Fundamentals of Semiconductor Devices
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Lecture – 02
Introduction to energy bands

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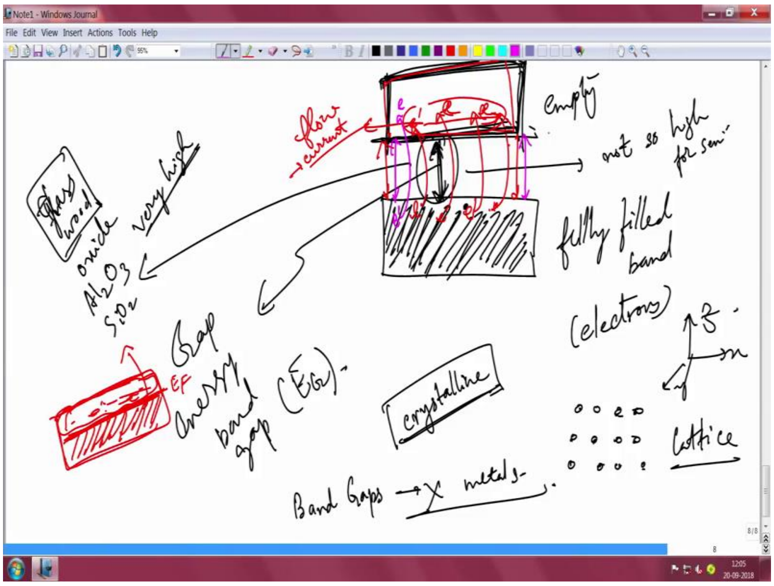

Welcome everyone. This energy band gap is the beauty of semiconductor; metals do not have this energy band gap and for insulators like glass actually this energy band gap this energy whole this energy band gap concept will only come when the material is sort of crystalline what is crystalline?

Crystalline means no matter in what direction you look in a crystal right. So, I told you x y z so, these are the atomic arrangement in lattice right. So, crystalline material means that no matter in which position of the lattice you go it will always look the same which means the arrangement of this atoms as lattice points are always the same there is no distortion to this.

Everywhere in all direction they will always look the same there is a continuity, there is no local variation of this if somewhere it is like that somewhere it is like that its not like that its all uniform ok. And the atoms are arranged periodically the atoms are arranged periodically and this periodicity is not violated. So, they are highly periodic in all direction this is the crystal structure.

And only a crystalline material actually has you can define a band gap technically speaking, but even then qualitatively you can assign a band gap to insulators also ok. Like say for example, a piece of glass or a piece of like plastic or wood we they do not actually have a band gap, but we can qualitatively assign and say or even oxide for example, you can take an oxide. For example, aluminium oxide or silicon oxide you can sort of assign a band gap to this materials and this band gap actually for those materials for this materials is very high.

When I say very high what do I mean? I will come to that this is very high for semiconductor this is not so, high not so high. Again high is a qualitative number this thing we have to come up with some quantitative number we will do that we will do that this is not so high for semiconductor and band gaps do not exist for metals band gaps do not exist for metals.

So, what happens is that I told you this is now band which is fully filled with electrons and this is a band which is empty. So, what happens is that you can excite electrons from here you can excite electrons from here to go there, another electron here to go there what happens then, how do we excite them we excite them by different ways we will come to that. But if we can excite electrons from here to there, what will happen is that this band is empty know.

So, whenever the moment the electrons are here they can flow; they can flow under the application of a electric field they can flow and if they flow they carry current what does it mean it means I can change the conductivity or the resistivity by what by deciding how many electrons I send there. If I send more electrons the current will be more if I send less few electrons current will be less. If I send no electron there will be no current so, that is how you tune.

In metal this is not there that is why you cannot tune what happens in metal is that your actually in metal we have not discussing on metal, but the highest fill states the highest fill states you know this is the highest fill states for example, we call it some E_F for example. This is actually there is no band gap per say, but it is the electrons are the highest fill states they have lot of available states here this is you see empty. So, they can immediately transport they can immediately carry current they do not have to excite anywhere.

The highest occupied energy state per electron actually exists in such a way that you have energy states here itself you do not have to excite anywhere and in insulator this gap is so large. That from here you know that from here to excite there its almost impossible its very very large gap and that is why you cannot tune the conductivity that is where main reason of difference between insulator metals and semiconductor. So, in semiconductor we are able to tune it in semiconductor you are able to tune the conductivity that is the beauty of semiconductor devices right.

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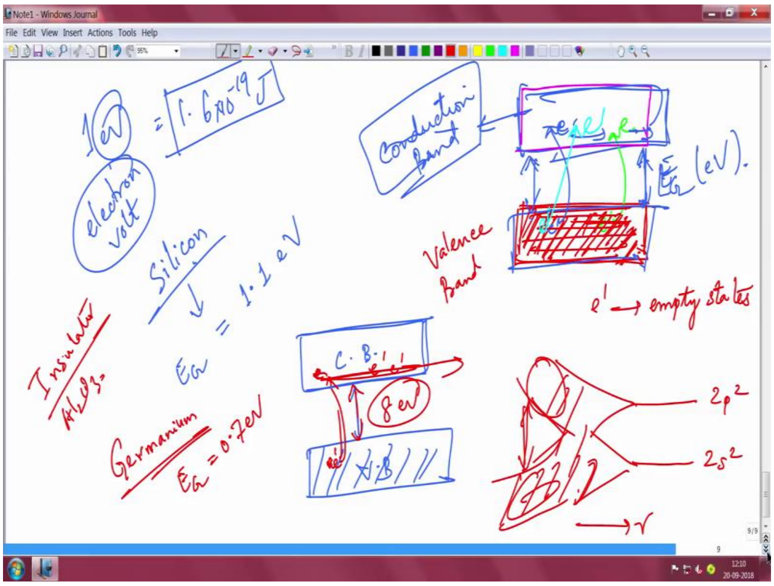

So, now I told you let us me use good color here right. So, this is a fully filled band you understand now how bands are formed right I told you 2s level is here, 2p level is here as you bring the distance closer they split they split right. These are filled and then this is a gap this is empty this is completely filled this is band gap this is distance by the way. So, as I am bringing the atoms closer, I get this splitting up the band and that is why band gap is formed right.

So, this is how energy band gap is formed and this is how we come to this particular state that this is filled this particular fully filled band is called valence band please remember, this is called valence band and this is fully filled with electrons. So, they cannot carry current why because electrons are completely filled know how will they move.

For current to flow electrons need empty states where they can move; electrons need empty states where they can move to and only then current will flow if this is completely filled with electrons then current cannot flow because electrons do not find any empty state to go. But the moment, but the moment you excite one electron here right the moment you excite one electron here this is empty so, that electron can now move and that is why current can flow.

So, electrons can only move here technically speaking and then this is called conduction band conduction band. So, conduction band is this empty band where electrons can be excited, valence band is fully filled band where electrons cannot move and the energy difference between them is the energy band gap. This unit of this energy we call electron volt do you know what electron volt is 1 electron volt is how much that $1.6*10^{-19}$ joule remember.

Electron volt electron volt is the energy not voltage and I told you 1 electron volt is $1.6*10^{-19}$ joule and this electron volt is the unit of energy for semiconductor band gaps and energies ok. So, the electron this is the band gap for example ok.

Now, what is this gap in semiconductor this is the gap that is not too large I told you only ok, only then you can excite the electrons from there to there know only then you can excite electrons from here to there. So, that band gap cannot be too large, now what is too large what is too small? So, typically the most commonly used semiconductor is silicon ok, the most commonly used semiconductor is silicon and silicon has an energy band gap E_G is equal to 1.1 electron volt, that is the value. That means, silicon this is conduction band I call it C.B. and this is valence band I call it V.B. this is fully filled with electrons this gap is 1.1 electron volt ok.

You know one electron volt is this many joules right. So, this is the gap between conduction band and silicon and the valence band of silicon. So, for you want to make silicon conducting you have to excite electrons from here to there only then you can conduct electrons to right. So, this is the basic concept of energy band and your band gap difference semiconductors have different band gaps. For example, in case of Germanium its another semiconductor right Germanium is another semiconductor and in Germanium the band gap this gap is around 0.7 electron volt which is smaller than silicon you know for Germanium this will be 0.7 which is smaller than silicon.

Some materials can have much larger like 2 or 3 electron volt also even more than that insulators have very very large band gap. For example, if I take an insulator say I will take the insulator and for example, I will take aluminium oxide in that case the band gap might be very large it can be say 8 electron volt that is a very large large gap you cannot excite electrons from here to there. So, easily that is very difficult right.

So, those are insulators and they do not conduct electricity the beauty of semiconductor lies in the fact that you can actually change the number of electrons available here and that will help conduct electricity. So, that is why you can tune the conductivity or resistivity and you enable all these different wonderful devices LEDs and so on and so forth ok. Then many many rich phenomena they are associated with semiconductor devices we shall only go step by step there we shall only go step by step there.

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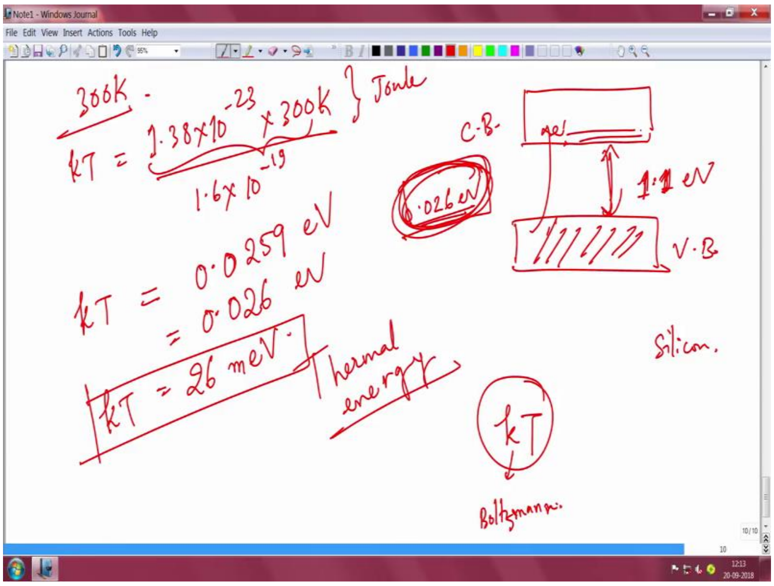

So, you see when you have an empty band conduction band here and a fully filled valence band here and I told you 1.1 electron volt is the energy band gap between this two in silicon in silicon this is semiconductor.

Now, at there is always something called thermal energy you agree there is always something called thermal energy. At room temperature, any other temperature except 0 Kelvin you will have thermal energy the atoms will vibrate there is always a thermal energy associated with it. And if you have read your, you know high school physics you know that thermal energy is given by kT you know what this k is this k is actually Boltzmann constant.

I hope you have learned this kT is the sort of the thermal energy and T is temperature right. So, let us see a room temperature what is the thermal energy ok. So, for example, I take room temperature you know room temperature is around 300 Kelvin ok. So, what is kT, k value the Boltzmann constant is $1.38*10^{-23}$ s i unit into 300 Kelvin this is in joule this quantity is in joule I want it in electron volt. So, what should I do what should I do?

I should divide by $1.6*10^{-19}$ because this is the 1 electron volt is so many joule right. So, I get in electron volt. So, I will see that if I solve if I calculate this I will see that this is roughly 0.0259 electron volt or I can say it is roughly 0.026 electron volt or you can say 26 milli electron volt this is room temperature energy.

So, at room temperature electrons will have this energy which is 26 milli electron volt. Now 26 milli electron volt, which is 0.026 electron volt how much smaller is it compare to 1.1? It is very small and we know eventually we learn that many of this processes like exciting carriers, that the combination, the light emission, the carrier dynamics everything most of these things are actually exponentially depended on the energy ok.

So, if you have 1.1 electron volt as the band gap and only 0.026 as the thermal energy then it is very less probable their electrons would be able to excite from this to that by thermal energy only right, but you are wrong actually it is possible and there are many things behind this why it is possible this thermal energy is very low.

Despite that you can excite electrons from here to there you can excite electrons from here to there low probability, but its ok, we can still excite and that is why we have to understand the statistics of the distribution that is very important. So, that is a lesson for another class we shall definitely come very soon ok.

Now, before we move ahead with those the statistics of how you can excite electrons even it is low thermal energy how you will get some electrons here and how you will get current flowing and all these things we have to introduce something a little different.

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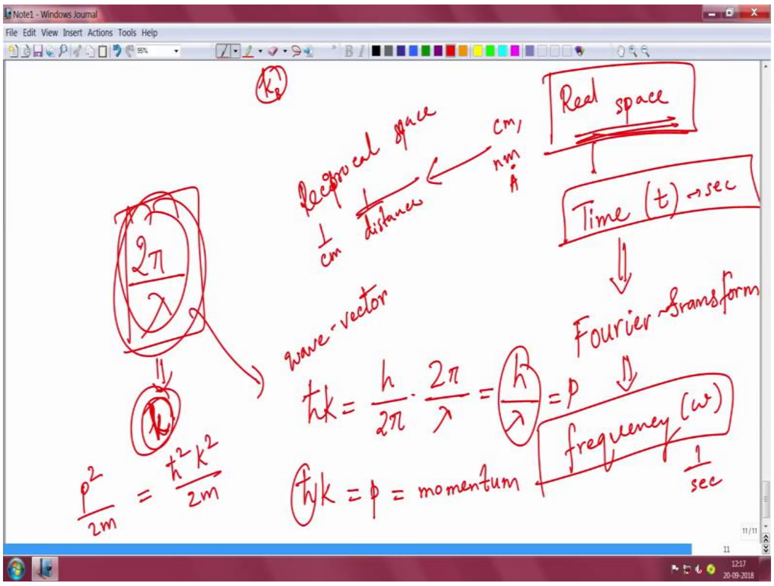

Everything that we are talking about here was in respect to real distances or real space for those of you who are from electronics back ground who have done your mathematics probably its not necessary to know, but its good thing to know.

You know if you have a time domain if you have time domain a signal you can do something called Fourier transform I do not know how many of you know it, but you can do a Fourier transform we do not have to necessarily know it ok. Fourier transform of time gives you frequency and frequency omega has a unit of 1 by time or 1 by second this is second.

You need time to understand the time domain analysis of signal, but if you do a Fourier transform mathematically you get frequency domain signal it also helps to understand many other aspects similarly, a real space we are talking about centimetre, nanometre, angstrom and so on right.

This is the real space like time it has a Fourier transform its called the reciprocal space its called reciprocal space, its unit is 1 /cm or 1/m 1/distance and that is useful in understanding many important things actually that is why we do that. Now sounds are little bit of abstract so, let us not go to deep immediately right now let us go step by step.

Most of you know wavelength lambda not most of you all of you know all of you know lambda or wavelength corresponds to even electrons by the way because electrons are both particles and waves you know that right. So, wavelength can be for electrons also it need not be only for like waves it can be like particle like waves also. And there is something wavelength unit is by the way centimetre or meter that you know the something called $2\pi/\lambda$ have you come up this term $2\pi/\lambda$ you call it wave number probably I think right wave number.

Here in this course we call this quantity as wave vector ok, $2\pi/\lambda$ do you know what this quantity signifiers actually. In a way this quantity signifies the momentum of electron we will come to that you know momentum right of course, all of you know momentum. You know this is wave vector and we call this represent this as k this k is not the same as Boltzmann constant k by the way this is just a k.

So, we can put Boltzmann constant k is k_B to represent that is Boltzmann constant and this is just k we call it k and this is a unit this is just $2\pi/\lambda$ is actually k we call it wave vector. In some sense it actually represents the momentum of electron what do I mean you know what is h planks constant of all of you know that right and you know what is $\hbar$ its the reduced plank constant it is given by h by what $h/2\pi$ ok.

You know this is reduced plank constant this is $h/2\pi$. Now if I multiply $\hbar$ by k, k is this k what will I get what is k? k is $2\pi/\lambda$ what will what will you get? You will get h/λ now if you recall de Broglie equation or Debra equation as you can pronunciate differently h by lambda is what? P, what is p? P is momentum and this is from your high school physics by the way.

So, $\hbar k$ is actually p which is actually the momentum of the electron if I am talking about electron is the wave right you see that is why I told you k actually represents momentum because $\hbar$ is constant know your $\hbar$ is constant. So, constant times k is momentum. So, your k which is $2\pi/\lambda$ actually represents the momentum of the electron in some way its a momentum of the electron you know what is momentum right and you also know that the kinetic energy is given by momentum by p^2 by 2 m right.

So, it will become $\hbar^2k^2/2m$ this is your kinetic energy of the electron and if you look at this equation very carefully right.

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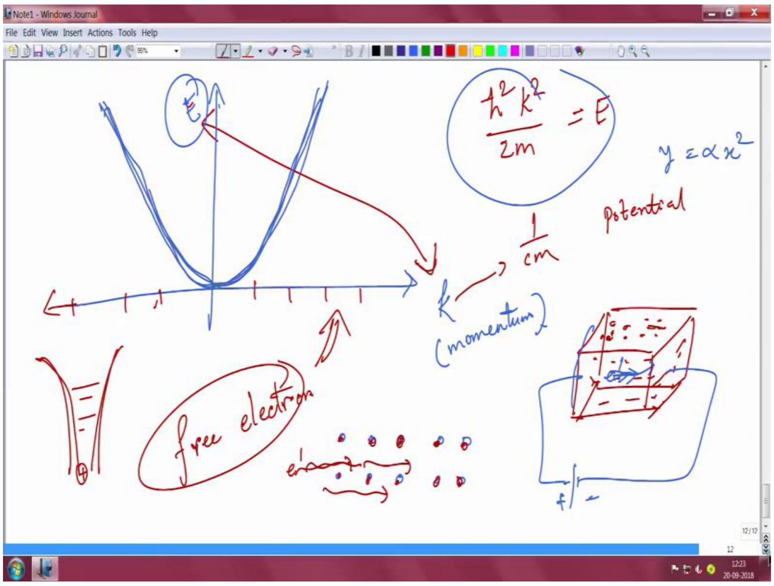

If you look at this equation very carefully $\hbar^2k^2/2m$ this is the energy kinetic energy ok. So, if I plot sorry. So, if I plot E and if I plot k what is k actually? K is $2\pi/\lambda$. I told you it is actually representative of momentum, higher the k higher is the momentum ok.

If I plot E versus k, what is this $E = \hbar^2k^2/2m$ sorry its looking like y equal to some alpha x square do you see its a parabola. So, the parabola will look like this its a parabola right. So, the energy the energy is dependence the energy dependence on the momentum is actually a parabolic relation right energy dependence on momentum is a parabolic relation and what is this context?

The context is actually of free electron. So, if I talk about a free electron then this is the energy and momentum relation which is parabolic in nature it is parabolic in nature and this is for a free electron k by the way has a unit of 1/ distance. So, it can be 1/cm the k has a distance unit of 1/cm so, this is good.

Now, this is a free electron its called a free electron and this is your you know the energy and momentum relation very good. But a electron is not free inside a crystal right if I take a three dimensional crystal right real crystal like silicon right, if I take a real crystal like this they all this atoms they are now I mean they are periodically arranged not randomly arranged by the way.

They are all periodically arranged they are all periodically arranged, its a crystal if you put an electron there, an electron will move you apply some voltage and there is a field here. So, you apply an field electron will move know the electron will move when the electron moves it sees its surrounding of a crystal which is periodic in nature, it sees a surrounding or an ambience which is periodic in nature in three dimension right its a periodic crystal.

So, this equations and this diagram parabolic diagram it only holds true for a free electron which is free to move in vacuum in a real 3 D, no in a real periodic crystal an electron sees this periodicity that sort of effects its movement or its properties and so, it is very smooth parabola that we have here is actually not correct for an electron inside a real crystal.

Now, you might ask where we trying to study this it is going to become to physics right we are talking about energy bands and we are going to study the devices, but we are coming back from energy band and we are coming to disk kind of an E-k diagram its called an E-k diagram by the way. And we are talking about reciprocal space and momentum energy what is the relation of all this, the energy band that we are studying with the actual practical devices like LEDs or transistor that you are studying.

The relation is enormous kind of very very critical significance because this particular energy bands this is also by the way actually an energy band by the way except that this is not with respect to x or distance, but this is with respect to momentum or k. All these things will help us understand the basic physics of electron transport and electron properties in a semiconductor and that is why that is the reason why we are trying to study this ok.

Now, a free electron inside a crystal will not see this more parabola in terms of in the sense that it will not have an energy k dependence as more as it is it is supposed to be for a free electron ok. So, what we do now mathematically; mathematically we have to solve some question equations which we are not going to solve here mathematically you are going to solve some equations in the presence of periodic list lattice right here periodic lattice right.

In a in the presence of a periodic lattice an electron might move right, it will be scattered by this atoms because they are vibrating this atoms also setup potential, the electrons will be scattered there will be impurity there will be so many things. So, real electron when it moves inside a crystal has a real world potential there you know and so, we have to solve and equation in the presence of this periodic potential or a periodic you know atoms to enable the actual representation of the E-k diagram and the equations ok.

Now, the one simplifying assumption is that all this its not a assumption its actually true, but this atoms that are their periodically they set up a potential each atom will set up a potential like this right. There will be a core, there will be atoms these electrons are their of course, but this is a potential its like an infinitely deep potential and to make things simpler to make things simpler we will only talk about one dimensional period, no two dimensional its a same thing you can extrapolate two and three later on, but these are atoms that are periodically arranged.

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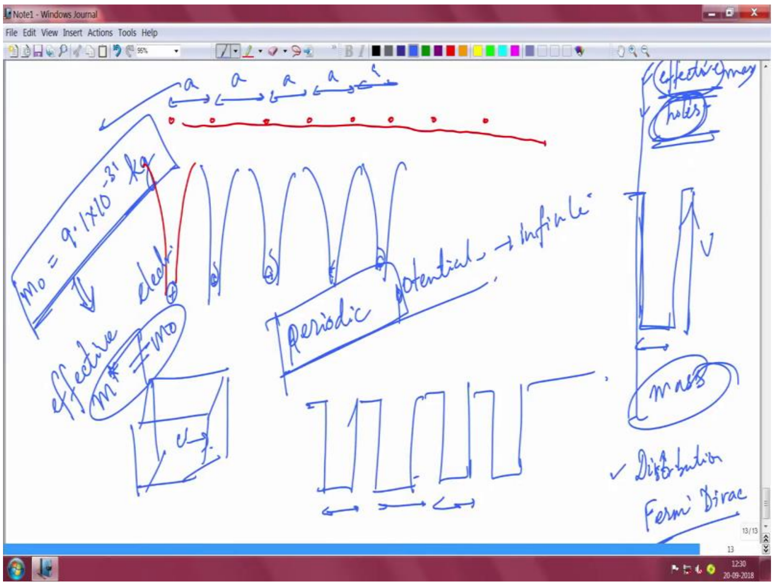

All of them have a spacing sorry all of them have a spacing a, a is lattice constant it can be say 5 angstrom may be or 4 angstrom or whatever right that's depends on the crystal. So, this is spacing is 'a' everywhere my drawing may not be accurate, but this is all 'a' ok. So, essentially I am talking about a potential all of them are potential they are generating some potential like this its called periodic potential.

I can draw this and I will assume these periodic potentials are nearly infinite which means I can draw this as like this, what am I drawing actually? I am drawing the periodic potentials as wells you know you know this energy well this is a infinitely high potential and this is an energy well its called like a quantum well ok.

So, my drawing is not accurate of course, but these are energy wells. So, we can have a periodic potential which is infinite in number and electron will move in this presence of this periodic potential well. So, we have to solve and understand the electron movement in the presence of periodic potential well ok.

Now, you might say that what is the point of all this, the point of all this is that we will able to understand some very very important concept what on the most important concept is the mass of electron inside the periodic potential you know. If I take a three dimensional crystal lattice, I told you right if I take a three dimensional silicon, an electron is moving inside the crystal then the mass of electron inside the crystal is not the free electron mass.

You know electron mass is free electron mass is $9.1*10^{31}$ kg that is the free electron mass of the electron as it moves through vacuum or free space, but the moment the electron moves through a crystal this mass will change why because there are so many imperfections in the crystal there is the periodic potential. The periodic potential of this atomic arrangement will disturb the electron movement it will interact with the lattice.

So, this effect this mass the electron mass that moves inside a crystal that mass that it feels is actually different from this mass its called effective electron mass effective electron mass. And we represent which are m^* and that is different from the free electron mass and that effective electron mass how much it is their inside a crystal, but its a value is the most important thing we need to know the current flows and many other things and this effective mass can be understood from this periodic potential then I am discussing about ok.

So, we shall end the class here today there is a lot of introduction that we have brought about. So, what we shall do in the next class is we will take from this point we will go into where we will go into the concept of effective mass and we will also introduce the concept of hole what is hole there is something called hole ok. We will introduce the concept of effective mass, we will introduce the concept of holes and then we will also introduce the concepts of distribution of electrons distribution of electrons how electrons are distributed in valence and conduction band.

You remember this diagram that I keep drawing here, this diagram right this is conduction band, this is valence band how electrons are distributed here, how many electrons are there, how many electrons are here all these things depend on statistics ,its called Fermi Dirac statistics.

So, we shall introduce the concept of Fermi Dirac statistics in next class, introduce the concept of Fermi Dirac statistics we will also introduce the concept of effective mass and holes what are holes and those will helps us basically go ahead with the 3rd lecture where we introduce doping and other things ok.

So, today’s class what did we recap we should have a quick recap for 1 minute today’s class I told you that semiconductor devices are very important that most important probably you know in the electronic industry everything depends on semiconductor devices.

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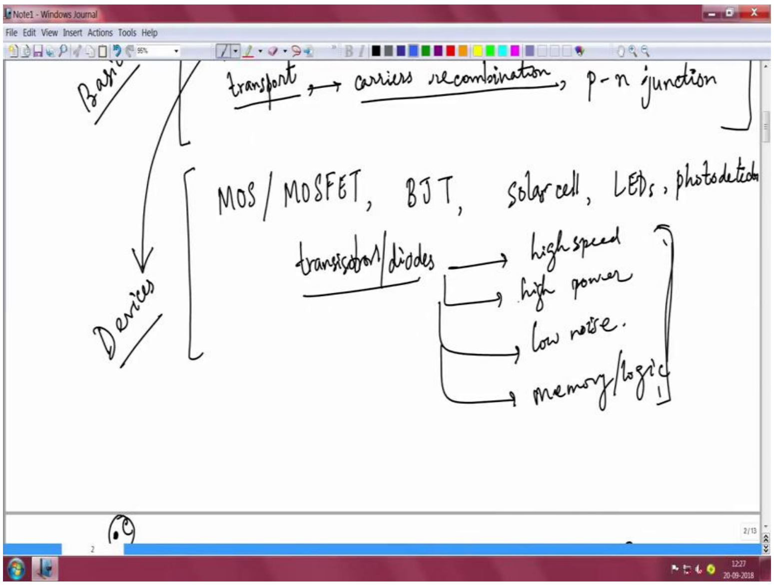

So, many types of semiconductor devices there that we may not be even aware off right and it as had a long history from 1948 right.

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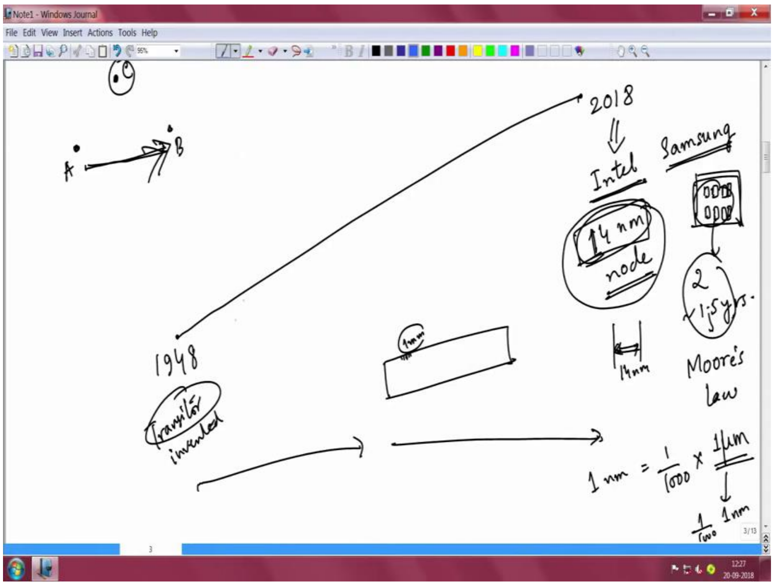

When first transistor was invented in BJT I mean and to 2018 when we have transistors of the scale of 14 nanometre, 10 nanometre you know its very sophisticated platform now. Moore’s law is there and this scaling of transistor is continued over so much so many years, but this is not transistor only for your processor chips that going to laptops and cell phones.

There are many other transistors very which are not scaled up because they are required for RF power or radio power you know radio frequency power application those do not scale like this there are many kinds of transistors or LEDs or solar cells do not scale like this there are many other devices their right we talked about bands.

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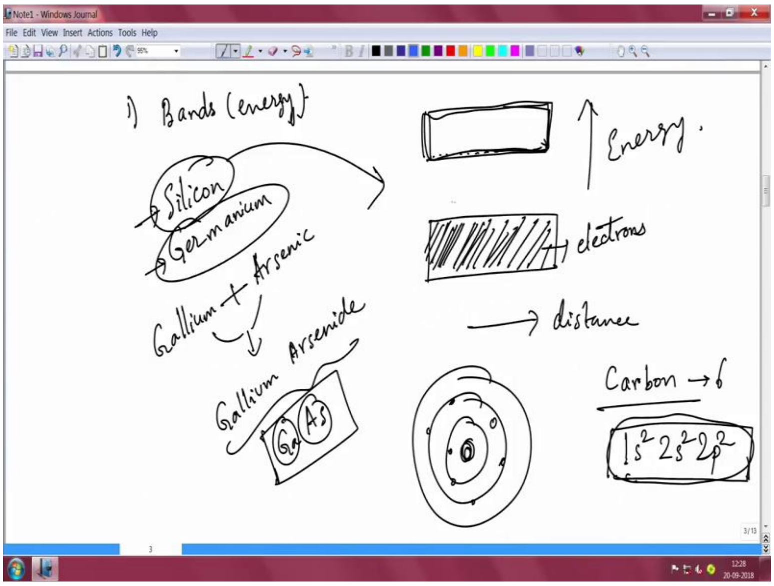

What are energy bands and how do they come about there are different kinds of semiconductor I told you and to introduce the concept of band I told you that you have to go to a single atom, We have to talk about the discrete energy levels.

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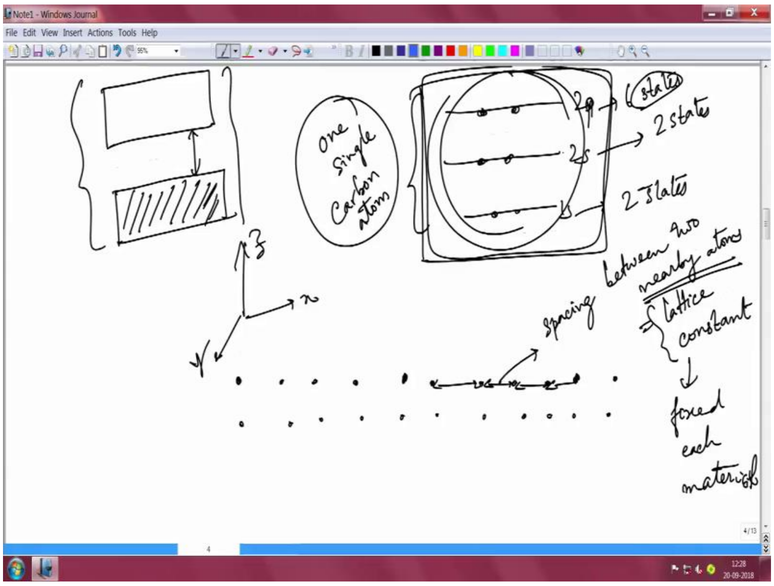

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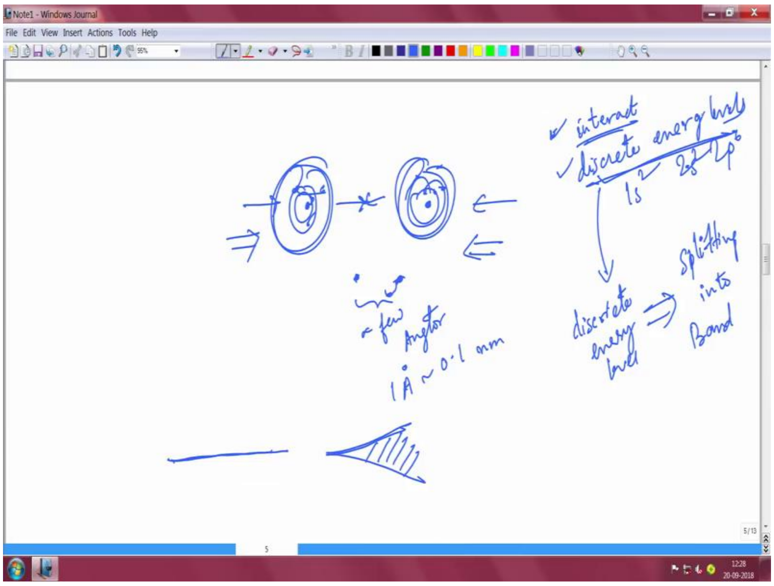

The moment you start bringing the atoms close together this discrete energy levels will split up they will split up to form some bands.

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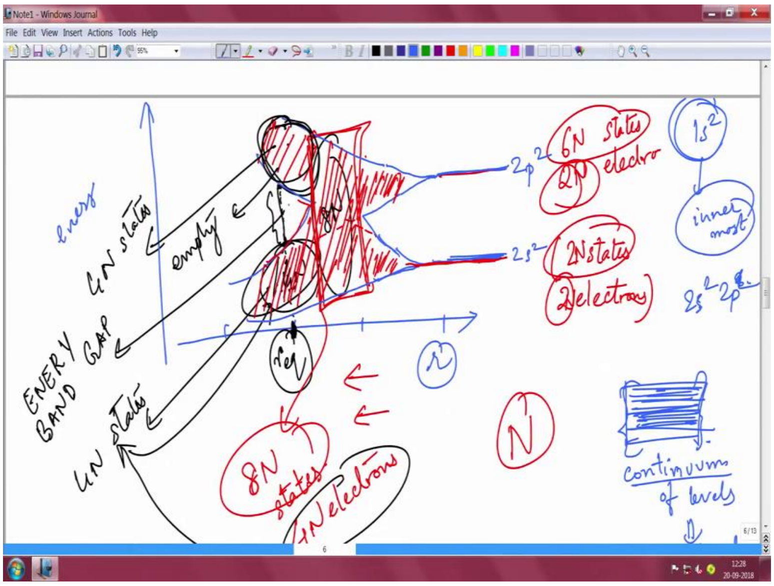

And this bands will give you band gap and that’s why you have a highest fill band sorry highest fill band and empty band here the separated band energy band gap for insulator this is very large, for metals there are no band gaps, for semiconductor this band gap is appreciable. So, that you can actually excite electrons from the fully filled valence band to the empty conduction band and but doing that you can increase the conductivity or resistivity of the material that’s the beauty of semiconductor you can tune the conductivity and then we talked about the electron volt the concept of electron volt how much is the energy silicon.

Germanium and different materials have different band gaps this is dictated by many properties of the material and finally, we came to the in the reciprocal space I introduce the concept of $2\pi/\lambda$ as k, which is sort of an momentum actually $2\pi/\lambda$ is the k is a sort of a representation of momentum. I told you we are that E-k diagram or the energy and momentum relation is a parabolic relation for free electron in vacuum or in space and I told you that the moment electron is put inside a real crystal like silicon or germanium or so on and so forth.

The periodic potential will basically effect the moment of electron and. So, the mass of electron as experienced inside the crystal also changes we call it effective mass ok. You please recall that all these atoms that are there arranged periodically in a crystalline solid, set up this periodic potential and that's why the periodic potential distorts the movement of the electron and that is why we get this you know different effective masses inside a crystal.

And that's why the energy the concept of energy band gap actually arises only when there is a crystalline solid because, if this crystalline or the periodicity of this distance is not maintained then you cannot solve the equations you cannot actually gap practically speaking you will not have a periodic potential and so you cannot have a uniformed band gap also ok

So, we will end the class here today and in the next class we will continue with the concept of effective mass we will introduce holes you know electrons are as much important as holes. Holes are also some kind of quazi particles that carry current. And we will introduce the concepts of if possible doping and before that distribution Fermi Dirac distribution that will tell you how electrons are filling up the bands you know how many electrons are there in a semiconductor, what is a probability that electrons are there and how many electrons are there all these things are captured by Fermi Dirac statistics and then we introduce the concept of doping and by doping you can actually change the conductivity ok.

The other approaches are for example, by shining light that is a different thing that is used for photo detector and solar cells you know, but without light you can also change by adding some impurities called doping.

So, those things will try to introduced in the next class we will also try to correlate practical applications. As, I keep telling you in the beginning how these devices correlate with practical life examples right we shall have that in mind. So, we do not lose track of that ok. So, with this will end the class today and I will hope to see you in the next class where we shall discuss about effective mass, holes and Fermi Dirac distribution ok.

Thank you.