Physics of Materials

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Lecture No. # 35

Semiconductors

Hello. Welcome to the 35th class in our course the physics of materials. In the last class we looked at how bands come about and how bands gap come about from the approach taken by two different ways of approaching this problem one was the free electron approximation and the other was the tight banding approximation. So, we have actually looked at the free electron approximation in considerable detail, we briefly looked at the tight banding approximation.

And I told you the reasons why we focus more on the free electron approximation because that is more relevant for metallic systems in search, but in principle both of them should give as the same kinds of the results they should predict the same make; the same predictions. And largely they do it is just that the tight banding approximation is most suitable for insulators and semiconductors and such.

So, and the free electron approximation is most suitable for metallic systems more appropriated at least in the context of both these approaches we have seen where bands arise from in in particular the fact that (( )) interact with Fermi surface. And tell us the bands and band gaps that exist in a in a material if the free electron approximation and the importance of inter atomic phasing when it is comes to tight banding approximation. In this context, in both approaches, we see that in principle they have the details and place of to tell us why an isotropic should exist in a material certainly, in the case of free electron approximation the geometry of this crystal structure is reflected in the geometry of the (( )). And therefore, that is directly reflected in the manner in which the (( )), now interacts with the Fermi surface.

So, and therefore, the locations where there is a interaction the extent to which an interaction exist all of these are directly related to the space of the (( )) and where it is with respect to the Fermi surface and therefore, the directionality arises as direct result of this interaction. So, in this context we have seen the importance of the Fermi surface, we also briefly saw that you know once you can once you understand that there are bands and band gaps you can actually even manipulate materials, and increase or decrease the band gap. And therefore, change their properties also in the context that we know that there are bands and band gaps we have.

We briefly saw how metallic systems differ from semi-conducting systems and differ from insulating systems with respect to those band gaps and bands in this class we will spend more time on the semi-conducting systems semi-conductors in general we will see where many of the concepts we have learned. So far or how they are relevant to the semi-conductors for example, the Fermi surface and we will see the importance of the E verses k diagram and what is tell us about properties more specifically, we will see why the E verses k diagram gives as much more useful detail of the system than a plot band diagram which. In fact, in some sense captures a same we will tells as what an allowed energy level is and what band gap is. So, the E verses k relationship is important and we will see why it is important and also in the context of the semi-conductors will also get an idea of the optical properties and how all of this information comes together in in when we talk of optical properties of materials.

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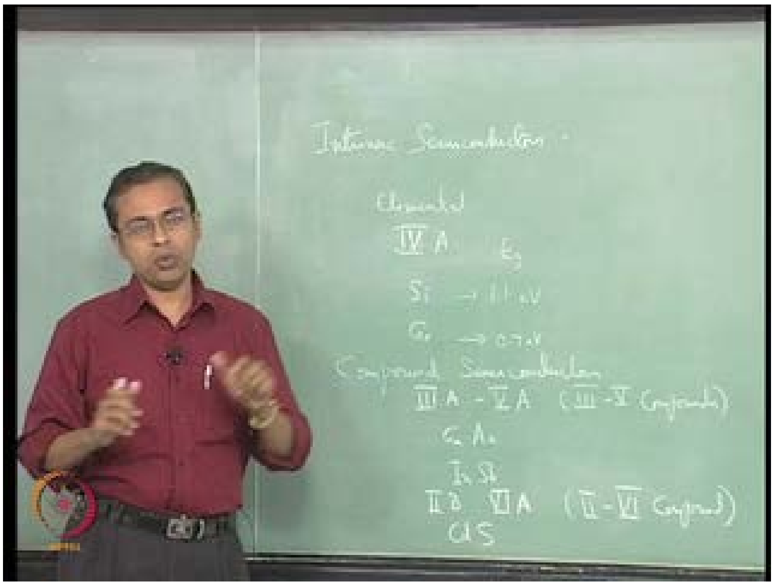

So, this is what we will do. So, when we look at semi-conductors in principle we have ah they are classified as intrinsic semi-conductors and extrinsic semi-conductors. in in principle the main difference early is that in intrinsic semiconductors the properties that you see is that of as pure a material as you get, and there are at least there are no deliberate attitudes to this material, you are seeing the property of that material. And in extrinsic semiconductors we have deliberately added some depends which change the manner in which the material response. But in a more fundamental sense what we are saying is that intrinsic semiconductors are those where the properties, we have measuring at least in the case they say the carrier concentration in search is a direct result of the temperature of the material.

It is primarily depended on the temperature of the material that is what decides the carrier concentration in in an intrinsic semiconductor in an extrinsic that conductor that is not necessarily so. In fact, there are regions in ~~a~~ of temperature where the the behavior of this semiconductors is dictated by factors that are completely unrelated to temperature they depend entirely on the extend of doping that you have done to it the extend of additional elements that you have added to it. So, in intrinsic semiconductors, we will first look at intrinsic semiconductors, then will talk about extrinsic semiconductors. So, of course, the standard classic examples as basically the intrinsic semiconductors can be elemental or compound phase.

So, these are elemental semiconductors that are intrinsic they are group 4 A elements silicon and germanium and we could also have compound semiconductors that are still intrinsic and they would consists of elements which are an either side of this ah group 4 A. So, we will we could take a 3 A element and mix it with a 5 A element and then you get a compound semiconductor you could also take a group 2 b element and mix it with a 6 A element and you would get a compound semiconductors. So, that is basically what you looking at. So, we can have 3 A and 5 A elements. So, these are called 3 5 compounds right. So, these are called 3 5 compounds, and so an example would be we could have gallium arsenide, gallium arsenide we could also have indium antimonite these are compound semiconductors, but they are intrinsic in nature.

So, their behavior responses is really based on temperature you could also have 2 6 compounds; so 2 B and 6 A compounds. So, an example of that would be a say cadmium sulfite. So, this would then be called 2 6 compound for obvious reasons. So, this is A 2 6 compound, you can go further, and further and in the periodic table an either side of group 4 A, but the problem then arises as you go further and further away the electron.

The electron negativities an electron affinities of theirs begins to change, so much that you are favoring more an ionic bond rather than a covalent band. And these are elements that this kind of behavior you see mostly within situations where you have a covalent bond rather than a anionic bond in anionic bond the electron simply gets localized. So, is not position to be shared or moved moved around whereas, here they moved around. So, this is this gets trapped and so this is not what we are looking at us looking at covalent bonded elements. So, the yes are the further away you go it becomes more and more ionic. So, that is the issue that you face so.

So, this is a compound, these are compounds semiconductors 3 5 and 2 4 we could look at these elements depending on where you encounter or them you will either here the description in terms of bonds and how the electrons shared between bonds or alternatively we look in terms of the band structure. So, in hours in our discussion we preferred to use the band structure ultimately we taking of the same thing. So, therefore, only whatever is convenient to us a solve that we use. So, you are going to talk in terms of band structure.

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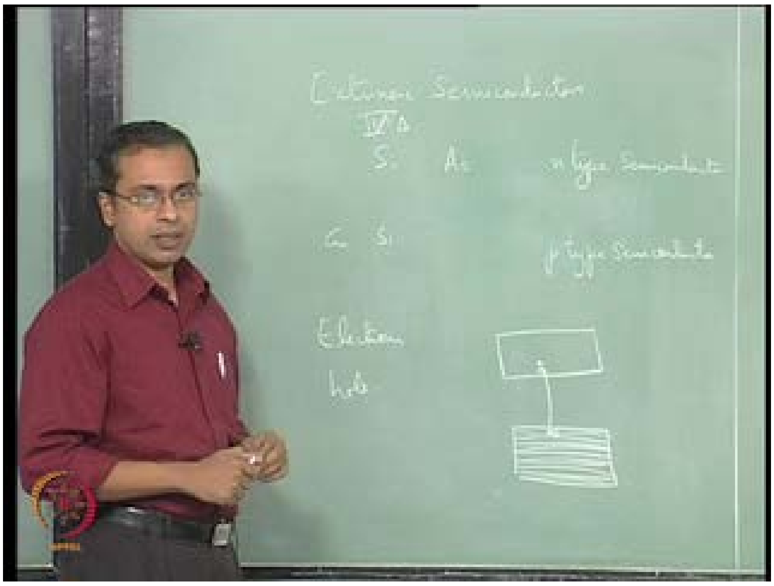

So, this is what we have, if you are talking of extrinsic semiconductors then we could take silicon and so we can dope it with say gallium or if you say dopiest with arsenic for example, then we you will have additional electrons. So, this would. So, any basically a group this is group 4 A. So, if you dopiest with a any elements that is from the group 5 A then basically you have on n type semiconductor because you have the additional electrons from the arsenic which can room around or you could dope it with A. So, for again again silicon with say gallium which is three a then you have A p type semiconductor which means you have sort an electrons and. So, there and that is why it is called p type in principle they have ultimately there are some charge carriers in this materials and two charge carrier that we define or that we are that the first on we were familiar with it is the electron.

So, electron as charge carriers and. So, that is our discussion when we talk of intrinsic semiconductor and so on, this is what we are starting out with, but every time an electron if you have an electron that is sort of consequents by its absence. So, to speak, so then if an electron is absent from a location then we treat it as though an entity with opposite charge exist are that location. So, that and that would be a hole. So, it has the opposite charge of an electron. So, that is what we have we have electrons and holes. So, in terms when you talk of bands, when you talk of field a valance band in an empty conduction band every time you take an electron from here and move it across here. So, now, you have an electron here you have left behind a vacant location here you are leaving you are leaving behind a vacant location here.

So, that is treated as a hole. So, for every electron that is going into the conduction band it leaves behind a hole in the valance band. So, that is how we look at the system all right. So, so we have electrons and holes which could participate in the conduction process both of them contribute in some ways to the conduction process, and so therefore they are important charge carriers if you have a system, where you have dominantly large number of electrons relative to holes that would be on n type semiconductor. And an another case were you have significant amount of holes relative to the number of electrons that that can move around then that would be A p type semiconductor, and those are accomplished by doing appropriate doping to a material in a group 4 A. So, this is what we are looking at fine. So, so this is what we are looking at in terms of the possibilities of an electron being present at some location and hole being presented some other location.

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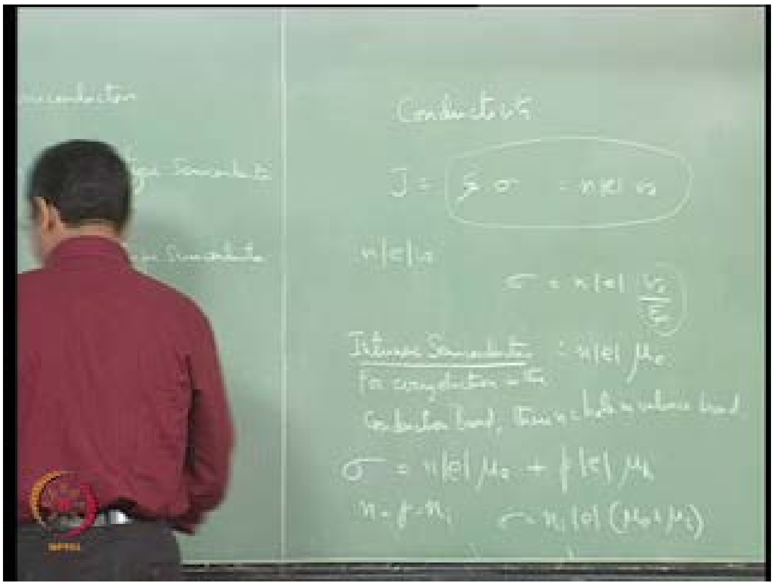

So, now, in terms of conductivity right us originally wrote the flux of current of the current density. So, J is simply E times the conductivity sigma E right. So, this fluxes of current is also the number density of the charge carriers times the charge that is being carried times the velocity with which they are moving. So, let us say that is a drift velocity, so n E v d. So, this is also equal to n E v d or rearranging this if you just take this second part of the equation here this equation here. So, sigma equals n E v d by the field.

So, this is the filed this is the conductivity this is the number density of the charge carriers this is the charge on the charge carrier and this is the drift velocity of the charge carrier. So, if you look at this this term here is the mobility mobility of the charge carrier we define this is the mobility it is the velocity attained by the charge carrier per unit driving force driving filed that that exist there. So, therefore, this is simply n E and mu E is the symbol used for the mobility of the charge carrier. So, that is what we have here. So, this is what we have as I mentioned in a in an intrinsic semiconductor for every electron if you look at intrinsic semiconductors for every electron in the conduction band there is a hole in the valance band.

So, there is the hole in the valance band for electron in the conduction band, because there is a as it moves away it leaves behind hole. Now, when you apply a field the electrons in the conduction band can move, and effectively the holes in the valance band can also move except they will move in the opposite direction in principle you can actually you step back and say. In fact, it is only the electrons that are moving, but as the electrons fill up that hole location it you can think of the hole moving in the opposite direction. So, in principle the charge its its easier to describe it in terms of electrons and holes. So, we talk in terms of electrons in the conduction band and holes in the valance band. So, both of them can participate in the conduction. So, in fact for a semiconductor the conductivity that we get is n times E times mu E plus if n is the number of electrons per unit volume. We can designate the number of holes per unit volume using p times the charge again its charge is simply the charge of the electron, it is just an opposite charge times the mobility of the hole mobility of the hole. We have n E mu E plus p E mu h; that is the conductivity of a semiconductor at a given temperature.

So, that is what we are looking at now in an intrinsic semiconductor for every electron in the conduction band; there is a hole in the valance band; therefore, n is equal to p the whatever is the number density of free electrons the charge carriers. We want call it as free electrons the number density of electrons per unit volume in the conduction band the number of electrons holes per unit volume in the valance band is going to be the same p right. So, n is equal to p and that is called the intrinsic charge carrier concentration or intrinsic carrier concentration. So, n is equal to p is equal to n i or the intrinsic carrier concentration n, so that is for a intrinsic semiconductor. So, therefore, sigma is simply n I times E times n sorry mu E plus mu H.

So, n I times E time times mu E plus mu h, this mu E and mu h are not actually the same even though you are saying you know I mean electron moving in the in this case, we are talking of electrons moving in the conduction band. And that case we are talking of holes moving in the valance band, so but the mobility of the electron is different from the mobility of the hole in general electron mobility in this situations is higher than there of the hole mobility and in a sense we can rationalist by thinking that you know.

If you are going to have electrons moving in relatively in a situation where most of the states are empty which is the case of the electrons which are now running across in the conduction band they are more likely to move around more freely right. So, it is a direct reflection of their environment, in which there moving, where as the electron which are sitting in the valance band, where they are largely field except for the few electrons that have few electrons state, which have become vacant. In other words for the holes that are there those electrons are actually moving with a much more. Because they have to there are phase in a they they are sort of moving in a crowded area. So, therefore the holes the which is effectively the other way in which we are looking at the electron moment in the valance band their mobility is less. That is the way that is one way, in which we could rationalize the situation, but any way the point is that the electron mobility and the hole mobility or not necessarily the same. And therefore, we write n I the intrinsic charge carrier concentration times the charge times the mobility’s of those two species.

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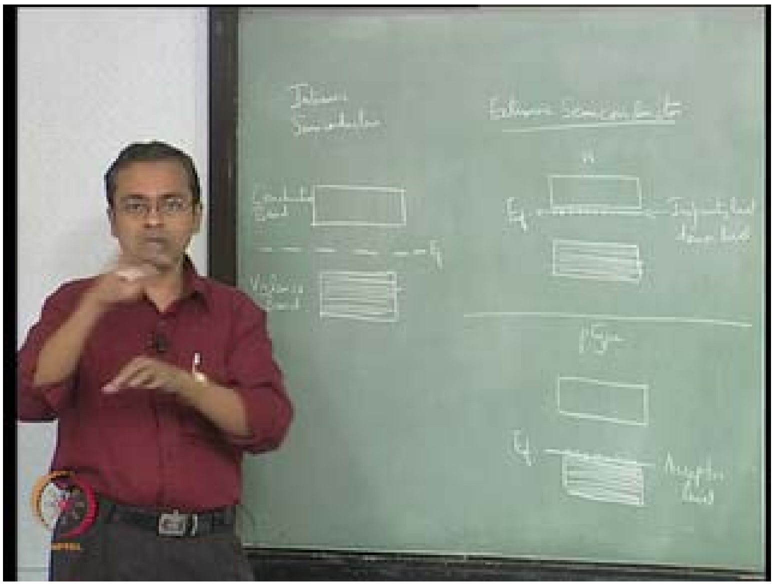

So, this is what we have now in this context, I also want to point out that when we wrote the intrinsic semiconductors in terms of what we have already discussed I pointed this out towards the end of last class for. So, this is the ~~a~~ valance band and that is the conduction band, in terms of what we have discussed the important parameter that we have of relevance is the Fermi energy and. So, for an intrinsic semiconductor the Fermi energy is ~~I~~n fact, defined as being the midpoint of this band gap. So, this is where you have the E f. So, this is how you write it for a intrinsic semiconductor now the situation is slightly different for an extrinsic semiconductor extrinsic semiconductor.

We in we could have on n type or p type. So, let us start with an n type in an n type we have again have conduction band and valance band and say for example, we have introduced a group 5 A element into this group 4 element. So, what will happen is you have additional electrons, those electron levels are actually very close to the conduction band. So, they can very easily get into the conduction band. In fact, that is the reason why they dominate the behavior of an n type semiconductor alright. So, so this is the impurity level; and therefore, for in terms of the highest energy level now being occupied by the electrons and so on.

This is what defines it much more then what is sitting here. So, therefore, for an ah extrinsic semiconductor n type extrinsic semiconductor this is now the Fermi energy Fermi energy moves to a value very close to the conduction band there are bottom of the conduction band. So, that is what happens for an extrinsic semiconductor of n type if you go to p type. So, let us see 2 p type here an analog a situation, but with opposite ah effect is what we are going to see. So, p type would looks something like this we have the conduction band we have a valance band this is full. Now, the impurity are introducing is ah group three a type of element let us say that that is what we have done and therefore, that has less electrons then the then what the group 4 A is in a position to provide. So, in terms of bands and search it has a one less electron in terms of a band structure it means that in terms of energy levels it has an acceptor level which are indicate a circles here it has an acceptor level very close to the top of the valance band of the parent material.

So, what happens is the moment you raise temperature the electrons do not have to go all the way up to the conduction band to contact the simply have to get in this acceptor levels here and they can start conducting; and therefore the… So, this now defines the position of where the highest energy electrons are show to speak or in or in in in that sense if you want to describe it and. So, this this now defines the Fermi energy for A p type semiconductor. So, the Fermi energy of A p type semiconductor is virtually add the acceptor levels of p type semiconductor which is very close to the top of the valance band of the p type semiconductor the Fermi energy for an n type semiconductor is effectively add the donor level. So, this is the impurity level donor level and this is the acceptor level. So, for n type semiconductor the Fermi energy or the acceptor level or virtually at the acceptor level I am sorry virtually at the donor level of the n type semiconductor.

So, Fermi energy is virtually at the donor level for the n type semiconductor. So, this is the important to understand this picture, because when you look at what is happening, when you make when you make you know semiconductor devices when you take an n type semiconductor. And put it in contact direct physical contact with A p type semiconductor I mention that you know the Fermi energy is like the chemical potential of the electrons. So, if the chemical potential of electrons is high on one side and low on the other side they will flow it will flow till the chemical potential becomes equal. So, that is how when you put different types of semiconductors together electrons move between them to ensure that the Fermi levels attempt to equalize.

So, that is how this process occurs. So, now, we have spoken often about the conductivity of the materials and we have seen now that for for most materials I mean we are looking at the charge carrier concentration is a very important factor that contributes to the conduction process right. So, it is of interest to see how this the charge carrier concentration varies for an intrinsic semiconductor verses an extrinsic semiconductor as a function of, let us say the temperatures at which your subjecting the material.

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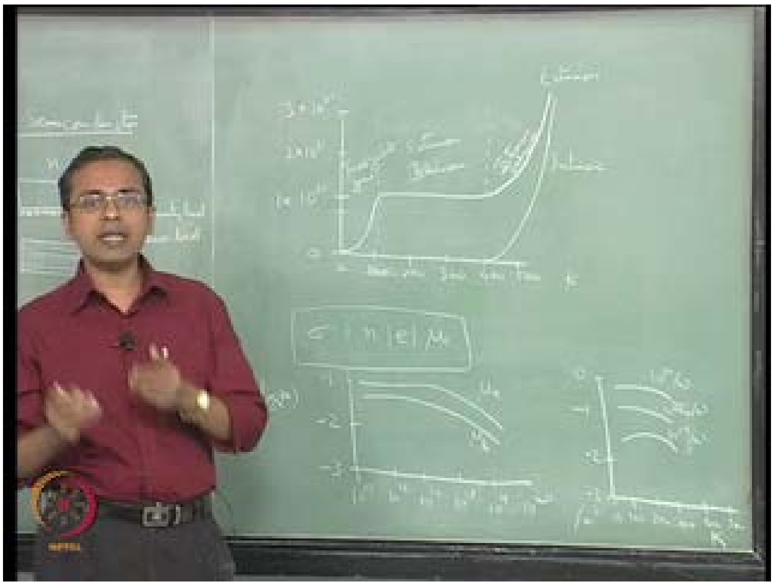

So, what you will actually see is something like this. So, this is in linear scale. So, let us say this is about 200 Kelvin, this is 0 this is. So, this is 0, this is 100, this is 200, this is 300, this is 400, this is 500 Kelvin and this is, this is also 0, this is it here 10 power 21 per meter cube 2 into 10 power 21 per meter cube charge carrier concentration and. So, on what happens is if you look at the extrinsic semiconductor at very low temperatures we will I will just draw he behavior.

I will explain to you, you see a behavior with respect to the temperature with looks likes this of charge carrier concentration for an extrinsic semiconductor; for an intrinsic semiconductor you see a behavior looks like this. So, intrinsic semiconductor you see a behavior that looks like this, the point is this for an extrinsic semiconductor what happens is as you initially there is region at very low temperatures, which is called a freeze out zone, where the energy is simply too low for any electron transition to occur. And so therefore, the electrons remains frozen they do not get in to the conduction band not to the get in to the acceptor levels nothing happens everything looks frozen then at some once you crosses certain threshold that is enough energy for the extrinsic the depend levels to participate in the process. Because they require only a very small amount of energy to either you know take electrons from the conduction band in to the acceptor levels, which are very close to the conduction band or to take electrons from the donor levels, and put them into the conduction band, which is very close to the because it very close to the conduction band.

So, you need only a tiny amount energy to do that suppose to taking an electron form the conduction band from the valance band all the weight of the conduction band. If you wish you can look here you will require a very small amount of energy to move this electron appear or to move an electron into this acceptor level relatively speaking, you need a larger amount of energy to move an electron from here all the up to here. So, that is the different.

So, this is the larger amount of energy this is energy in the axis. So, this is the larger amount of energy, this is a small amount of energy, this is a small amount of energy. So, at very small temperatures you have enough energy to do this to do this and so and you essentially saturate the process everything that can go goes off as shown as you cross some temperature threshold all most everything that can go here goes off their immediately. And that is a finite amount of levels here as acceptor levels or donor levels because that depends on what doping, you have done to the system what percentage doping you have done to the system.

So, that is finite. So, immediately the conduction process starts you have fair number of charge carriers, but the states constant that is state constant for a long period of time a because that is a finite a process relatively speaking. Because they has a very not just finites very small number of depend that the small amount of depend, that you have put here, on the other hand you will take a lot of energy before you start moving electrons across. But once you do once you cross an certain threshold, you can keep on as you raise the temperature you can keep on increasing the number of electrons that get into the conduction band.

So, you can keep increasing the charge carrier concentration by raising the temperature. So, that is what you see here in the for the extrinsic semiconductor initially everything is frozen there is not enough energy to move the electrons across even the small distance they have to move in energy small amount of energy, once you crosses certain threshold all the acceptor levels participate or the all the donor levels participate. So, you saturate out.

So, this now becomes representative of the dopant concentration because the dopant concentration will will impact the charge carrier concentration directly, and so this becomes based on dopant concentration this can move upward. But it states constant as you the raise the temperature you have already saturated out this nothing more to put into the dopant level I have or from the dopant level. So, it is state constant as you go to very high temperatures relatively speaking then intrinsic transitions also begin to occur even in ~~a~~ an extrinsic semiconductor nothing prevents a transition from the valance band to the conduction band you simply you have to enough energy to or enable the transition.

So, if you get to high enough temperature the transition will occurs. So, therefore, you can start seeing the charger carrier concentration once second increase and that will of course, if you look at an intrinsic semiconductor there is nothing happening till you come to that temperature high enough temperature. So, that you provide enough energy for that transition from the valance band to the conduction band from then on as you raise the temperature this keeps going on, so because you have putting more and more electrons into the conduction band.

So, in terms of an extrinsic semiconductor this is of this is called freeze out zone up to with up to this temperature it behave like an extrinsic semiconductor extrinsic zone or extrinsic conduction or an extrinsic behavior. So, extrinsic behavior you have here and then once you cross this temperature range here you starting intrinsic behavior right. So, you can get extrinsic behavior here and then intrinsic behavior here. So, as you raise the temperature eventually its starts behaving like an intrinsic semiconductor the materials begins to behave like on it is.

So, this is what you see, the other parameter we wish to know. So, this is how the charge carrier concentration. So, when we look at the fact that conductivity is a function of the charged carrier concentration, the charge of the electron and the mobility of that carrier right. So, you have conductivity sigma is n charge carrier concentration charge of that charge carrier times the mobility of that charge carrier mu E or mu H or whatever you want to do. So, these are three parameters you already seen how n can vary for an intrinsic semiconductor or an extrinsic semiconductor E is fixed, it is of interest to see how the mobility of the electron will change.

So, the mobility of the electron to wish to see what you will see mobility of electron or mobility of hole, we can look at it as a function of temperature or as a function of impurity concentration. So, if you see in general what you will see is let us say this is it are log scale this is minus 3 minus 2 minus 1 log of mu and this is the impurity concentration 10 power 15, 10 power 16, 10 power 17, 10 power 18, it just put something down 10 power 19, 10 power 20. So, this is the impurity concentration per meter cube, so per meter cube. So, or this is partic atoms per meter cube.

If you want to call it what you will see is that in general you will a see trend at look like this as you rise the impurity concentration the mobility’s decrease. So, this is something like this is mu E this is mu h, I told you that mu h generally tends to lower than mu e. So, the mobility of the carriers carriers begins to decrease. So, in terms of our understanding, these are all the things that are occurring this is how the charge carrier concentration is going up or changing with temperature, this is how the mobility is changing with the impurity concentration and similarly even with respect to temperature if you would put of mobility values as a function of temperature. So, again we will say you know same kind of temperature range 0, 100, 200, 300, 400 and 500, these are in Kelvin Kelvin. So, this is Kelvin, this is also Kelvin and if you look at the you know mobility values similarly we can write you know minus 3 minus 2 minus 1 and 0.

So, that is what we can look at. So, if you see what you will see is for we have to now define this is as a function of temperature mobility as a function of temperature which we can define at specific impurity concentration values. So far a given impurity concentration values, the general trend will look like this we are only draw in semantics here you are looking at some behavior that looks like that with temperature it is going down or something like that is the and this is impurity concentration increasing. So, whatever if you want to look at these values here let me just say this is 10 power 20 per meter cube and so on, 10 powers 19 or this is that higher concentration. So, this is 10 power 20, 10 power 22, 10 power 25 per meter cube. So, as you basically as you increase the impurity concentration the mobility is coming down as you raise the temperature mobility is coming down. So, so these are all the parameters that affect the conductivity in terms of this equation here and this am just I will remove this mu. So, that there is no confusion it is just mobility of whatever is your charge carrier right, so but ultimately conductivity goes up. So, we I have we have to understand this fundamental idea that you know when I mention this that when we looked at metals.

If you look at the conductivity of a metal it has a positive coefficient of for the thermal coefficient for resistivity. So, as you raise the temperature of the metal the resistance of the metal goes up or conductivity of the metal comes down, this is not true for semiconductor it is not true for ionic conductor and. So, on and the fact that it is not true for semiconductor should become consist ant with this picture that we have here what we see is as you raise the temperature actually the mobility's of the of the species decreases, but is what is. So, therefore, this term is going down mobility of the conducting spices going down and in that sense it is the same as that of the picks the situation is the same as that experience in a metallic system in a metallic system, also the conductivity comes down as you raise temperature. Because the mobility of the spices the electrons begins to come down, because it is now having more collisions with whatever are the other scattering its having encountering more scattering events right.

So, therefore, in terms of mobility the general trend is not is basically the same whether, you are talking of semiconducting material or you talking of a metallic conducting material. In general as you raise the temperature mobility's going to come down in general, but what changes the pictures dramatically is this value of n, in a in a metallic conductor. We simply talk of the number of free electrons per unit volume that number of free electrons per unit volume is a fixed number we are not it are largely its fixed number it is not something that we have manipulating in a significant way, it is a large number. But it is a large, but largely constant number, we are not really manipulating it in a in any significant manner. Therefore, this sort of remains constant, the charge on the charge carrier remains a constant mobility keeps coming down in a metallic conductor. Therefore, the conductivity of the material comes down as a function of temperature for a metallic conductor, for a semiconducting material again mobility is coming down as a function of temperature this E is a constant. But this n actually increases with temperature right you have seen here as you go up in temperature the number of charge carriers per unit volume is actually going up. So, this is per unit volume per meter cube is. So, charge carriers per meter cube.

So, the number of charge carrier per meter cube is going up it goes up appropriately in the case of an extrinsic semiconductor it goes up gradually if it is intrinsic semiconductor, but it is goes up. So, therefore this n is always going up it temperature, what we generally see is that for the semiconducting systems, the manner in which the n goes up more than compensates for the manner. In which the mu comes down the rate at which n goes up more than compensates for the rate at which mu comes down as a result we see an increasing conductivity.

So, from all that we have now understood, we now see that there is a fundamental difference between what a metal is and a semiconductor is in terms of its conduction process, and were able to see it. Because were able to find out the parameters that affect the conductivity process we see that the charge carrier concentration is the way in which the charge carrier concentration is varying as a function of temperature significantly different for a semiconductor than it is for a metal and that is the reason why the conductivity behavior is. So, different in terms of the mu actually the behavior is more or less the same, I will also point out that for a metallic system, the n is actually a very large number for a semiconductor relatively speaking the n is actually a small number compare to a metallic system. That is the reason why overall the conductivity of a semiconductor is less than the conductivity of a metallic system.

So, the electronic conductivity of a semiconductor overall average is going to be less than the average metallic average conductivity of typical metallic systems. So, the sigma value of a semiconductor is going to be less than a sigma value of metal, but the behavior of the sigma is going to be different a for a metal as you, we it will start it a high value, but it will keep coming down as you raise temperature for a semiconductor. It will start at a low temperature, but as you raise the temperature it will go up. So that is the difference between the two, and this is how we understand it from fundamental principles in terms of how the constituent of the material are behaving in this case the electrons are behaving what is happening in terms of transition and how they are contributing to this the parameter the conductivity which is what we measure. So, we have now had a reasonably good overview of the semiconductor system, and we have seen how important characteristics of the semiconducting system correlate with a lot of things that we have learn. What we will do is also look at the optical properties are displayed by different materials in the context of all the band gaps, and so on.

And then see if what we have learned helps us get better inside into the optical properties of materials which we will do right now. So, now, when you talk of optical properties we are talking first of all of often we are talking of a light in the visible spectrum. So, we are looking at wavelength in the visible spectrum.

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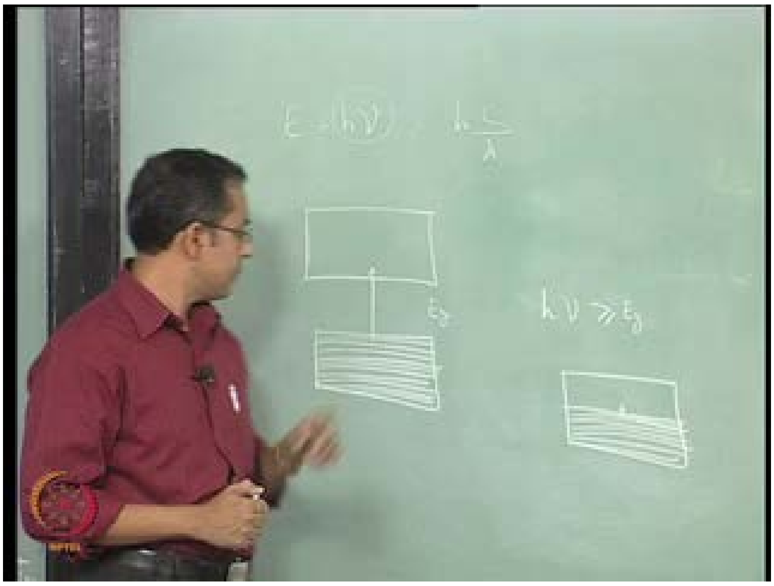

So, what happens is the energy of those wavelength is E equals h nu is equal to E h c by lambda, now if the incoming radiation has enough energy if the h nu is large enough that when it encounters a material with a band gap E g. So, this is E g if E g if h nu is greater or than or equal to E g. So, h is a constant Flank’s constant. So, it rather it therefore, if keep raising the frequency at some frequency you will have enough energy in the incoming radiation that it is greater than the band gap of the material that is that is which the radiation is incident, then it will enable at transition from here to here and. So, at that point the material begins to observe the radiation. So, that is what is happening now the important thing is, so any frequency higher than this any energy higher than this this material will observe any frequency less than this will actually get transmitted through the material the material will not be able to interact with that radiation. So, if you make a defect free material physically defect material it will of this kind of with this kind of band gap, what you will generally see is if you put low enough frequencies the it will be transparent to those low frequencies only when cross some certain frequency. It will start observing that frequency by the same token this is the reason why metallic systems are opaque because in metallic systems there is virtually no gap you have you have either half field energy level.

So, therefore, there is there is virtually know even for tiny amounts of energy there are available states immediately above what is filled. So, therefore a metal can keep observing energy over a very wide range of frequencies and that is why essentially when you look at a metal it looks. So, opaque light falls on it gets observe. So, that is why its look opaque whereas, this looks depending on what semiconducting materials you have and what band gap it has it can be transparent. So, that is how we see this behavior, but there is one important detail that we would like to add to this picture which is based on or understanding or the level of detail that we have learned of this systems.

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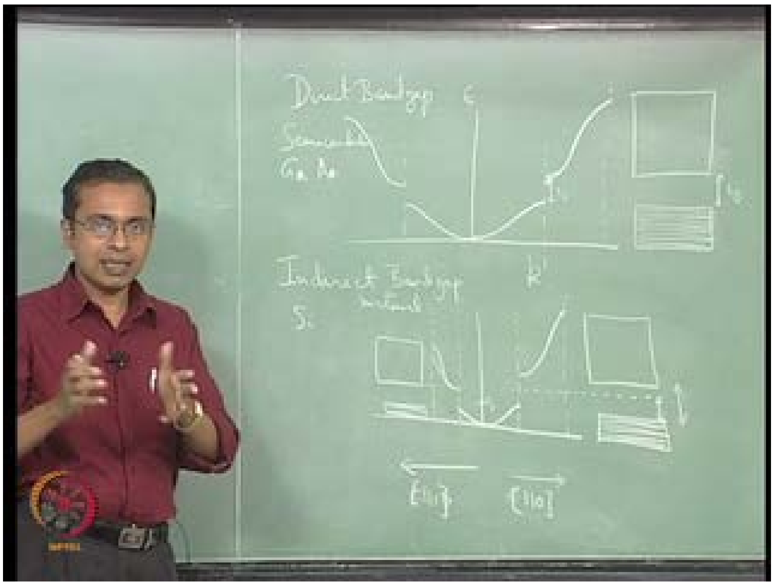

And what we have understood and build in our models. We have seen, we do E verses k relationships, and we basically saw that based on where the (( )) zone is we saw behavior that looks like this. And we said that this is the bands, and this is another band; and let us assume that this is filled. Now, so in our discussion we simply pointed out that you know in flat band structure, this would then be the E g, which is then corresponding to this value here E g. So, if draw it scales of that is where it is so this would be somewhere here then so that it matches of correctly. So, that is the E g that you are looking at.

Now the important thing to note here is that this is a diagram as I mentioned you know when you look at three-dimensional structure, the (( )) has a certain shape to it and therefore, exactly where the Fermi surface touches it is going to differ based on the direction in which you look at that the (( )) on the Fermi surface right. So, in some places it my touch the Fermi surface the (( )) very quickly in some cases it may be little further away from the (( )). So, these possibilities are there therefore, the location of this and. So, it is important to understand that the location of the (( )) boundary or rather the black plane in this case is going to differ based on the direction right.

So, it based on the direction that we look at it they this is going to differ. So, we can easily have a situation where I am plotting now one direction in one direction in the lattice symmetry along this side and I completely different direction along this and just say let us say this is the 1 1 0 direction this is the 1 1 1 direction. So, so these are two different directions in the lattice just for arbitrary description say and we will just say that in one case we see a behavior where the (( )) looks like this or rather the band structure looks like this. So, this is how it looks and in another direction we have situation where the bands structure looks something like this.

So, now, what we do here we have a situation where the location of the (( )) I am just saying that it is a little further of part here. So, so it is further of part here these are much narrower because they are much narrower this band ends faster here it turns at ends at a much lower energy level in this direction. So, the band ends in low is at a lower energy level in this direction the next bands start at a correspondingly lower level at in this in this direction relative to the as end and start of bands on in this direction.

So, now supposing the Fermi energy level is here I will just say this is f. So, we have a situation where the valance band is defined by the band structure in this in this direction I just say this is 1 1 0 direction let us say right and this is 1 1 1 direction. So, just put it this this is just arbitrarily we are just picking two direction just to illustrate the point let us just say that in the 1 1 1 direction it looks like this in the 1 1 0 direction it looks like this just a semantic. So, now, what we are saying is that the band structure is like this in the in terms of the plot band depiction it look like this on the side where on the in the 1 1 0 direction in the 1 1 1 direction we are actually seeing something else. So, the next available band here in the 1 1 0 direction is here whereas, the next available band empty location in another direction is actually lower in energy right. So, this is this is again of field band here.

So, if you look at the in both cases may be the band gap may be the same, but regardless we if just look at this level here. We find that the highest occupied level in the valance band is closer to the lowest unoccupied level in the conduction band in a different direction in a different location in case phase in a different location in case phase then. So, the band gap rather than being defined by this is now defined by this. So, with less amount of energy you can take electron from here, and move it to here, because the band structure is different in different directions this picture clearly shows you that you can have anisotropy, why there is anisotropy in the material. Because the E verses k relationship is the same, but where the (( )) boundary sappier is different for different directions.

So therefore, you can get a transition from here to the next available level which is the closest in terms of energy in terms of energy it is closest by going to a different direction, but in terms of direction it is a different direction. So, that is a thing. So, the lowest available energy level is coming up here closer to this highest level here relative to the band at showing up there. So, so you can have a transition that goes just this much distance and gets into an available empty low energy level here that is permitted and therefore, this transition is around.

So, the band gap tends to get define by this distance rather than by that distance when you have such a situation where the lowest energy the highest energy; that is occupied in case phase. And the next available lowest energy in that is vacant in case phase which are there in two different directions then that is called an indirect band gap material or in this case an indirect band gap semiconductor. So, this is an example of an indirect band gap semiconductor where an electron the highest occupied energy level is one direction in case phase or one location in case phase and the in lowest unoccupied the next lowest unoccupied level is in is certain different location in case space.

So, these are two different locations this is in this direction that is in the other direction is completely different directions. So, so this is how we have this. So, such a material is called an indirect band gap material whereas, there are definitely other examples where the lowest occupied the lowest unoccupied state and the highest occupied state are both in the same direction in case phase. So, where you do not have this situation where you simply have only this part of the picture holding true and that is fine.

So, in that case you the band gap are stilled defined by this original material. So, that would be a direct band gap semiconductor. So, from here to here if you go that is a direct band gap semiconductor the way we have drawn it here is an indirect band gap semiconductor I will just for clarity sake I will just add that here. So, that we can see that this is, this is a direct band gap semiconductor.

So, we see fundamentally therefore, that we we see the there can be an isotropy, we clearly see anisotropy can exist and that these are two difference situations. What is the result of it result of it simply this when you use a material for optical purpose the material that ultimately, you have to provide the amount of energy corresponding to the band gap to enable the transition. However, how easily the transition occurs also depends on where the whether the location of the transition is in exactly the same position or it has to go to some other location in the lattice side.

So, therefore, in general it is found at indirect band gap semiconductor or less efficient in participating in optical processes then direct band gap semiconductor. So, direct band gap semiconductors are much more efficient in handling optical processes than indirect band gap semiconductors. So, for example, this is silicon is an indirect band gap semiconductor gallium arsenide is direct band gap semiconductor gallium arsenide is a direct band gap sillicon semiconductor this is an indirect band gap semiconductor. So, when you try to make a laser or things that this is the kind of material that are preferred not this.

So, we will viand of discussion today basically, this commons we have seen today we have looked at semiconductors and detail we have looked at optical properties of materials, and and we have looked at both of these from the perspective of all the things that we have learned. So, for Fermi energy is the (( )) the (( )) and the band structures and we have recognized now that the E verses k relationship is a very important feature which gives as much more information about what the material will do, then simply the flat band structure.

The flat band structure will not tell you whether something is a direct band gap semiconductor or an indirect band gap semiconductor. Simply looking at the flat band structure we cannot decide we whether the material is useful for a particular purpose or not knowing the E verses k relationship we can say, so because that will tell you whether the electron has to go to a different location to undergo the transition or it can undergo the transition the same location. If it has to go to a different location, it has to have energy to go up up as well as go to the different location.

So, these are two different process here its simply has to have the energy to go up. So, the probability of this occurrence is much higher here than it is here and that is why this works better for optical purposes. So, with that we will conclude this class, we will take it up in the next class were we will look at other properties of the materials. Thank you

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