Optoelectronic Materials and Devices

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Optoelectronic Materials Device Physics
Lecture - 28
Drift

In continuation with our discussion on carrier actions in semiconductors, we are going to look at what is the response of carriers to an applied electric field today.

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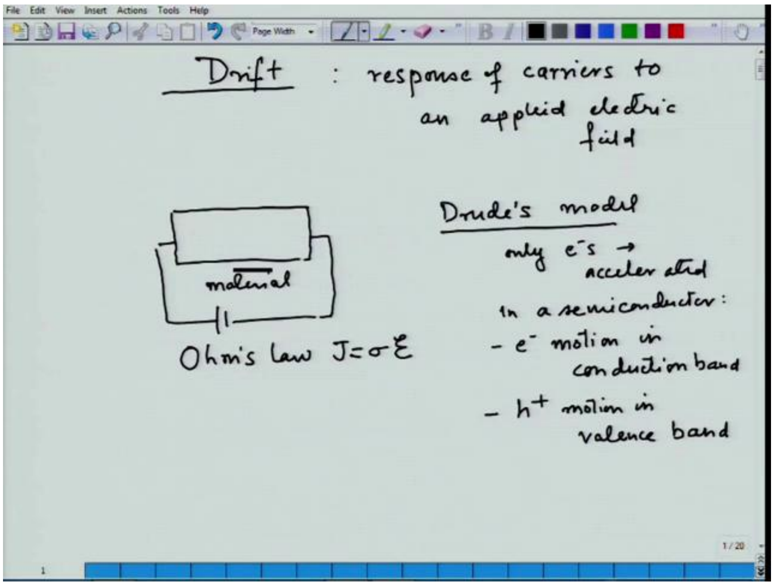

Drift : response of carriers to an applied electric field

Drude's model

only e^-s → accelerated

In a semiconductor:

- e^- motion in conduction band
- h^+ motion in valence band

material

Ohm's law $J=\sigma E$

The process is called drift this is basically, response of carrier to applied electric field response to an applied electric field. As you can see it is important because we are talking about opto-electronic devices. So, this signal to the devices mainly in terms of an applied voltage. Hence, we need to know what happens inside the material when we apply a voltage. So, if you recall the first lecture in this course is started with the similar discussion, we started with the discussion on how do we understand conduction of electricity in a material.

And the discussion is started with Drude's model, where if we have any material and we apply a bias to this. We know that this will follow the ohm's law which is basically, current density that is current per unit area in the conductor given by conductivity times the electric field. Now, in order to explain this Ohm's law we started the discussion in this course to understand how electricity is conducted inside a material, and then you know the progression from there.

We realize that the classical picture of just a negative carrier as electrons carrying the current, was not sufficient to explain the electrical conductivity in all materials. And so, it led to quantum mechanics and in from quantum mechanics to electronic structure of materials, and we have a very different picture of electronic structure of materials because of that.

We explained it in terms of effective mass of electrons in different bands the energy band diagram and now, we are back to again answering the question of how do these carriers as we understand now, respond to a electric field. So, in Drude's model there were only electrons and they were responding to the field by getting accelerated. Now, having gone through this whole circle of understanding electronic structure of material as we do today, we have in a semiconductor not only electrons which we look at the behavior in terms of electron motion in conduction band, but as described earlier.

We also think of the motion of electron in valence band in terms of hole motion in valence band. So, in contrast to what happened in Drude's model, when we apply a field to a semiconductor electrons in the conduction band would respond to as if, they are actually electrons in the conduction band with the effective mass of the electron in conduction band. And the electrons in the valence band would respond as if, they are holes with the effective mass of hole that would be the response of the holes in the valence band.

So, with this distinction now what we are about to do is we are going to now, again apply the classical theory that we developed earlier, to understand the conduction of conduction in semiconducting materials, or the drift process, or response to electric field by the carriers. So, with this introduction let me.

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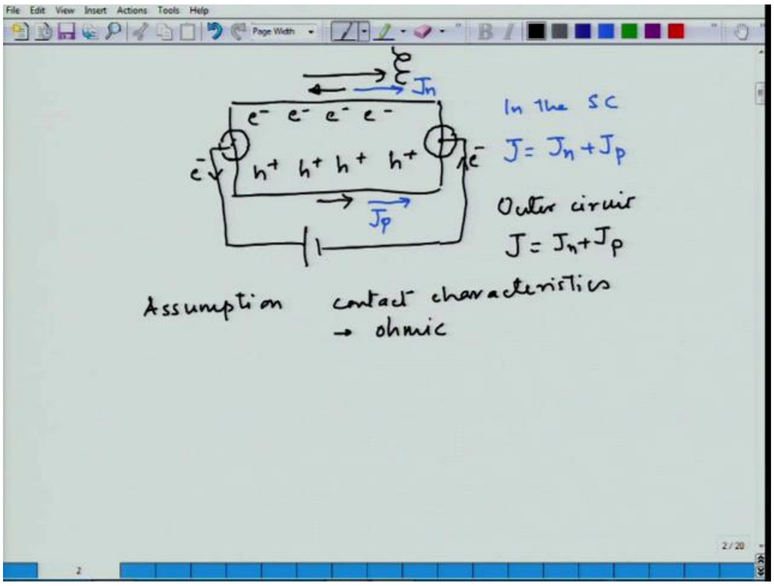

In the SC

$J = J_n + J_p$

Outer ciruit

$J = J_n + J_p$

Assumption contact characteristics

→ ohmic

First look at what is happening microscopically in a semiconductor, when we apply a electric field. So, this is my semiconductor as we just described we have basically, electrons in the semiconductor and we also have holes, electrons are in the conduction band as we know. And holes are the effective response of electrons in the valence band. So, when I am going to apply electric field, and I am going to use this symbol because we have to many e symbols for energy, e k diagram and hence, I am going to use this for electric field. I can apply electric field by applying a bias to this material semiconductor.
Now, with this electric field we know that the holes which are effective positive charge are going to move in this direction, and electrons in the material are going to move in the opposite direction. And as a result what would be the current, the current is going to be due to the hole inside, the inside the semiconductor there is going to be a hole current in this direction. What about the motion of electrons? Since, the current conventionally is the motion of the positive charge, it is going to be in the opposite direction to the direction of the electron motion.

So, the current due to electrons is going to be again in the same direction. So, if I am looking at the current due to applied electric field in the semiconductor, then the total current is going to be due to the current in the due to the holes and due to the electrons. What is happening outside the semiconductor? If I look at the rest of the circuit the holes which are coming to this end here, cannot continue into the in the conduction line outside because you only have electrons in the conductor line.

In order to then satisfy the current requirement that the current should be same in the semiconductor and outside the semiconductor they are going to be electrons, which will be moving in this direction to recombine with the holes that are coming here. On this end there is no problem because these electrons are coming to this contact and hence, they can continue to move in the in this direction, and provide the current in the outer circuit. So, the electrons in the outer are the carriers which are moving in the outer circuit, and compensating for both the electrons in the semiconductor, and the holes in the semiconductor.

So, if you look at in the outer circuit current as expected would remain same as J n plus J p except, the carriers involved are different. You only have electrons here electrons coming out and electrons moving in to recombine with the holes. Since, there is no holes available in the conductor. Now, in this picture there are certain assumptions, which I just wanted to state here and the assumptions here are about the contact of semiconductor with the wire, contact characteristics.

As I just mentioned that the electrons which are coming at this end can easily move out move to the outside circuit which means, that there is no barrier for electron motion at this at this interface, the same way if I am saying electrons move in to recombine with the hole at this interface, there is no barrier for the motion of electrons. So, this is same that the contacts are ohmic and hence, I need not worry about the characteristics of the contact at this point, and I am only looking at the behavior of carriers inside the semiconductor. And if this is true then now I can start looking at what happens in the semiconductor, when I have applied electric field, what is happening to the potential inside the semiconductor as well as the energy band diagram. So, taking the same example further.

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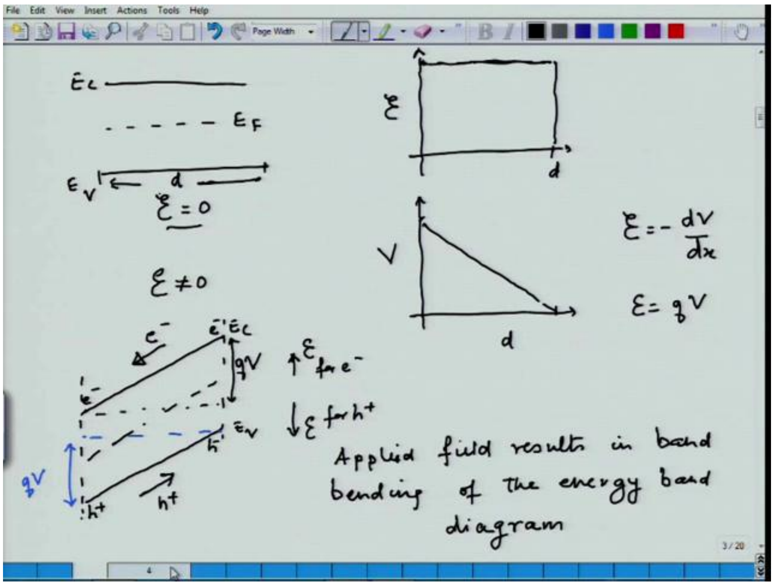

$\mathcal{E} = -\frac{dV}{dx}$

$\mathcal{E} = qV$

Applied field results in band bending of the energy band diagram

If I am looking at the semiconductor, when there is no field than I have conduction band valence band a Fermi level and the field is 0. Now, I go to a situation where I have applied a field e which is not 0. And if e is not 0 and I plot in the semiconductor, what is happening in a semiconductor of let us say distance x at this end, distance d. If I have applied a field and there is no drop of field at the context, then the field inside the semiconductor is constant and it is given by this value e.

And if I than look at if the if the field is constant inside the semiconductor, and there is no accumulation of charges anywhere, material remains neutral throughout in that case, what is going to be the potential inside this semiconductor. I can get that because electric field is nothing but a negative derivative of the potential. Which means the potential here is going to be decreasing linearly, throughout the semiconductor.

Now, if I want to know if I have potential and a field inside the semiconductor, what happens to this energy band diagram. This is the band diagram when field is 0, I want to know what will happen to energy band diagram when field is not 0. So, as we can see that if the field is not zero which means, that the hole which are at x is equal to 0 are at higher potential compared to the holes, which are at x is equal to d. Why is that? Because we know the potential is defined in terms of the energy, or the work done on a positive charge. If I want to think in terms of electrons which means, that at x is equal to 0 electrons have less potential compared to the electrons at x is equal to d.

So, which means that if I want to convert this potential difference into energy band diagram, I have to have energy band diagram which is, which is inverse of the behavior of the potential. And in this diagram I would be plotting e c e v with the positive slop which basically means, electron here have a less potential compare to electron here. And since, this is energy band diagram which is if you recall is plotted for electron energy increasing in this direction, electron energy increases in this direction for electron and the energy value increases for holes in the opposite direction.

Hence, for the hole this is higher potential and this is a lower potential because band diagrams are plotted for electron energy. What is this slope then? This slope is the potential difference between these two end and potential we know that energy is equal to q times v. Hence, this will be equal to the charge on the carrier times a potential difference. Same thing we can write about the holes this difference is equal to charge times the potential for further holes.

So, when we have when we have applied a field we are basically, taken a flat energy band diagram and the energy band diagram is now bent in order to accommodate the field applied. And it also shows the behavior that we predicted earlier, which says that electrons will move from higher potential to lower potential. So, they will be moving in this direction this would be the electron motion and for a holes. Since, holes potential is opposite they will be moving in this direction that is what we also expected, just looking it looking at the motion of carriers in a classical manner.

So, when I apply a field this is what has happened to energy band diagram. I have a field induced band banding in the semiconductor. Now, with this result basically I can say that the applied field results in vice a versa can also be said to be true for semiconductor. Which means that if you have band banding which means, there is some sort of built in potential or field existing in the in the material and this we will see later when we discuss devices. Currently we are discussing only effect of applied field here. So, with this picture now let us go to the discussion on what is happening, how are we going to get the conductivity of a semiconductor? So I will recall that when we were discussing conductivity of any material.

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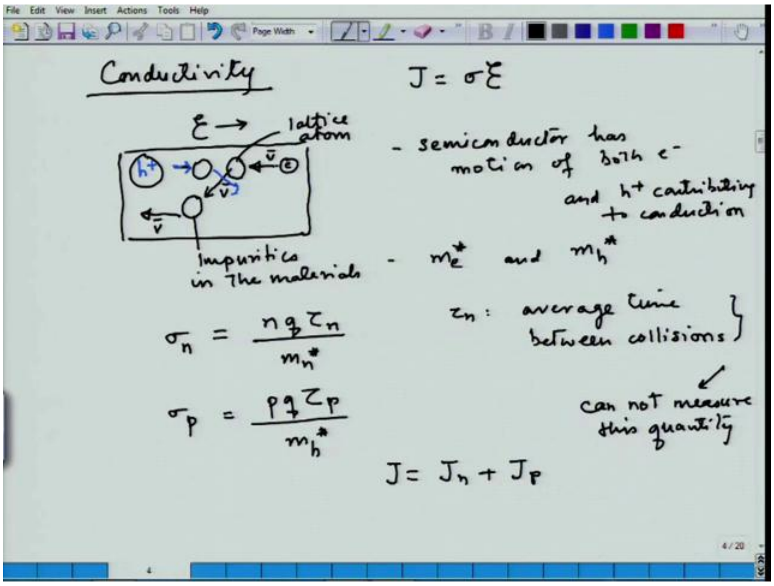

Conductivity

$J = \sigma \mathcal{E}$

- semiconductor has motion of both e^- and h^+ contributing to conduction

- m_e^* and m_h^*

$$\sigma_n = \frac{n q \tau_n}{m_n^*}$$

τ_n : average time between collisions $\}$

$\swarrow$ can not measure this quantity

$$\sigma_p = \frac{p q \tau_p}{m_h^*}$$

$$J = J_n + J_p$$

You know that current density is given by conductivity times the electric field, and current conductivity there was dependent on only on electron concentration, but here we are going to talk about conductivity of the material, which is going to depend on both electron and holes. So, this is this is what we are going to assume in this model basically, we are going to now assume that the conduction, in the semiconductor is like a like the classical picture we used in the Drude’s model. What are the differences?

The differences being that semiconductors has both electron in the conduction band, and holes in the valence band. So, semiconductor has motion of both electrons and holes contributing to conduction. And I am going to treat it as if now these electron and holes are classical particles that we did earlier, the only difference being the electron mass in the conduction band is going to be the effective mass of electrons in the conduction band. And the hole mass is going to be the effective mass of holes in the valence band. So, this is what I have taken from my quantum mechanical picture, I have changed the effective mass otherwise I am going to assume the similar picture that we had earlier.

So, let us take an example of if I am looking at only right now, electrons which are in the conduction band and I am applying a field then because of this field, this electron is going to. Let me take the electron on the other hand because if I am taking the field in this direction electrons going to move in the opposite direction. Now, this electron will have some average velocity because of this field, and then just like a classical particle it may have a collision with the lattice atom. In the process it will transfer its energy to the lattice atom and then, it would come out with this collision from this collision with the thermal energy at of the, of the electron.

And then again in this direction and again get accelerated, again having a average velocity v for the hole collective ensemble of electrons in the material. It may again have a collision with impurities in the material or acceptors and donors, which could be accept dopants or deep level impurity. Mainly dopants because dopants concentration is much, much higher than impurity concentration that is a major effect, and then from here again this electron comes out of this collision with the overall average velocity of v.

So, a electron in this path being accelerated by the field and having collision over all reaches a velocity drift velocity v average, which results into the in current of j in the material, when I am applying the electric field e or potential v. So, if I look at look at the classical picture then, I can write the conductivity due to electrons in the conduction band will be given by the carrier concentration of the electron in the conduction band, the charge and tau n which we have defined earlier divided by m n star.

What is tau n tau n is the average time between collisions, which are the scattering events in the path of electron motion. And as we described these collisions can be due to the lattice, or it can be due to the impurity atoms in the material. Similarly, a hole which is in this material will have will have a similar path, it will be accelerated then it will have a collision and so on so forth. So, for similarly, I can write for holes the carrier concentration of holes in the material, the charge, average time between collisions for holes in the valence band, and the effective mass of hole in the valence band.

So, basically when I am applying a field to a semiconductor then I have two carrier moving one electron, one hole. And in order to get the total current I need to add these two currents which would then be overall J will be J due to the electrons plus J due to the holes. Now, in this whole picture the average time between collision is something which is not measurable, you cannot measure it what is the average time between collision cannot measure this quantity. And so, for practical reasons there is another quantity which has been used in describing the drift motion of carriers in the semiconductor. And it is referred as the drift velocity, which is the average velocity that electrons gain.

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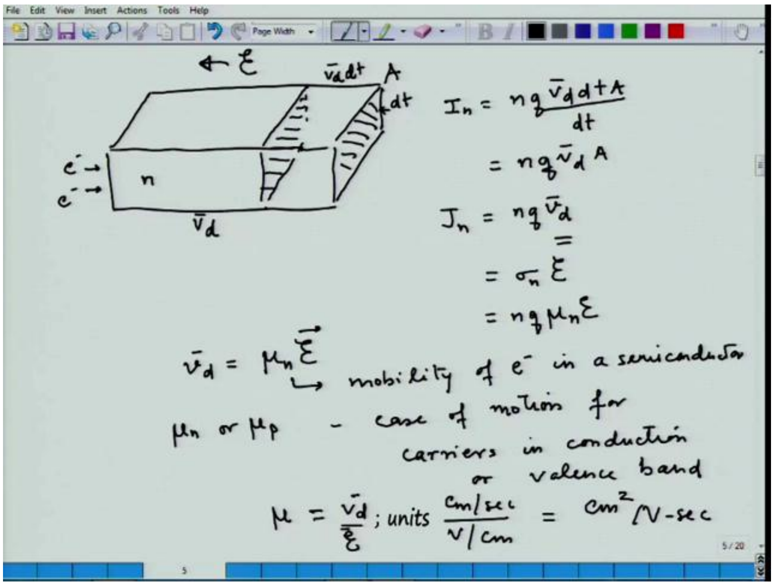

$$I_n = nq\frac{\bar{v}_d dt A}{dt}$$

$$= nq\bar{v}_d A$$

$$J_n = nq\bar{v}_d$$

$$=$$

$$= \sigma_n \mathcal{E}$$

$$= nq\mu_n \mathcal{E}$$

$$\bar{v}_d = \mu_n \vec{\mathcal{E}}$$

$\hookrightarrow$ mobility of e^- in a semiconductor

μ_n or μ_p - case of motion for carriers in conduction or valence band

$$\mu = \frac{\bar{v}_d}{\mathcal{E}}\text{; units } \frac{cm/sec}{V/cm} = cm^2/V\text{-}sec$$

And in order to understand, what we are talking about in terms of this microscopic property. If we take a semiconductor slab with the area A and we apply a electric where let us look at the motion of electrons, electrons are moving let us say in this direction. Then the current due to the electrons is going to be given by the total number of electrons let us say, this is n is the number of electron density in conduction band. The number of electrons the charge that will pass through this area in unit time.

So, how many electrons will pass through this area in unit time? Let us say if the drift velocity is v d. That is the average velocity that electrons gain in a electric field e, and let me make the electric field in this direction because I have given the direction of electrons in the positive direction here. Then the number of electrons which will cross this in time d t will be given by the average velocity v d d t, all the electrons in this volume in time d t will cross this interface which means, the total number of charges crossing this interface is going to be the drift velocity of electron due to field d t multiplied by a divided by if I want to give it to the current times d t.

So, my current due to the electrons can be thought of as n q v d A, and if I am talking about current density this is nothing but n q v t. Now, this equation is similar to the equation earlier only difference being earlier, we are talking about the microscopic phenomena, collision between electron and impurities. Defining a quantity as tau, which is a average collision time between two scattering events, and here I am taking all that phenomena into a parameter called drift velocity, which is the effect of the electric field on to the electron.

What kind of drift velocity it will gain and then I can define my current in the same manner. This discussion is further developed by equating this current density to conductivity of due to electrons multiplied by the electric field, which is applied if I take that equation then this is basically, saying that I can define this will be n q times mobility of electrons time e field, or what I am trying to say is that v d the drift velocity generated is nothing but the mobility of electron in applied field e.

So, this is the definition of the drift velocity and this is mobility of electrons in semiconductor, which is in the conduction band. Now, what is this mobility, this mobility is basically defining what drift velocity can I gain, if I applied a electric field e. So, it is defining the ease of motion of a electron in a given applied field. If mobility is very large which means my drift velocities will be large and I can accelerate electrons easily with the given applied field if mobility is low which means I have many scattering events and I cannot accelerate electrons easily in such a material.

So, mu n is nothing but mu n is for electrons or mu p if I take the same discussion for the holes it is nothing but ease of motion for carrier in conduction or valence band. What is the unit for this mobility? The unit for mobility is basically the drift velocity divided by the field, which is going to be centimeter per second divided by volts per centimeter. So, the units of this thing is going to be centimeter square per volt second.

Now, we have coined a term called mobility, which is how easily electrons in the conduction band or holes in the valence band can move, and it is units will be given in terms of centimeter square per volt second. Now, rest of the discussion will be what is this mobility, how does it depend on different parameters in a semiconductor and how would we use this equation, when we actually talk about optoelectronic devices. So, what are the typical values of these mobilities?

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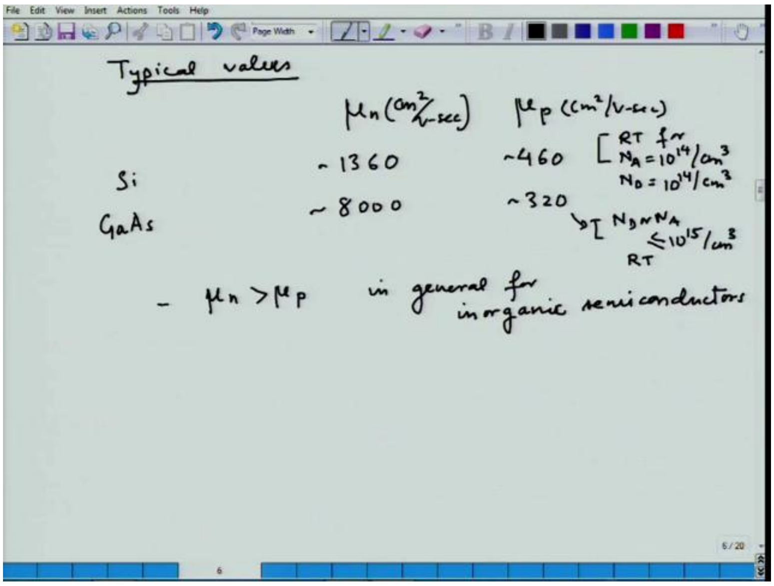

Typical values

	μ_n (cm^2/V-sec)	μ_p (cm^2/V-sec)
Si	~1360	~460
GaAs	~8000	~320

[RT for $N_A = 10^{14}/cm^3$, $N_D = 10^{14}/cm^3$

[$N_D \sim N_A \leq 10^{15}/cm^3$ RT

- $\mu_n > \mu_p$ in general for inorganic semiconductors

Let us look at some typical values in semiconductors. So, the mobility for electrons in conduction band, mobility for holes in the valence band. Let us take material silicon this mobility is roughly 1360 and this one is about 460. The units are given in centimeter square per volt second, this is centimeter square per volt second, this is also in centimeter square not a m k s unit, but this is what normally people use. In gallium arsenide, this would be 8000 and this would be about 320, what is important is this value is reported at room temperature for accepter concentration of 10 to the power 14 per centimeter cube, and donor concentration also 10 to the power 14 per centimeter cube.

While this value is reported for either donor or accepter concentration being less than equal to 10 to the power 15 per centimeter cube and room temperature. As you can see these number certain observations you can make in inorganic semiconductor generally, mu n is greater than mu p its easier to move the electrons in the conduction band then to move the holes in the valence band, this is true for in general for in organic semiconductor. It is you can also see differences between the two materials, as you can see gallium arsenide has much higher electron mobility compared to the silicon.

And for that reason gallium arsenide is a preferred material for many high frequency, or high speed devices because electrons can move much easily in the conduction band in these and these material. The other thing then you notice here is that when we are talking about mobility of carriers in semiconductor, we are always reporting at reporting it at a given condition at what temperature or at what dopant concentration. Which means, this is a property which not only depends on what the semiconductor is it also depends on temperature and doping concentration in the material.

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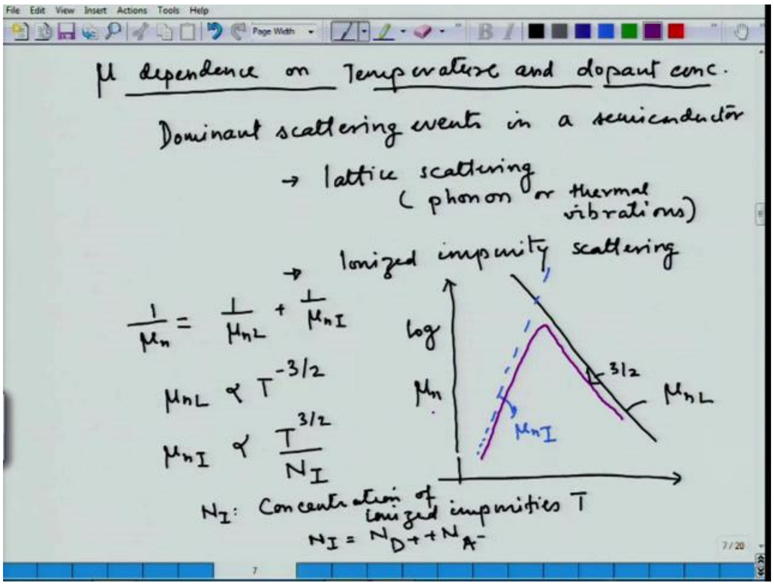

μ dependence on Temperature and dopant conc.

Dominant scattering events in a semiconductor

→ lattice scattering (phonon or thermal vibrations)

→ Ionized impurity scattering

$$\frac{1}{\mu_n} = \frac{1}{\mu_{nL}} + \frac{1}{\mu_{nI}}$$

$$\mu_{nL} \propto T^{-3/2}$$

$$\mu_{nI} \propto \frac{T^{3/2}}{N_I}$$

N_I: Concentration of Ionized impurities

$N_I = N_{D^+} + N_{A^-}$

So, how does that depend, how does the mobility, which is our new property which describes the drift. So, mobility dependence on temperature and doping concentration and dopant concentration. So, if we want understand this behavior, we need to understand what exactly is the mechanism. So, what is a mechanism for this mobility? The mechanism for this mobility is that the carriers are getting accelerated in the electric field, and then they have a scattering event where from the scattering event they come out with the thermal, thermalized energy and then they get accelerated again and they have a second scattering event. So, what we need to understand to understand this effect is what are the scattering events.

So, what are the dominant scattering events in a semiconductor. In general, we can talk about two main events the first one being scattering due to lattice scattering. So, here the electrons or holes are getting are having a collision with the lattice items, and this is this is also referred as phonons because it is the vibration of the lattice atoms, which effect the scattering with atoms. So, phonons are the thermal vibrations are the cause for scattering of a carriers, when they are moving in a applied electric field.

The second one which is dominant is the ionized impurity scattering, and this is electrons getting scattered by the impurities like dopants acceptor or donor, where they would collide with these ionized impurities and get scattered. And so it depends on the concentration of the dopants, and this is what results in that over all dependence of mobility on these two terms. Now, we can there are other scattering events, but we need not go in to that many details, these are the two dominant mechanisms for scattering.

If I want to look at the mobility effect due to lattice scattering on ionized impurity scattering. Mobility is basically, overall effective mobility of the material, or n would be for electron would be due to the lattice scattering plus the mobility due to the impurity scattering. I can always add them these two scattering event as if they are two parallel event, and the overall effect is what I will see in the material. So, if I do that then and I look at the behavior of these two mechanisms then, I can look at the temperature dependence of these two mechanisms, and I am going to plot then the mobility on the log scale on the y axis, and I am going to plot temperature this is a schematic on the x axis.

If I am only looking at the effect on the electron mobility due to lattice vibrations, I find that mu n l and this is from some simple theoretical calculation is generally, dependent on temperature with the negative 3 by 2 exponent. So, if I plot it on this curve would be something like this where the slope is 3 by 2. Now, this is understandable because if you have higher temperature which means, that the lattice atoms are vibrating at a higher frequency which means, they can scatter a electron which is moving due to electric field much more.

And hence, at higher temperature the mobility of electron will reduce because it is having to face many scattering events. So, this is the behavior that one sees and if you look at the electron mobility due to impurity is then that comes out to be proportional to T to the power 3 by 2 divided by the concentration of the ionized impurity. So, N I is concentration of the ionized impurities since, in general in the semiconductors it will be the acceptors and donors, which will be dominating the type of impurities one can say that N I is the donors, which are ionized plus the acceptors which are ionized.

So, this is the ionized concentration and this dependence if we plot, turns out to be something like this. So, this is this is due to mu n due to impurity this is due to the mobility due to the due to the lattice vibrations. So, if I see the overall effect on the mobility, I should see mobility changing in this region like that. Again the, this impurity effect can also be a understood in terms of the fact that when you have low temperature, the thermal energy of carriers is low. When you have higher temperature and enhance, the velocities are on the lower side. When you have higher temperature they are moving around much faster, and the scattering probability is basically inversely propositional to it.

So, the carriers which are at low thermal energy are more probable to scatter compared to when they are at a higher thermal energy. And hence this is the behavior that you see due to impurity scattering. So, overall this is what one expects when one sees the mobility, the effect of temperature on the mobility of electrons, I can have the same discussion for mobility of holes, it will remain similar and the behavior is going to be similar. So, with this we can then look at some again some more typical data what we see.

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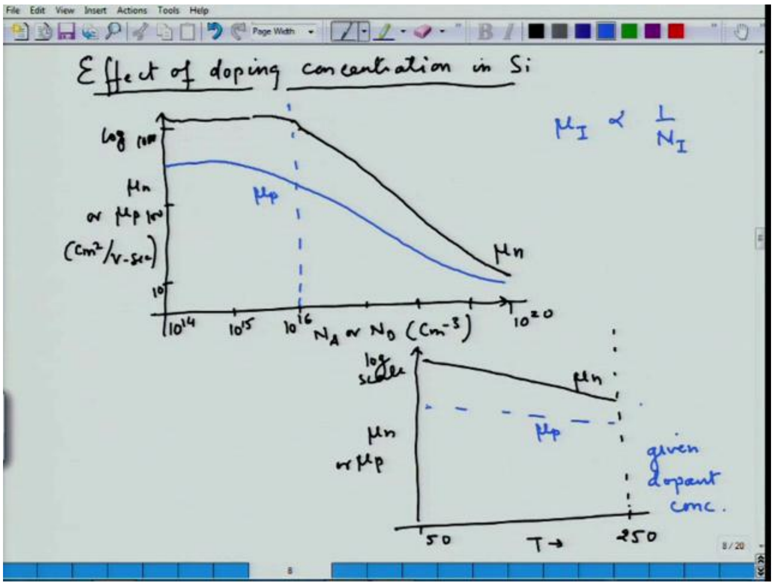

So, if I am looking at effect of doping concentration in silicon and I am drawing some schematics here, more precise data can be obtained from the text books and other resources. And if I plot mobility of electrons or mobility of holes on the same scale, the unit being again centimeter square per volt second, and then I plot on the axis scale. The carrier concentration sorry dopant concentration, which is in centimeter cube per centimeter cube and I am going to take it from low level of doping to let us say about 10 to the power 20 with 15, 16, 17, 18 and 19 something about 10 to the power 20 and this is in log scale.

So, in the log scale this number is about 1000, 100 and 10. So, for silicon the mobility starts at a higher number up to 10 to the power 15, 10 to the power 16. It sort of remains constant and then it drops quite linearly up to the high doping level, this is the electron mobility. If I look at hole mobility it starts somewhere here, and then again it follows similar behavior. So, up to about 10 to the power 16 I can probably use with some assumptions a one mobility number for the devices, but if the doping concentration increases to the range of 17, 18, 19 or onwards I must use the function, which describes the mobility as a function doping concentration because it does change by order of magnitude.

And the effect is because of that inverse the mobility, mobility due to the impurity is basically inversely prepositional to N I, and you can start seeing this effect at a higher concentration of the dopants here. The same behavior if I try to see for silicon in case of temperature with temperature, if I would plot again on the log scale mobility of electron, or mobility of hole in silicon as a function of temperature. Let us say going from 50 to 250 then I would find this behavior is going for mu n and similarly, for holes it is going to be mu p. Over here we are basically seeing the effect of the lattice vibrations here, for a given value of for given dopant concentration.

So, unlike what we had shown in the temperature effect it first increases and goes down, what we are seeing is only the effect of the lattice vibration, where the mobility is continue to decrease with temperature. So, these are the typical values of mobilities that you will see in semiconductors. So, if your dopant concentration is changing in the device, or if the temperature is changing then one must use the expressions, where the mobility is to be corrected for the given dopant concentration and temperature. With this let us look at the effect of this mobility on conductivity of the material. So, let us take an example.

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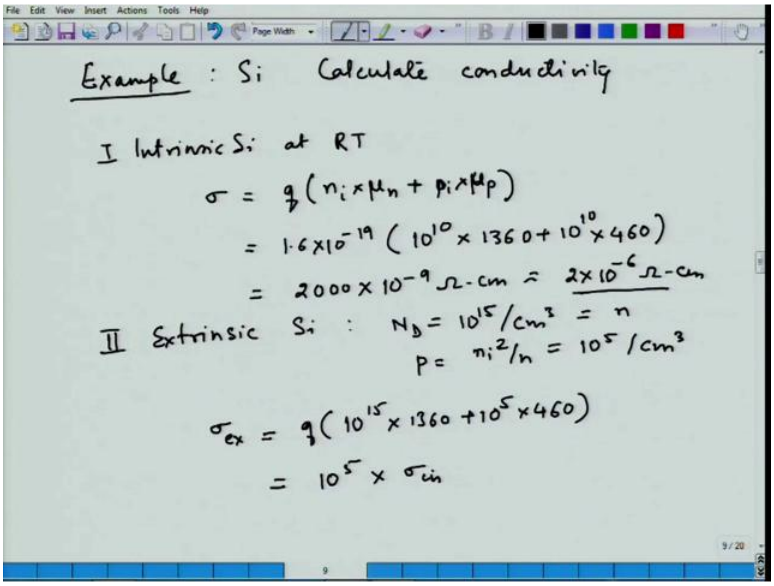

Example : Si Calculate conductivity

I Intrinsic Si at RT

$$\sigma = q(n_i \times \mu_n + p_i \times \mu_p)$$

$$= 1.6 \times 10^{-19} (10^{10} \times 1360 + 10^{10} \times 460)$$

$$= 2000 \times 10^{-9}\ \Omega\text{-cm} \approx \underline{2 \times 10^{-6}\ \Omega\text{-cm}}$$

II Extrinsic Si : $N_D = 10^{15}/cm^3 = n$

$$p = n_i^2/n = 10^5/cm^3$$

$$\sigma_{ex} = q(10^{15} \times 1360 + 10^5 \times 460)$$

$$= 10^5 \times \sigma_{in}$$

We take a example here for us, for a intrinsic example we take for silicon and we are going to calculate based on our discussions so, far calculate the calculate conductivity first for intrinsic silicon at roughly room temperature. So, what would be the conductivity, conductivity is going to be nothing but as we discussed earlier is going to be q times the concentration for intrinsic silicon multiplied by the mobility for silicon, which we have just shown in few slides earlier what is this value. Then the intrinsic concentration hole concentration and multiplied by the mu p.

So, taking these values from a earlier examples I can write this as q times n i. Let me write the value of q directly the coulombs n i is taken as 10 to the power 10 and mu n is just given to as 1360 plus 10 to the power 10 because n i will be equal to p i for a intrinsic semiconductor, multiplied by 460. And if you do this calculation you will get a value for conductivity, which is about 2000 times 10 to the power minus 9 Ohm centimeters, or you would write it in terms of 2 times 10 to the power minus 6 Ohm centimeter, this is for a intrinsic semiconductor. So, the intrinsic semiconductor is has this conductivity.

Now, if I do calculation for a extrinsic semiconductor, extrinsic silicon and let me give values for this extrinsic semiconductor, where the donor concentration is equal to 10 to the power 15 per centimeter cube. And this if all of them are ionized, this will be equal to your n extrinsic material, and p will come out to be then n i square divided by n, which is going to be 10 to the power 5 per centimeter cube. So, if I calculate for extrinsic semiconductor then, this will be equal to q times 15 multiplied by 1360 plus 10 to the power 5 times 460. And if you do this calculation, the value that comes out to be is approximately 10 to the power 5 times sigma intrinsic.

So, this is what the power of semiconductor is if I look at the conductivity of the material by just doping by the amount of 10 to the power 15 per centimeter cube. I have changed the conductivity of the intrinsic semiconductor from minus 6 value to 10 to the power 5 times of that value. So, this is how one uses the drift motion and it can explain the conductivity of a given material, but drift motion cannot be used everywhere. Drift motion as explained the Ohm's law is good for low level of fields, or intermediate level of fields if you have a very, very high field if the fields are very high.

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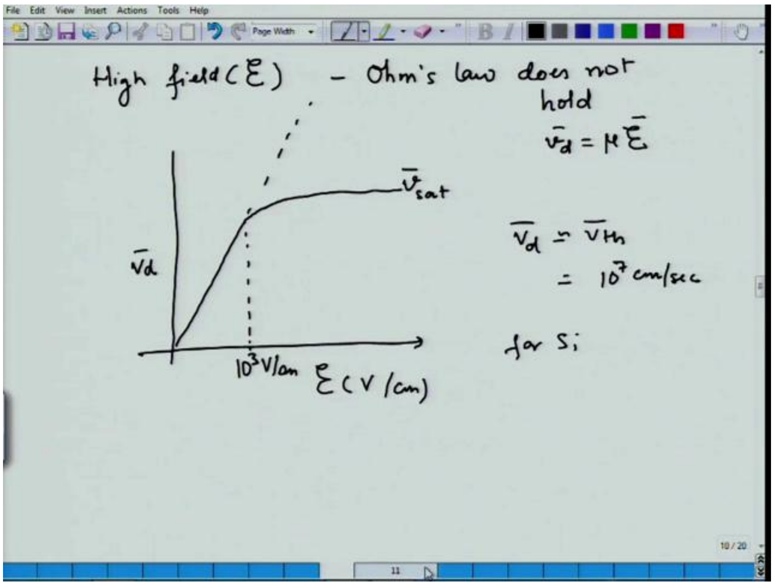

High field ($\mathcal{E}$) - Ohm's law does not hold

$\bar{v}_d = \mu \bar{\mathcal{E}}$

$\bar{v}_d \simeq \bar{v}_{th}$

$= 10^7$ cm/sec

for Si

At very high field the Ohm's law breaks down. Which means, if I am trying to plot the drift velocity in a semiconductor, let us say in silicon as a function of electric field then from my earlier discussion, the drift velocity is nothing but mobility times the electric field. And that is then expected to be linear in nature, and it is good and this linearity holds for up to certain field. Generally, in case of silicon for silicon this field is about 10 to the power 3 volts per centimeter, this is given in volts per centimeter. And after that it is not following the Ohms law anymore and it saturates to a value, which we call as v saturation.

What is happening is that as I increase, I keep increasing the field the carriers are responding to the field, and they are getting accelerated and your drift velocity is increasing linearly, but if the fields starts becoming very, very large. All the energy that you are providing to the carriers through the field is getting lost in heat, in terms of may be emission of optical phonons and so on so forth. And you are not increasing the average velocity anymore and that reached to the v saturation, this is the limit at which point the drift velocity at this field.

The drift velocity of electron is approximately equal to the thermal velocity of the electron. Which means, beyond this field we cannot further increase the drift velocity of the electron, and there is a saturation in the drift velocity. And this field comes at roughly the velocity of about 10 to the power 7 centimeter per second. So, all the discussion on that we have had so far on drift of electrons due to the electric field is good in this regime of linear Ohm’s law, for the v saturation we must use a different expression for response of the electron to the electric field. So, with this now we have the tools to incorporate drift of electrons in semiconductors.

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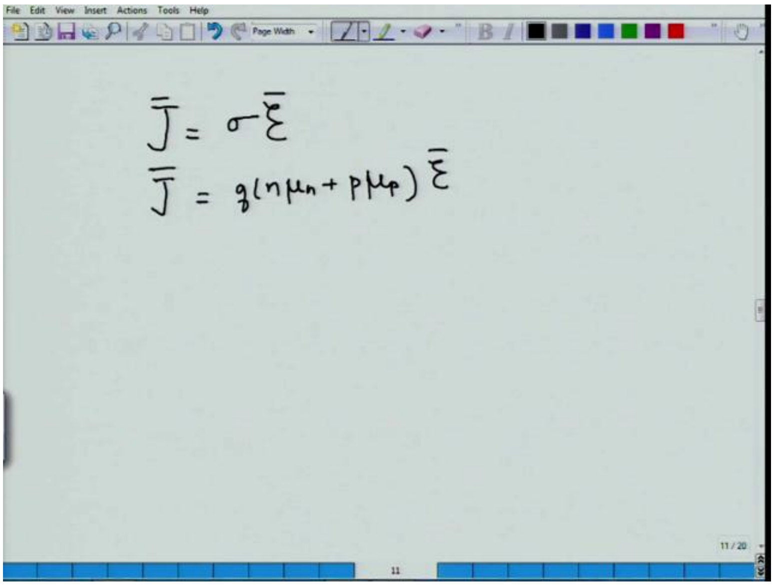

$$\bar{J} = \sigma \bar{\mathcal{E}}$$

$$\bar{J} = q(n\mu_n + p\mu_p)\bar{\mathcal{E}}$$

So, as a result of this discussion, we know that we can write the current density in a semiconductor in terms of the conductivity of the semiconductor due to the applied field. And the conductivity of semiconductor, we can write in terms of the carrier concentration in conduction band the mobility of electrons, the hole concentration in valence band, the mobility of holes we can calculate in this manner. And so, this is the behavior of carriers in semiconductors, and how we characterize them in terms of the carrier mobility in semiconductors. And next, we will discuss the second type of carrier motion, which is due to the change in carrier concentration itself that would be the next lecture.

Thank you.