, resistivity is going to be, $\rho = \frac{1}{\sigma}$.

$$\rho = \frac{1}{\sigma} = \frac{1}{e(n_i \times 1350 + n_i \times 480)} = \frac{1}{e \times n_i \times 1830}$$

Estimate how much this is going to come to? And see, what the, you know, resistivity is for intrinsic semiconductor?

And before I stopped, I said that, you know, temperature and doping density are going to influence your mobility. I am really not going to talk in detail about this if you are if you want there are sections in the textbook which you can look at. Of course, if your temperature

increases, the crystal is going to vibrate, you know, stronger and stronger because of that mobility reduces.

And if you have doping density, you can think of it like the larger number of people on a railway platform, the slower you are going to move. The mobility is going to reduce as the doping density increases. This is very you know there are more subtilities to it. It is not that simple. And the last thing you know is also it is also dependent on the surface. For example, if I take a piece of semiconductor.

Let us say I will take a small rectangular bar of semiconductor. Actually make it into a bar. So, let us say you have a semiconductor of this form. What happens to its mobility? The mobility in the bulk of the semiconductor is going to be different from the mobility on the surface. Now, for example, I take this top surface or this surface. What will be the mobility? Will it be the same as a bulk? Of course, not.

Because, on the surface, you have this you know unsatisfied bonds, they are not going to be like 4 covalent bonds. Or, you know 8 electrons shared. It is not going to happen on the surface. Because of this, we call them dangling bonds, some bonds, which are unsatisfied. Because of that it will not have the same mobility. So, surface mobility is smaller than the bulk mobility. And we could talk more about it.

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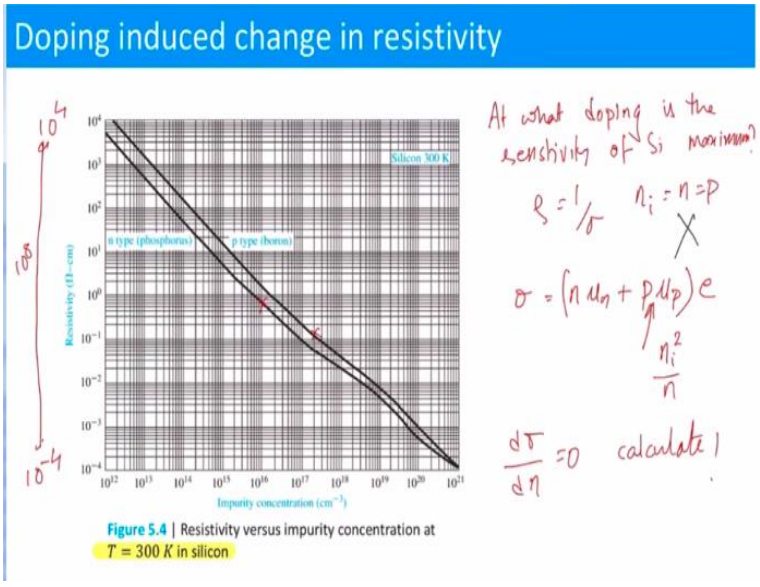

Figure 5.4 | Resistivity versus impurity concentration at $T = 300\ K$ in silicon

But anyway, let us will come back anyway. We will talk about when we talk about MOSFETs. we are going to introduce this again one more time. So, now, let us see how the, you could

calculate these numbers once for yourself and verify. Now, take couple of examples. Here there is a plot of resistivity versus impurity concentration for silicon, 300 degrees Kelvin in silicon. So, take a few numbers.

Take for example, take 10^{16} and calculate the resistivity and 10^{17} and calculate the hole resistivity. Sorry, if you have holes, impurity, accepted concentration of $N_A = 10^{17}$, what is the resistivity? If you have donor type doping 10^{16}, what will be the resistivity? You compute these numbers and verify that this is accurately coming.

So, you see that, if you look at this y axis, you are having resistivity of 10^4 and 10-4 in the bottom. So, you see this 10^8, 8 orders of change. And this is what I showed you in the first graph of the course, that in a semiconductor, you can have a resistivity that can be tuned over a large range of numbers. And that is why they are very interesting to us.

So, you see that as the doping concentration is low, you have large resistivity. And as it increases the resistivity drops. Of course, you know, we are showing 10^{21} that is a very high amount of doping. When you go into that regime, it becomes more tricky. So, now, I will ask you a question. At which at what doping is the resistivity of silicon maximum? You might be tempted to say that well resistivity $\rho = \frac{1}{\sigma}$ and that we have seen the expression in the previous case.

So, you might be tempted to say, $n_i = n = p$ is the intrinsic carrier concentration. Maybe the resistivity will peak there. We have to be careful. This is not going to be the answer. To do that, you have to write out. Let us say, you could talk of resistivity maximum or the conductivity minimum both are same. So, I will say conductivity minimum. Sigma is going to be what?

$$\sigma = e(n\mu_n + p\mu_p)$$

So, but remember in equilibrium conditions, this is going to be $p = \frac{n_i^2}{n}$. So, you can find out what is $\frac{d\sigma}{dn} = 0$. So, you will get the density at which your conductivity is going to be maximum. So, I will leave it to you as an exercise. You know calculate where the conductivity is going to be minimum.

That means at that point resistivity is going to be maximum. It is not going to be at $n_i = n = p$ Anyway, it is an exercise for you. Let me quickly try to introduce another concept. I probably will not be able to complete it today, but I will come back to it in the next lecture. So, this is semiconductor, you know, if you have it in an electric field, what happens in the bands? So, we saw this picture already. So, let us say I take piece of semiconductor.

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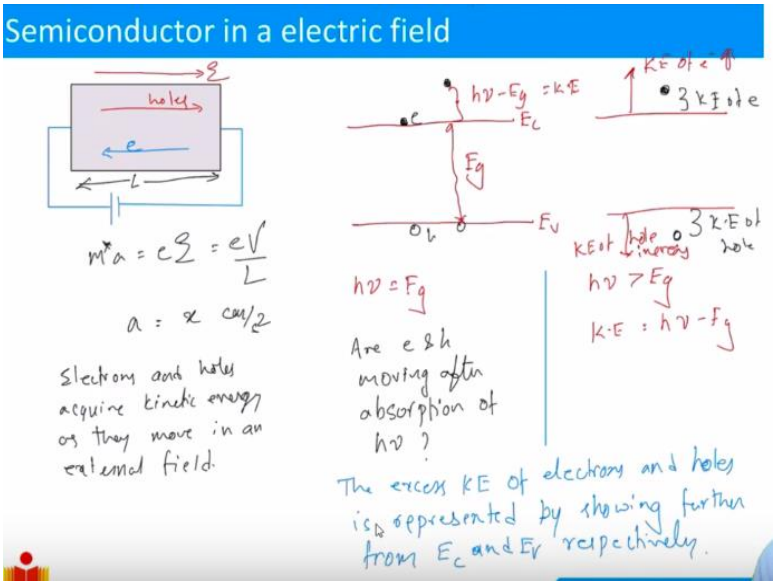

I apply certain voltage to it. I will do this. I apply voltage. And then if I do this, what happens? We said already that there is going to be the drift. We have talked about this already. So, the drift you know the field is going to be in the semiconductor is going to be in this direction. And so the field is in this direction, the holes are going to move in the positive x you could say holes and electrons are going to move in the negative x direction.

But, what is the acceleration? We talked about the velocity. What is acceleration? Which way they are moving? Are they going to accelerate? Of course, they are going to accelerate. Because we know from Newton's law that m_a or it will take it ma* because it is the effective mass we have to take not the real mass. Effective mass m into a is going to be what? The force applied force external force and that is simply going to be the electric fields times the charged density.

$$m_a^* = eE = \frac{eV}{L}$$

And, what is the electric field? Simply going to be the, whatever voltage you applied divided by the length of the crystal, length of this piece of semiconductor, L, if I call this as L. This is going to be this. So, you can find out you know, what is a? Is going to be some x centimetres

per second square. There is going to be some acceleration. So, what it means is, as the electrons move in the semiconductor, they are going to acquire some kinetic energy.

So, lets summarise that. Electrons and holes acquire kinetic energy as they move in an external field. So, now, we want to capture that in a band diagram. What happens to the band diagram when I apply an electric field? Think about it. So far, what we have seen is band diagrams was relatively harmless. They were simply this E_V and E_C. Now, if I want to represent an electron, which is actually acquiring kinetic energy, how will I represent that?

So, to understand that, we have to go back once, let us take a step back. And think about what happens when you shine a photon on a semiconductor with some band gap. Let us say I will shine a photon of let us say $h\vartheta = E_g$. This is the photon I shine. So, what happens? You had the lattice where you know electrons are essentially you know bonded. They are part of the covalent bond, so they are bonded to the silicon atoms.

And so, I will apply this photon will transfer its energy to the electron and make it go into the conduction band. So, an electron which was here in the valence band will actually get sorry I should no there was a electron here and that would travel up leaving you a hole and a electron at ehv we saw this before. Now, what is the, is the electron in the conduction band moving? Just after a photon is absorbed.

Is the you know, let us say, is the electron hole pair moving? Or, electrons and holes are moving? If not, electron hole pair moving, let us say, are e and h moving after absorption of $h\vartheta$? This is a question. It turns out that they cannot move. The reason is initially the anyway the electron is bonded to the lattice. So, the hole was not when the electron was not moving and it absorbed the energy of $h\vartheta$ and that was spent in breaking the bond.

So, it went to the conduction band, but then it does not have any more energy. Energy has to be conserved. So, initial energy was you know 0, it is not moving. It got absorbed. It absorbed a photon and that energy was spent in breaking the bond. And so, it went into the conduction band, it got free. But, it is not moving because it does not have any more energy to move. So, it is basically at rest, you could say kinetic energy is 0.

Now, consider another situation. Let us say, now, $h\vartheta > E_g$, what would happen? When you have this situation, let us say I will take the same case. I had an electron at edge of the valence band and then I will make it go into the conduction band. Now, it uses E_g energy to break the bond. But, then it has an additional energy that is spent basically given to the electron. Initially, electron was here.

You took the electrons from the edge of the valence band and you broke the bond. So, basically, you have an electron hole pair, but then it goes deeper into the conduction band. The reason is you have this additional energy. So, E_g energy was spent in breaking the bond. The additional energy which is there, this amount of energy is going to be $h\vartheta - E_g$. And that is the amount of energy that it got.

And that we will call it as kinetic energy. Basically, of course, it absorbs that energy it has to acquire some velocity and it starts moving. The velocity of the electron can be calculated. So, kinetic energy is going to be equal to incidental electron photon energy minus the energy which is absorbed sorry by the because of breaking the bond. So, this is the kinetic energy of an electron.

$$K.E = h\vartheta - E_g$$

And you could also have kinetic energy of a hole.

I mean, there is no reason for us to think that it is going to happen only at from the edge of the valence band. But, it could also you know you can absorb an electron in the deeper in the band can absorb. And then it can lead to some situation like this wherein your hole can have a kinetic energy, KE of hole. And this is KE of electron. So, essentially, what we are trying to say is this excess energy that an electron at a hole has is represented by depicting it away from the bandage.

I will write it down. This is important. Let me say this. The excess kinetic energy after breaking the bonds of electrons and holes is represented by showing them further from E_C and E_V respectively. So, what we are saying is, as kinetic energy of electron increases, it is going to move away. If you show an electron deeper in the conduction band, that means has a higher energy. Kinetic energy of electron increases and here KE of hole increases.

So, what we said 2 things now in this 2 concepts. One is whenever you have electrons or holes travelling in a electric field they acquire kinetic energy. And whenever they acquire kinetic energy, they have to be shown deeper into the bands, maybe deeper into the E_C conduction band or deeper in the valence band. That is how you represent them. So, we are running out of time. So, this is where I will stop.

And in the next lecture, we will start again, you know, we will take off from this point. We will actually draw the band diagram of a semiconductor and then apply the electric field. And then, we will also talk about some non-uniform doping and diffusion effects in the next class. So, what we did today was we started out with a brief review of what happened previously.

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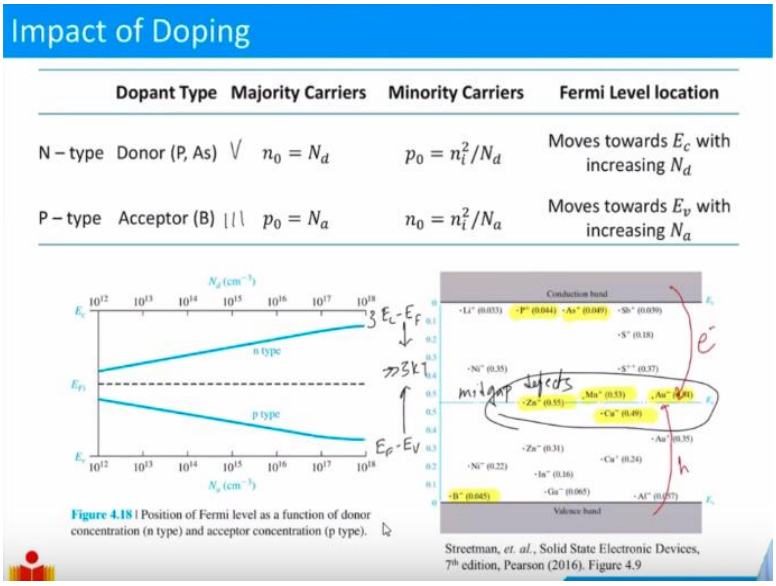

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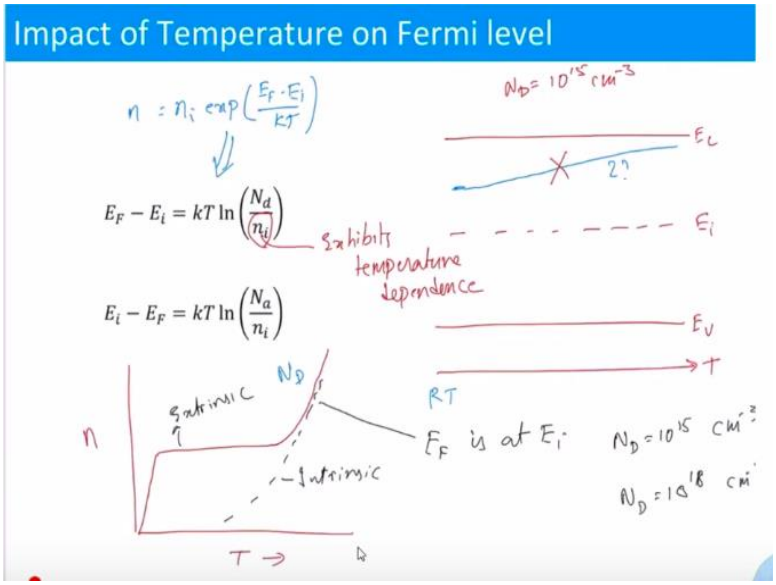

And then we talked about the impact of temperature. And also you know, we mentioned about different impurities and how they impact. And then we talked about the impact of temperature. After doing that, we introduced this concept of you know compensated semiconductor.

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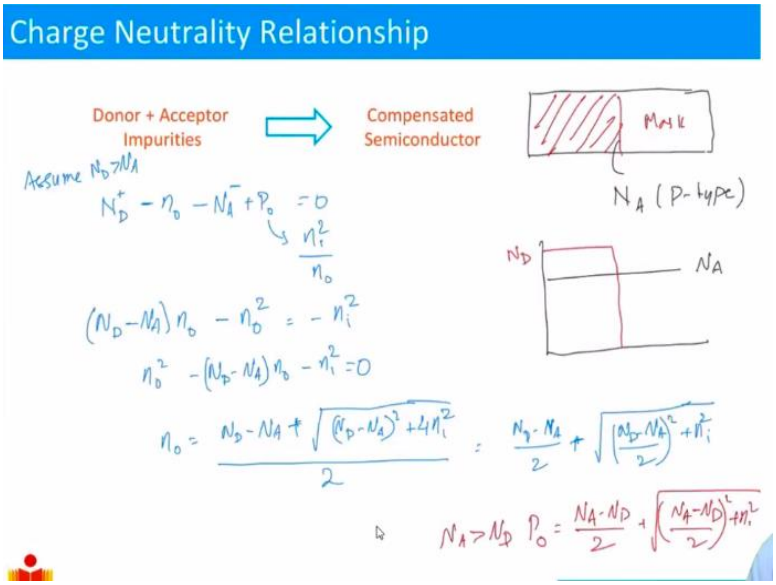

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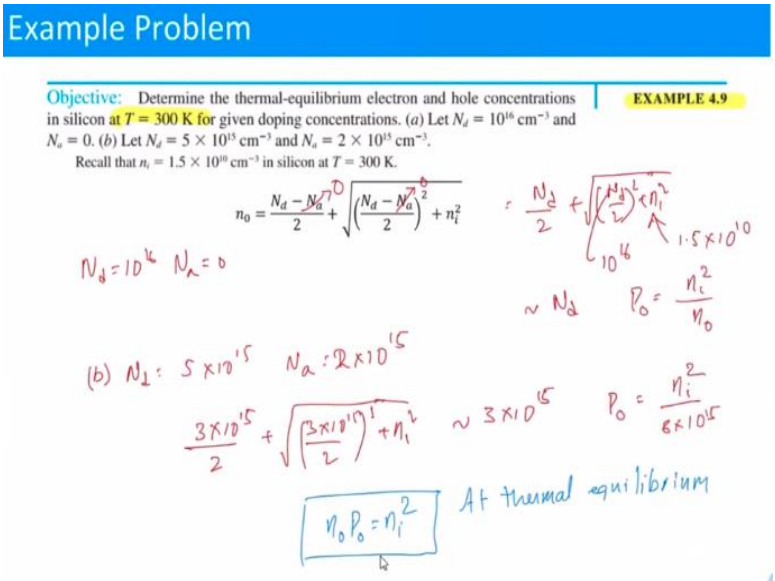

And then how to calculate the carry densities if you have a compensated semiconductor. And then we talked about basically carrier drift which is an important process. There are 2 main conduction mechanisms in a semiconductor. One is drift and the other one is diffusion. So far, we covered what is known as drift. We will also cover what is known as diffusion. And then we will talk about non equilibrium situations.

Once we do that, we are essentially ready. Our toolbox is ready. So far, what we have been doing for the last 2 weeks is basically build up this essential tools. And the next week also will build up a few more tools. So, by the end of 3 weeks, the toolbox necessary to understand the rest of the course is ready with us. Then we will apply it to different situations and then we will understand them. So, that is our goal for the next week.

By the end of next week, we are ready. So, in the week, after we will start with PN junction. That is a plan. So, thank you very much for your attention. And I look forward to seeing you in the next lecture. Have a good day.