Fiber - Optic Communication Systems and Techniques
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Lecture – 35
Basic properties of semiconductor lasers-I (Energy gap, Intrinsic and Extrinsic semiconductors)

Welcome to NPTEL MOOC on Fiber Optic Communication Systems and Techniques. In the previous modules we looked at basic properties of a laser we said that a laser is formed by at least 3 elements. one is a cavity in which the active medium this is the second component is confined and then there must be some way of pumping an external pump source which would raise atoms in the ground level to the next higher level right.

There are many different type of lasers. So, some of those lasers might be familiar to you. The earliest lasers were the ruby lasers then the more popular helium, neon laser which operates at roughly 633 nanometer of wavelength and then we have carbon lasers which are infrared lasers, then you have many different lasers. So, the basic idea of having an active medium and depending on the energy gap between the states e 1 and e 2 you can have lasers with different operating wavelengths right.

However, not all those wavelengths sorry all those lasers are useful for fiber optic communication purposes. Indeed in fiber optic communications especially in the long haul communications that is communications taking place over 1000s of kilometer, the only type of laser that we used is made out of a semiconductor material. So, these are called as semiconductor laser diodes ok.

For shorter link applications such as say Ethernet where the distances do not go beyond a few hundreds of meters one can substitute this laser diodes by a more economical version of light sources called as light emitting diodes or mix cells which are again you know kind of lasers, but there of made out of a different kind of a geometry.

So, there has been a tremendous amount of research in semiconductor lasers which still continues. The basic advantages that a semiconductor laser diode offers over other you know lasers are that.

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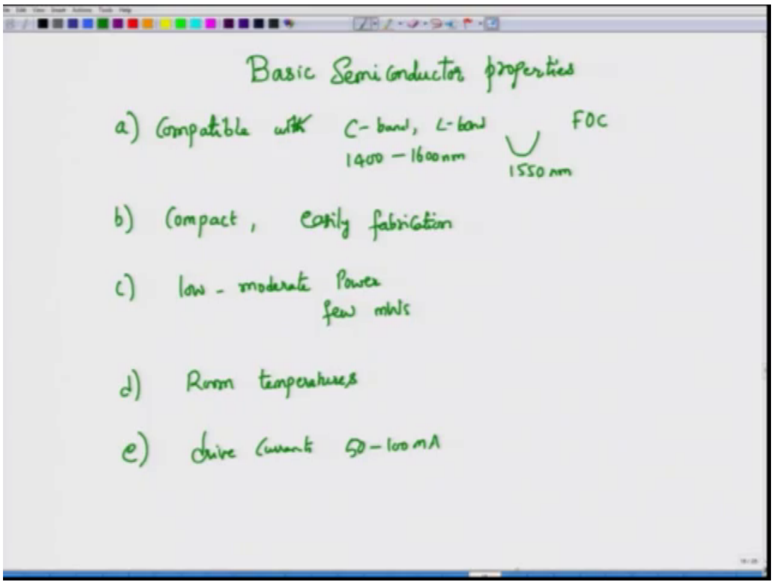

First of all it is compatible with fiber optic communication window. So, it is compatible with the bands of operation say the C-band or even the L- band up to L-band. So, which means that you know it can be operated over a wide wavelength range say 1400 to about 1600 nanometer with 1550 being the wavelength at which one actually sees that the fiber attenuation is minimum.

So, in this range the availability of a semiconductor laser means that we have a laser source or a light source which is compatible with the operation of fiber optic communication systems. Now, why is it compatible? In the sense that one can try out different lasers maybe even in this wavelength region, but they do not offer the advantage of being compact.

So, a typical laser diode would be no more than a few inches tail in which the fiber is attached if you exclude that when they no more it would be no more than a few inches. And this compactness is an important property of a laser and moreover, because it is made out of a semiconductor material, the semiconductor fabrication which is a very advanced state of fabrication and can produce cheaper IC's right. So, all that fabrication techniques can be used to obtain semiconductor or fabricate semiconductor laser sources.

So, this advantage of being compact and easily fabricatable or that is not a real nice word, but the idea is that it can be easily fabricated by using the well established techniques of semiconductor fabrication which gives them an advantage of being very economical compare to other light sources.

It of course, operate does not give you lot of power. So, it gives you low to moderate amounts of power. There are versions of very high power semiconductor laser diodes, but we are not really go into that one. For fiber optic communications you require a few milliwatts of laser power which is sufficiently generated by this semiconductor laser diodes or semiconductor lasers.

It operates at room temperature which is a very important advantage. Most lasers require some sort of a cooling mechanism and you know if you start having this cooling mechanism requirement if we did not have semiconductor laser, but some other laser with the cooling mechanism the cost of a laser would actually shoot up pretty much ok.

And because of this problem you would not have seen the optical revolution that has taken place. Therefore, semiconductor lasers which operate at the room temperature which are compact, easily fabricated using the same techniques that you actually fabricate I mean very close to the same techniques that you actually used to fabricate, the diodes is used to fabricate these semiconductor lasers ok.

And furthermore, it is just the right wavelength where it is compatible with the fiber optic communication window or the telecom windows of operating an optical fiber especially the C-band operation ok. So, these basic properties of semiconductor lasers are very crucial instituting this so, called fiber optic revolution.

The other ingredient of fiber optic revolution of course, is the optical fiber itself. So, it was very fortunate that in around 1969 or 1970 both low loss fibers as well as semiconductor diode lasers which were operated at room temperature. Therefore, they did not require lot of current and that is another advantage which I did not mention here.

So, the drive current requirement is not too high. So, drive currents of about 50 to 100 milliamps is sufficient for most laser diodes to start operating or start lasing and producing light output. So, these advantages which happened at around the same time where the low loss fibers were being developed by 2 different companies led to this optical fiber revolution, optical network revolution. And has since only increased in satisfying the customer requirements for the large bandwidth and low loss links.

What we want to do in this module is that we want to understand a few basic properties of semiconductor which are useful for discussion of lasers and LED's. The history and the theory of semiconductors is quite vast. The required device properties is something that one cannot; obviously, cover in a single module or even 2 modules. It requires a separate course.

I am not going to attempt the full mathematical detailed theory of semiconductors, but I will try to give you the basic ideas and some physical ideas behind some of the properties which are relevant for semiconductor laser operation or semiconductor laser emitting or light emitting diode operation. So, we start by looking at what exactly is a semiconductor.

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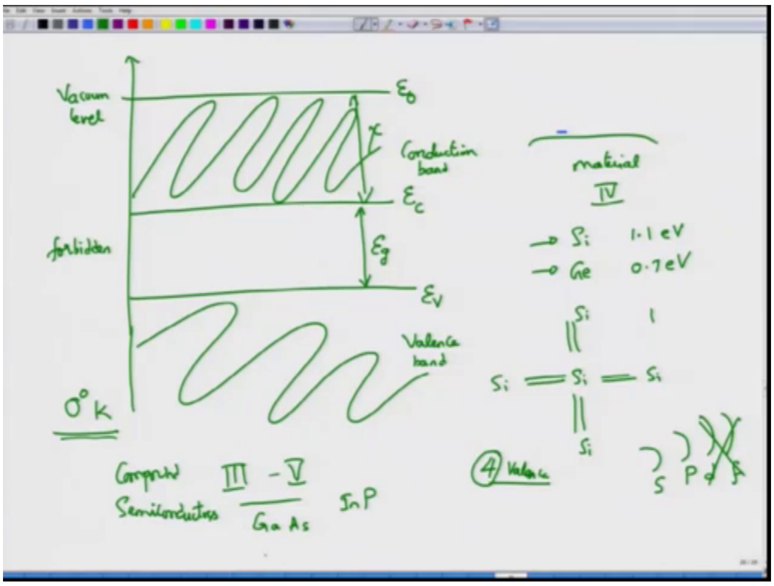

So, you must have known and we have also discussed that matter you know can be considered to be conductor, insulator or a semi conductor. Now, a conductor is something that is familiar to us, when there is a slight amount of electric field applied across a conductor there is a large amount of current flowing. It is limited only by the material properties or the losses in the material. Other than that there very easily or there capable of very easily conducting you know currents when a small voltage difference is applied.

And that happens because, matter energies can be you know divided into bands. And you start off with the highest level band for a given material which we will call as the vacuum level ok. Vacuum level simply means that you are not considering the electrons bound to the material, but these electrons are just sitting on the surface of the material. Of course, you do not really find an electron sitting on the surface. This is an idealization, but what it represents is that this electron which is sitting just on the surface is completely free of all the forces that it will experience if this electron work to be actually in the matter ok.

So, therefore, this vacuum level represents the energy of an electron of that particular matter or of that particular material which of course, will be the highest. And we denote this vacuum level energy by E 0. I am choosing this epsilon to denote energies you can also of course, choose the simple E letter to denote the energies. So, it just looks nice to use this epsilon. So, I am going to use that well.

So, vacuum level corresponds to this. So, this is the material that we are considering does not matter what material it is, but this material when you have an electron just sitting on the surface, you will find that it has the highest amount of energy ok.

So, on this y axis I am going to plot the energy levels and this energy level is increasing as you move up this particular page ok of course, when you go down the page then the decreasing. So, what you actually find in most materials is that the reason maximum allowed energies as you keep going or there is energy that is allowed.

So, as you keep going below and below there is a certain energy level E c and if an electron is somehow present in the region between E 0 to E c then when a short when a electric field is applied then this electron will move in you know according to the electric field applied across this material.

So, it means that if there are multiple electrons sitting in this conduction band or this band is actually called as conduction band. Of course, that is what I wanted to try and tell you that if electrons are found in the energy region between E 0 to E c. Then they will move in response to applied electric field and therefore, contribute to conduction of the current and therefore, this band is called as conduction band.

And the difference between E 0 to E c is called as the electron affinity and we denote that one by a rather non interesting symbol called chi. Of course, in a material which is kept at 0 degree Kelvin and if the material is not metal then there are no free electrons available in the conduction band. Now, the valence is not continuous, but that exhibits a gap which is a characteristic of that particular material.

So, for example, if we consider silicon which is a group 4 semiconductor then the energy band gap is about 1.1 electron volt and for germanium this is slightly less. So, it means typically around 0.7 electron volt ok.

So, different materials of course, have different energies gaps and this energy gap is important because it tells you the wavelength of operation. So, anyway we will come to that wavelength of operation later on. So, just understand that there is an energy gap. So, this gap is completely available. So, electrons can take up any energy in this region between e 0 to e c, but they cannot take up any energy in this gap.

So, sometimes this gap is called as forbidden region. It is forbidded for the electrons to actually acquire any energy that is in this particular region. Now, the region below this where again electrons can occupy any energy level that they want is called as the valence band ok.

Ordinarily, if you consider a material whether the material is a semiconductor or an insulator or a metal is determined by this energy gap and the presence of this conduction and the valence band. At 0 degree Kelvin all the electrons are located in the valence band; they do not have the energy to cross over the band gap.

And go to the conduction band in metals this band gap will be very very small. In fact, in most metals the band gap will actually overlap, I mean the band gap will be negative in the sense that the conduction band completely overlaps with the valence band. And therefore, even at 0 degree Kelvin there are sufficient number of electrons available for the metal so that it may conduct; when you apply a potential difference.

However, if you consider the material which is insulator then at 0 degree Kelvin all the electrons are tightly bound to the matter and have an energy which is below that of the valence band. Valence band would be the energy the highest amount of energy that an electron can possess at 0 degree Kelvin ok. So, all the electrons are below this particular level, they are sitting in this you know energy state, they are occupying these energy states and there are absolutely no electron available what so ever about this valence band ok.

And the material will be insulator provided that the difference between conduction and the valence and the conduction band which we have called as the energy gap is sufficiently large. So, maybe this is the example I mean this is just to show you how far they are, in the sense that at ordinary room temperatures when electrons have some amount of kinetic energy or the rather they absorb the thermal energy and then they can move. This energy that they absorb is insufficient for most insulator electrons to cross over from the valence band to the conduction band.

Therefore, even when you apply an external voltage there is hardly any conduction current ok. Of course, it does not mean that the probability, I mean it does not mean that no free electron will be available for an insulator. But, it means that the number is so, small that there is appreciably no current in an insulator. Of course, as the temperature rises then the energy acquired by the electrons also will rise linearly along with that temperature. And it may possible that an insulator may actually start conducting at very high temperatures and in fact, it does so.

So, all insulators become conductors at very very high temperatures, how high a temperature depends on what particular material that you are considering. Semi conductors or sometimes called a semi insulators are those materials whose energy gap is not very wide ok. Typical energy gap for you know insulator would be anywhere greater than 10 to about 100 and in fact, maybe more than that, but for a semiconductor material it could be anywhere between say 1 to 5 or maybe less than about 5 electron volt.

So, that at ordinary room temperatures when there is sufficient thermal energy or there is thermal energy which is present, which is sufficient for some of the electrons to actually jump over from the valence band and be present in the conduction band.

In the case of semiconductors which are found in the group 4 elements mainly and those examples of those group 4 I know elements are silicon and germanium. These silicon and germanium are semiconductors and they have a particular structure ok. This structure is called as a diamond structure, in which each silicon atom shares electron with it is neighboring atoms ok. There are actually the atomic number of silicon is about 14 I believe.

And what you have is that if you look at. So, I am going to use some spectroscopic notation which I know, I do not know whether you have studied this one or you remember this. But, you please go back to your high school or maybe about class eleventh and twelfth to understand that energy levels are typically represented by s, p, d and f, but for semiconductors we do not really need to worry about that.

So, I mean for this module we do not need to worry about this d and f because, we are dealing with only the, I mean the first 2 states here. So, you have these differentials and this silicon atom shares the electrons I know with the neighboring atoms. And the 3 dimensional case it will show up as a structure which is called as a diamond structure. And the sharing with the neighboring electrons or sorry with the neighboring silicon atoms for is the result of formation of what is called as the covalent bond.

The bonding represents the way in which the atoms share, other atoms or share their electrons. And then essentially distribute themselves to form the solid material and semiconductor materials are crystalline structures. So, you can actually grow them and they most native semiconductors are the group 4 elements of which silicon and germanium are the most prominent semiconductors that we want to study.

Of course, it is not restricted that they have to be 4 group. The meaning of 4 group is that each silicon atom shares with 4 neighboring atoms and it actually has 4 valence electrons. Which means that each silicon atom present in the material can potentially contribute 4 electrons to the conduction band provided there is sufficient energy to raise this electrons from valence to conduction band.

So, that is the meaning of group 4 elements. So, they all have 4 valence electrons and there is a way in which these electrons are arranged they are called as how they are filled with the you know shells s and p, but we do not need to go to those details of how the bonds are formed.

So, just remember that silicon has 4 valence electrons and if the right conditions exist then these 4 electrons can be raised from valence band and can go to the conduction band where they can contribute to the conduction current.

Of course, this is called as pure semiconductors, then there are called as then there are made semiconductors called as compound semiconductors. Compound semiconductors are formed by grouping atoms from 3 and 5 valence groups. So, if you take a 3 and a 5 because, 3 will have 3 valence electrons, 5 will have 5 valence electrons, 4 of them are involved in the bonding and again 4 of them are available for conduction out there.

So, you can mimic the behavior of a pure semiconductor such as a silicon by forming a compound semiconductor materials that is by growing these crystals of 3 and 5 groups together. And it is surprising that they actually you know are quite you know they like each other in the sense that they kind of become together in the sense that they can be easily grown on the same crystal type.

Some of them will not be like some materials will not just be miscible with each other. But, group 3 and 5 elements are miscible with each other of course, with certain conditions on how to choose a proportion of a 3 element or a 3 group element and a 5 group element. That is again we will leave that topic to some material science or semiconductor courses which you can look around.

So, these compound semiconductors mimic the behavior of the pure semiconductors ok. And they too possess 4 electrons 4 valence electrons after they have been grown together. Examples of these are gallium arsenide and indium phosphide, gallium of course, is a 3 element, arsenic is a 5 group element, indium is 3, phosphorus is a 5 element group.

So, you have these electrons at 0 degree Kelvin completely located in the valence band. When you apply an electric field the conduction band is completely empty therefore, there is no current. So, at 0 degree Kelvin there is absolutely no conduction possible in a semiconductor material. In that respect it actually looks more like an insulator. In fact, it is an insulator.

Now, let us assume that the temperature is greater than 0 degree Kelvin and then see what happens. Well, we have talked about this party analogy.

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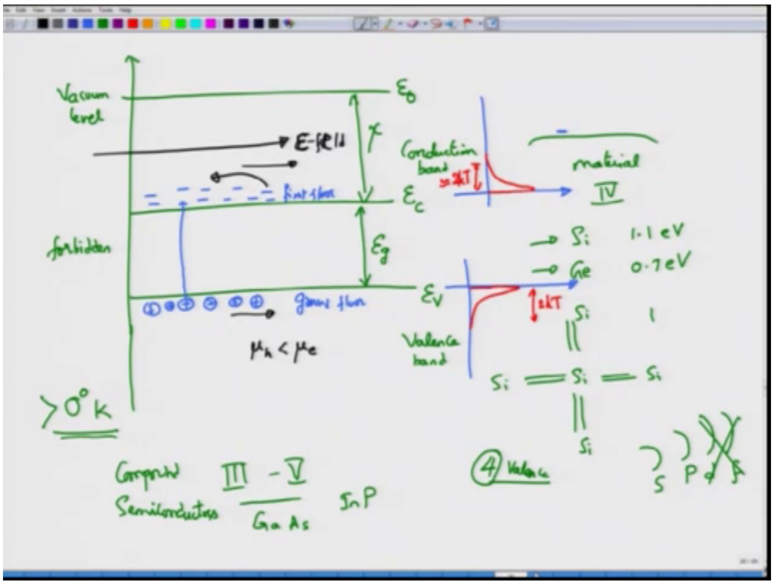

So, in that party analogy we took this as the ground floor and then we took this as the first floor right, where people from ground floor can go to the first floor and when they do so, they leave a vacant space behind. And we call this vacant space as a whole and in semiconductors it actually is possible that an electron can be excited ok, an electron which is bound here can be excited across the band where it becomes free ok. And when it does so, it leaves behind a hole which has a charge which is opposite that of the electron that is it is a positively charged atom.

And this is actually a vacancy right. So, a temperature greater than 0 degree Kelvin you will find that there are reasonably good amount of electrons in the conduction band, but they are all hugging the conduction band. So, you do not find electrons right near the vacuum level because, the energy is not sufficient for the electrons which is come out of the material. It is barely sufficient for them to just cross over the energy gap and therefore, we can see them that they are all hugging the first floor or they are hugging the conduction band edge.

And if you plot what is the concentration of these electrons? Ok, then you will see that right at this point you know at the band edge there is a large concentration which then decays out exponentially as you go upwards in the energy street ok. So, this is what you would see in the case of a temperature being greater than 0 degrees Kelvin. And the width of this one is around roughly 2 KT, where T is the temperature at which the material is present.

Now, because there are electrons which have been moved up there will be holes. I am showing this uniform holes, but it is not necessary that they are uniform, the electrons may jumps from any point here. So, they are not uniformly distributed, but for our representation purposes we have shown them to be uniformly distributed. And in a material which is pure semiconductor material which may be for example, a silicon or something then the concentration of electrons is kind of nicely balanced out with the concentration of the holes ok.

So, if you look at the concentration of the holes it will be again quite large at the center or sorry at the band edge and then drops out with the width being typically about 2 KT. So, after 2 KT there is almost no free holes here and about 2 KT from E c there is almost no electrons. So, this is just an example of electrons being you know always hugging the bottom of the band whereas, holes always floating to the top. So, you can imagine that this holes which were below have kind of floated. Of course, it is not really true that way, but this is some type of an imagination that people actually follow to understand the hole and the electron behavior.

Now, for this material when you apply an electric field suppose the electric field is applied in this particular direction. So, this is my sorry values E here. So, this is my electric field, we know that electrons would like to move in the direction opposite ok. And therefore, the electrons are moving in this direction of course, the conventional current would of course, be propagating in the same direction as the electric field or it would be moving in the same direction of the electric field.

And as the electrons moved to the left the holes or the vacant spaces will move to the right. So, there is a hole current, there is an electron current unfortunately the hole current the mobility of the holes which is denoted by mu h is not comparable to the hole electron mobility. It is in fact, much smaller than the electron mobility.

And therefore, the limitation of any high speed operation using these semiconductors comes mainly because of the hole mobility being smaller than the electron mobility which means that electrons are faster to move, but holes do not really move that fast.

So, this is what would be what is called as a intrinsic semiconductor or a pure semiconductor. But, now imagine that in this material we actually replace one of the atoms by say a group 3 element ok.

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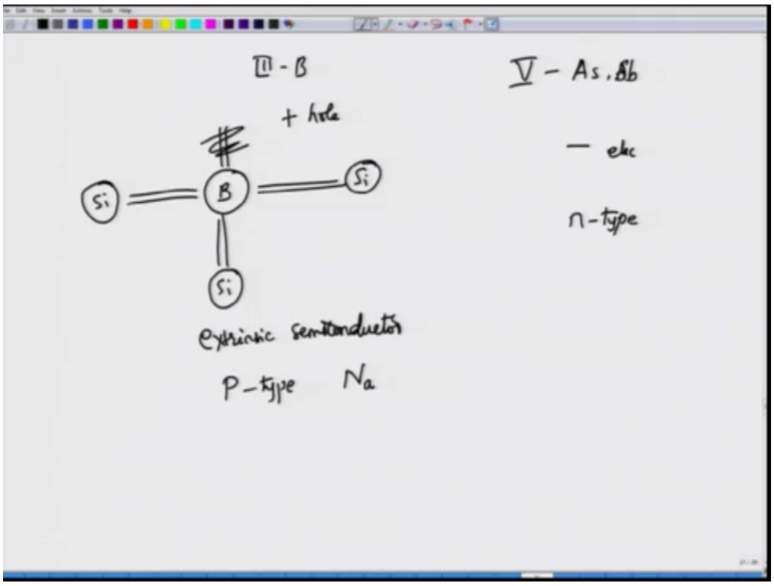

A group 3 element will have 3 valence electrons. So, therefore, it will go and talk to 3 silicon atoms. But, silicon atom bonds with 4 of them of which only 3 are being supplied by the gallium ion which is the 3 group element which we have considered to be an example of gallium it is not necessary that you actually use gallium. In fact, it is not used at all the doping is by typically by boron.

So, let me actually instead of talking about gallium let me go to boron which is group 3 element which is commonly used to substitute a few of those silicon atoms. So, now, because there are 3 electrons which have been bonded and there is a third hole which is now empty right. So, because there are 3 which have been bonded and then this is particular thing is not bonded ok. So, that particular bonding becomes available to us and it will contribute to a hole ok. See, it is it does not contribute an electron because electron is tightly bound to silicon ok. It cannot just go and then start roaming around in the silicon.

So, putting or substituting c of the silicon atoms by group 3 elements introduces what is called as lot of holes and these holes are now responsible or holes become what is called as the majority carriers in this elements. And because you have substituted some silicon atoms with some other atoms this material is now known as extrinsic semi conductor ok. So, this is called as an extrinsic semiconductor and this particular material in which the concentration of the holes is much larger is called as P type semi conducting material ok.

So, the concentration of P type semiconductor material is roughly equal to N a where N a corresponds to accept or ions ok. So, N a corresponds to acceptor because boron accepts is 3 and then does not accept the other valence electron ok. But, because it is bonded to this one it would not really be possible for it to just detach from itself. Therefore, substituting a few silicon atoms with group 3 elements will result in lot of holes. Similarly, substituting them with 5 elements such as say arsenic or antimony will result in excess of electrons which will now contribute to conduction.

So, while 3 contributes to lot of holes, 5 element contributes to lot of electrons and the material will now be called as n type material. So, these are 2 extrinsic semiconductors and this process of converting the intrinsic semiconductor or pure semiconductor into an extrinsic semiconductor is called as doping ok. We will have to say more about the basic properties in the next module.

Thank you very much.