Fundamentals of Semiconductor Devices

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Lecture – 03
Fundamentals of band structure

So, if you recall in the last lecture which was the first lecture of this course, we had introduced the concept of semiconductor, and why semiconductors are very essential in today's world. And we also introduced the concept of bands, energy bands, how bands are formed. We also introduced the concepts of reciprocal space and E-k diagram, but we shall revise that once again today. So, the main the main take home lessons we learned last time was that number one semiconductors have a unique property which is that you can tuned your conductivity between you know metals and insulators sort of you can do many order of magnitude change in their resistance by adding impurities or by doing some other techniques which is not possible in metals or in insulators right.

So, an another thing number two is that they have a gap between the highest occupied band and the lowest unoccupied band and that gap is called energy band gap which is not too high unlike insulator, and in metal there is no gap right. So, semiconductors have these two very important properties. And since semiconductor is a solid; it is a crystal right. So, many of the properties will depend on how the crystal is, and it is as much as material sciences devices and we shall learn subsequently in the course that we have to study both the materials physics as well as the device aspect together to understand how the devices work, how technologies are made ok.

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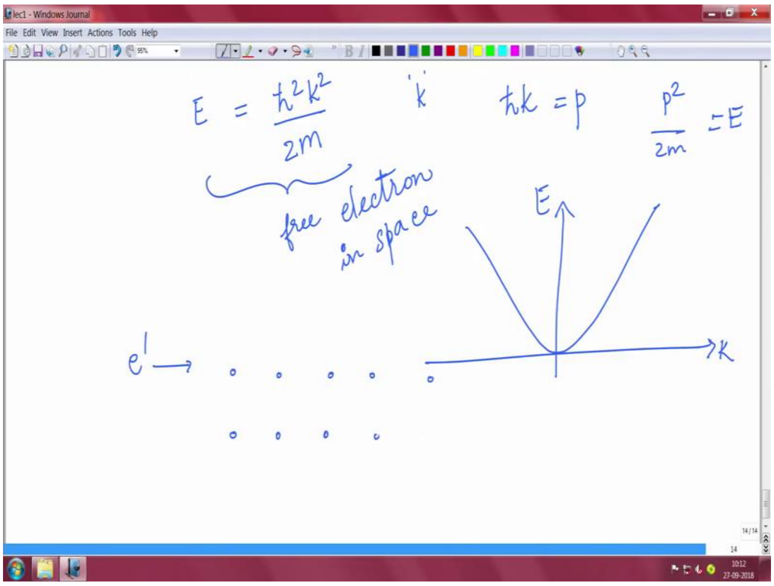

So, we shall come back to the whiteboard again. Last time I had told you that energy E and momentum are related by this relation if you recall $\hbar^2k^2/2m$. What was k here, k actually is a reciprocal space vector, but you can visualize it as momentum because $\hbar k$ gives you the momentum right. So, you can think of k as momentum, it is a momentum direction. And energy depends in a quadratic relation to momentum. This actually this comes from high school physics only $p^2/2m$ = kinetic energy if you recall right that actually what it comes from.

This all was valid for a free electron in a space right an electron free in space, where there is no you know no boundary no crystals nothing. In that case energy and k has a parabolic relation right like that. And we call that you know this is a parabola of course, and energy and k has this parabolic relation and that's very good we learn that. Now, I told you that when an electron move in a crystal, it sees this periodic atoms right there is a periodic arrangement of atoms in 3D, here I am drawing it only in 2D ok.

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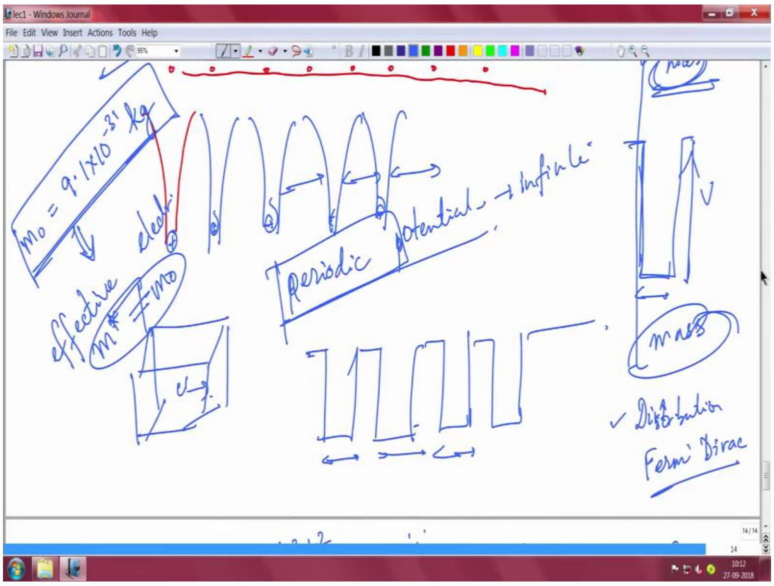

Here I am drawing only in 2D; sorry I will come back to the page again.

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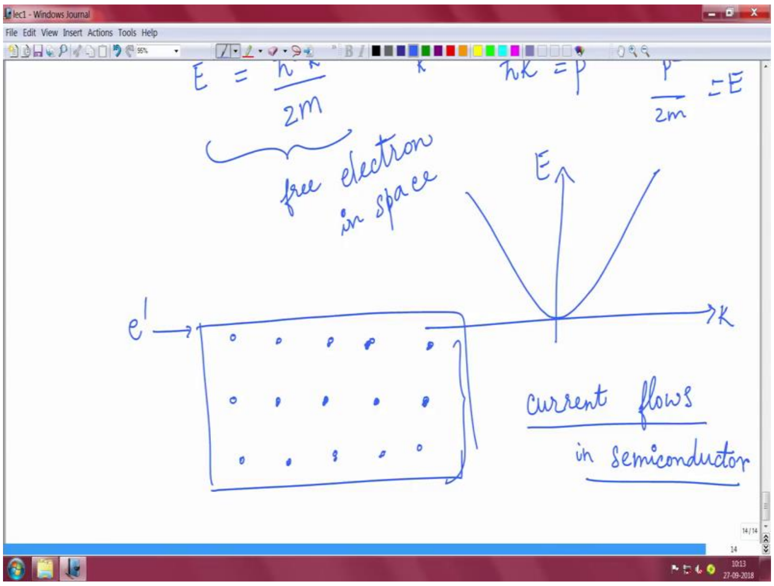

So, there is these atoms which are arranged in 3D, and an electron has to go through the crystal when an electron moves in a semiconductor. Why are we studying this, we are studying this because we want to eventually understand how current flows in semiconductor right. We want to understand eventually how current flows in semiconductor. And why do you want to understand why current flows in semiconductor, because only then we can understand different devices like LEDs, MOSFETs and so on right. So, how current flows in semiconductor, we need to understand the transport of electricity. And current is carried by electrons; and another type of particle called holes, I will come to that.

So, we need to understand how electrons actually move in a crystal. Now, a semiconductor to be actually a semiconductor and have a band gap, it should have this periodic arrangement of atoms which are highly periodic in nature ok. In any direction you look, the crystal structure will look the same. It is called crystalline material unlike a piece of glass or wood or you know like some oxide where basically you have an amorphous sort of a structure where the crystal these atoms are not arranged in a definite lattice ok. So, we are talking about semiconductor crystal.

So, we can assume that these are periodic actually these are periodic in a periodically they are arranged, and each of these atoms actually introduces a potential right, each of these atoms introduces a potential. And it is called a periodic potential [FL]. It is called a periodic potential.

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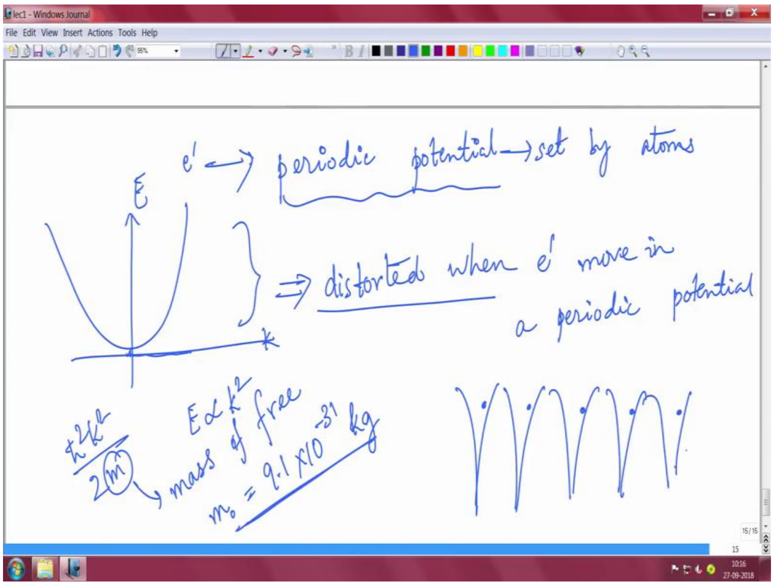

So, essentially an electron has to move in a periodic potential, it has to move in a periodic potential. And that periodic potential is set up by the atoms it right, all the atoms that are there in the crystal, setup this periodic potential and electrons have to move in the periodic crystal. So, when electrons move in a periodic potential in actually a semiconductor crystal like say silicon, then this E-k diagram that we have drawn know this E-k diagram if you remember this is E, this is k, this E-k diagram that we have drawn becomes a little bit distorted. It becomes a little bit distorted when electrons move in a actually a periodic crystal ok, periodic potential ok, it's not in free space. Only in free space electron has this E-k relation where energy is proportional to k^2.

Actually this diagram means that as we increase the momentum of a electron, the energy will increase parabolically with respect to the momentum that is basically what it means right. So, and you remember that there was the $\hbar^2k^2/2m$ there that m was the mass of electron we say right. In free space this is the mass of free electron, and you know that mass of free electron is m^o actually which is given by $9.1*10^{-31}$, but this mass actually is the mass of electron when it moves in free space.

Now, I told you that when electrons will move in a periodic potential in a semiconductor crystal, then first thing that will happen is that this E-k diagram actually becomes distorted and that is mathematically can be proved. We shall not derived that expression here, but you can mathematically prove that you this E-k diagram becomes distorted. And so when the electron moves in the periodic crystal, if you can try to visualize this physically if is not mathematically so much, when an electron moves in this periodic potential, then it sees that periodic potential along with variation know. So, the electron experience as a difference sort of acceleration, it experiences you can say that it has a different mass inside the inside the periodic potential.

So, I told you that this different atoms if I take a one-dimensional string of atoms only right, this atoms will introduce you know they have a own potential. So, I told you that they actually introduce a potential wells like that right. And this potential profile can be actually modeled by a very simplistic argument you know like people do that kind of a this is suppose a ok, this is again a, this is like a lattice constant.

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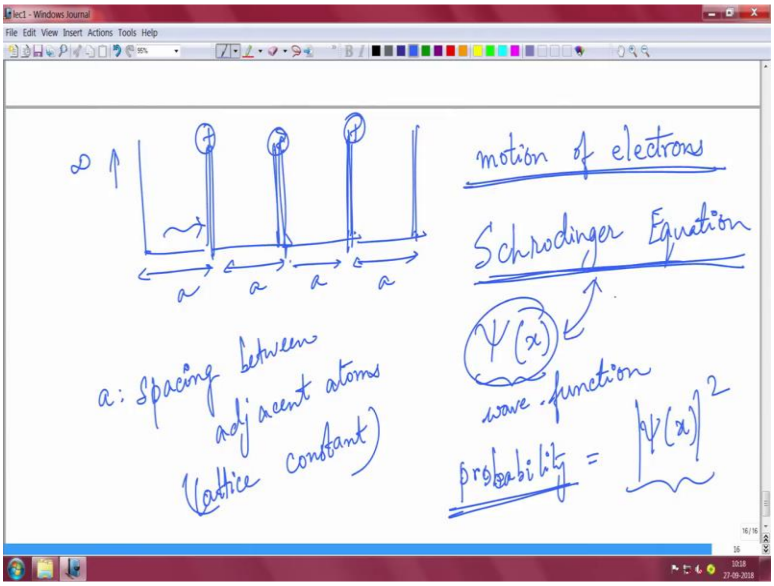

Remember a is the spacing between adjacent atoms, it is called lattice constant. Spacing between adjacent atoms ok, adjacent atoms, it's call lattice constant. It is also called lattice constant. So, so you have this infinitely deep potential well, this is infinity you can assume, this is infinite. And these are delta functions. You know where essentially you are electron, the nuclei of the atom slide, they are like delta functions, they are delta spikes and you have this periodic potential.

So, you solve the equations you know like you solve the equations basically of an electron as it moves inside a periodic potential that's what you do. You have to solve some quantum mechanical equations; we are not touching in those in this course. But if you solve that, then you will find out there actually this E-k diagram ok, this E-k diagram becomes distorted. How does it become distorted you know I will draw it a better picture.

So, what did I tell you I told you that when the electron actually you can model the periodic potential of atoms as this infinite quantum wells with delta function of this (Refer Time: 08:04), they are all a here. And you have to solve the motion of electron inside the inside this periodic quantum well or periodic potential well ok.

The motion of electron, when an electron moves because electron is a subatomic particle, now it basically has both electron and particle and wave like nature. So, to understand the motion of electron, you have to solve an equation called Schrodinger's equation ok, you have to solve an equation called Schrodinger’s equation. It was actually derived and proposed by Erwin Schrodinger; he was a physicist in the 1920s. He got the Nobel Prize at a very young age for doing this pioneering work.

So, a Schrodinger’s equation is actually an equation that basically equates the energy of electrons in a way, and there is something called a wave function ψ. We will not going to the details ψ is actually call a wave function. And it basically just like you know if you throw a stone in a pond of water, you have this waves right. So, you can model the electron also as a wave in and there is a wave function associated with it ok. You know that it is impossible to exactly find out the location of electron, and determine it’s velocity of momentum simultaneously right that is Heisenberg uncertainty principle.

So, what you can do is always, you can give a probability of finding the electron. You can always give a probability of finding the electron. You can never guarantee and say that this is where the electron is you can only give a probability. And apparently $\psi(x)$ ok, it is modulus whole square gives you the probability of finding electron ok. So, this is a wave function of the electron. And you have this Schrodinger’s equation actually depends on this wave function of the electron.

You solve that you know for a free space, then you get the E-k diagram of also you know. And if you solve it for this periodic potential, where there is this periodicity of this potential, then you can get the actual Schrodinger’s equation solution for an electron inside a semiconductor crystal which is periodic in nature. And as I told you, it has to be periodic only then the concepts of energy band gap actually can be used right, so that is why another reason why it has to be periodic by the way. So, you if you do that, then you will see that the E-k diagram actually becomes distorted.

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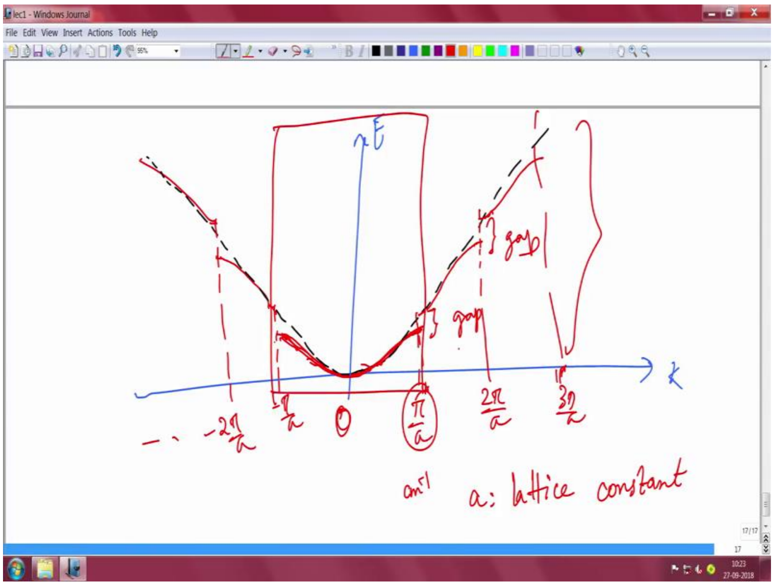

So, what was the E-k diagram; before let me draw it again. So, this is E ok. What I keep telling as E-k diagram actually is an energy momentum diagram in a way you can think of it. So, initially the E-k diagram was something like this, my drawing is not very good, but it is a parabola a very nice parabola. But this is in free space when in periodic crystal the E-k diagram becomes distorted in the sense that it will have a shape here like almost like that, but after sometime it will become like that ok. It will open up. And there is a discontinuity here, there is a discontinuity.

So, again it will start from here not doing it very well sorry I made it any ways. So, it will again start from something like that. It will again start from something like that. So, there is gaps that appear here right, there is gaps that appear here. My drawing is not very good, but of course, they are symmetric. So, you have these gaps here. And if you remember thus the in free space, it is a smooth parabola like this; it is a smooth parabola like this no discontinuity.

But in a periodic potential, there has this discontinuity that is discontinuity because if you consider this first band here, first curve here, it has a band here there is a gap there is a gap here you see, there is a gap here you see. And this discontinuity, this distortions you know that deviation from the smooth parabola happens, this actually it is like that actually it here and here does the same point actually by the way ok. This is the same point; this is the same point. This all happen at spacings of π/a, 2π/a, whatever you know then again there will be destruction at $3\pi/a$, here similarly $-\pi/a$, $-2\ \pi/a$ and so on ok. You have these distortions actually.

You know a is the lattice constant of the crystal which means the spacing between adjacent atoms. So, you know that. So, pi by a is of course, the unit is centimeter inverse by the way. So, every $-\pi/a$, $2\pi/a$ $3\pi/a$, $n\pi/a$, you know you have this distortions that come out ok. And this is the actual shape of the E-k diagram for an electron that moves in a periodic potential. And you can see that this first lowest level or even the higher levels, they are not exactly parabola, they are parabola towards k equal to zero point, this is k equal to 0. But as you go away from the k equal to zero point, your deviation occurs substantially, and it is no longer parabola, it becomes little curved, other way around right. So, the curvature changes the curvature changes.

And to understand now why are we studying all these. You have you have to always ask this question as to why are we studying the E-k diagram of electrons that are moving in a periodic potential because electrons move in actual semiconductor crystal when they carry current. And this E-k diagram is very much there we cannot see it physically, but it is actually there. And this relation you know the energy and momentum relation of electrons is most fundamental in understanding the transport properties, in understanding the band diagram in understand in making designing devices so many things ok. It is very fundamental to understanding the electron transport in a semiconductor crystal that is why we are understanding.

There is a lot of physics that has gone into it, lot of Nobel Prizes have been awarded you know on this, but we shall actually talk about it very simplistically not going too much of mathematical details that's what I am trying to do here. It so happens that most of the semiconductor devices that we learned or we will study in this course whether that is BJT, MOSFET, LED, photo-detector, does not matter, we can always consider everything to be happening or we can basically understand everything by understanding this first block here. We do not have to go to this we do not have to go to this ok. These are higher order you know we can say zones, you can only consider between $-\pi/a$ to $+\pi/a$ ok, only this particular zone, of course, this is here. So, let me draw it again ok.

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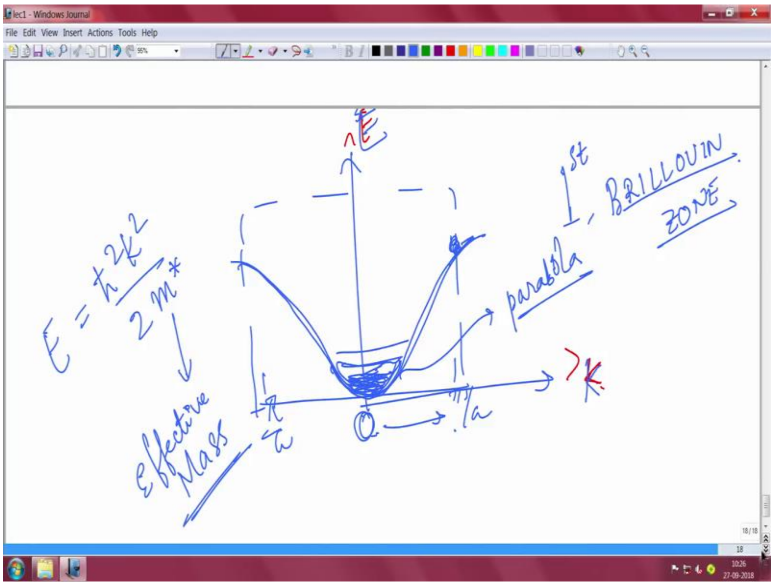

All the semiconductor transport, all the devices, all the concepts of physics and transport everything can be understood only in the first gap here. So, this is k ok. And I told you this is -π/a; and this is say -π/a right. So, it will be something like that right. I told you so little deviated from parabola. Of course, they are higher order bands that start here, but we will not need that so much ok. This zone that I am talking about within + π/a. -π/a is called the first Brillouin zone ok, Brillouin zone. This is a scientist actually name Brillouin actually he made this things, so first brillouin zone.

So, this is the first zone where sorry this is the first zone where most of the electrons actually will be there, and most of a device transport physics will also happen here ok. This is the E-k diagram of a real electrons that are moving inside semiconductor crystal that is one number one thing. Number two is that this is not exactly a parabola. This is a slight nonlinearity as you go away from 0 to π/a. When I say you go from 0 to pi by a, it is not physical distance you are going by the way 0 to pi by a, your k is changing, it means your momentum is increasing.

So, at k equal to 0, your momentum is 0, but at here the k the momentum as become some finite number. So, when you increase the momentum essentially you have this non parabolic sort of relation eventually ok. And this essential, but most of the things you know this you can see that this is energy on the y-axis. So, this point is that higher energy than this point. Most of the electrons will be close to here only ok, very low energy we can we talk about low energy. And so at close to 0, it is perfectly parabola ok. If you can say, it is a very nice parabola at close to k equal to 0. And mostly we will talk about k equal to near 0 only ok.

So, this is the energy and you can say this is like a you can say this is like a band of course, where electrons are populating. Electrons will populate as you have more electrons we will start populating more, but we will mostly have we will concern only about near k equal to 0. So, this is actually E equal $\hbar^2k^2/2m$ still holds true for this particular distorted parabola of a real semiconductor crystal when electrons move except that is m is no longer the free electron mass that we are talking about in space this m has a special meaning now. This m actually we call it m* ok, and it is called the effective mass ok, it is called effective mass of electron. So, effective mass of electron means what is the mass of electron as it experiences when it moves inside a periodic potential in a semiconductor crystal ok. And it is mostly different from the free electron mass ok.

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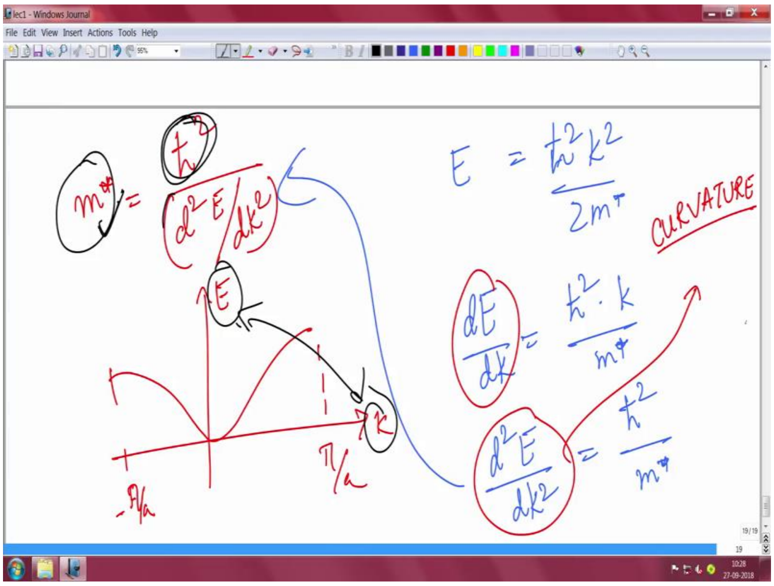

So, another way of looking at it is that if I write $E = \hbar^2k^2/2m$, and then I take a derivative of E with respect to k ok, the slope of E-k diagram then I get $\hbar^2k/m^*$ right that is the derivative. Now, we take another derivative $d^2E/d\,k^2$, what do you get, you get h^2/m^* square by m star.

So, what I can write is if I can write it again here right, I can write

$m^* = \hbar^2 / (d^2E/dk^2)$.

So, what does it mean actually, you know if I take a E and k diagram, and I told you this looks like this for example, this is π/a, this is $-\pi/a$, of course, this line does not exist, this is my testing ok. So, you know dE/dk is basically the slope, but d^2E/dk^2 is called actually what you know it is called curvature it is called curvature of a plot or diagram ok. So, essentially h^2 essentially h^2 which is constant divided by the curvature of the E-k diagram that ratio gives you the effective mass that actually tells you the mass of electron as it moves inside a crystal.

Now, h^2 is constant. So, forget about it. So, basically the mass of an electron as it moves inside a crystal is actually inversely proportional to the curvature of the E-k diagram. So, the energy and momentum has a relation this energy and momentum has a relation. The curvature the inverse of the curvature ok, the inverse of the curvature is proportional to the mass. It may not makes physical sense to you right now. What we will try to see what physically it means. One thing is that this E-k diagram comes from actually a quantum mechanical solution I told you Schrodinger's equation and everything has to be solved to get this exact thing.

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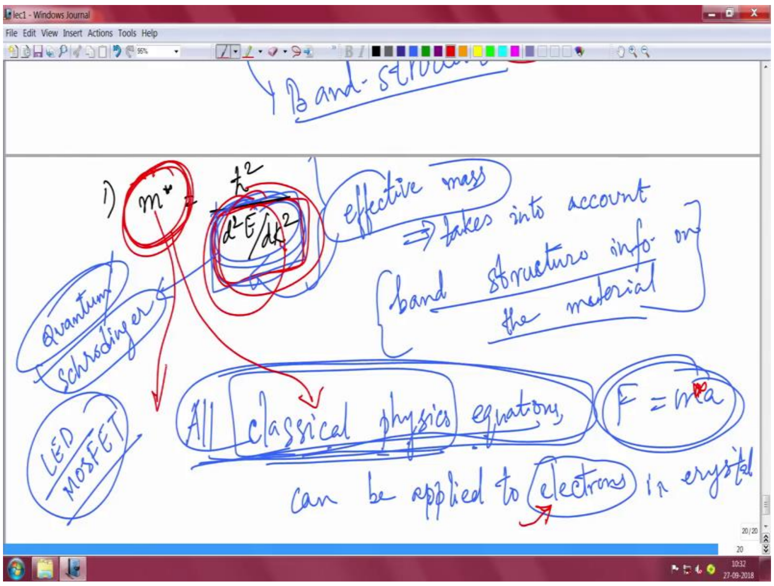

So, the number one thing that is there is that because you define the effective mass as you know $\hbar^2 / (d^2E/dk^2)$.

And I told you that this comes from proper you know quantum mechanics this E-k diagram right, and the Schrodinger solution right Schrodinger solution it comes right that E-k diagram. So, essentially when you define effective mass like that, this effective mass, this effective mass concept takes into account takes into account, what does it take into account, it takes into account the band structure information of the material, the band structure information on the material on the particular material you talking about.

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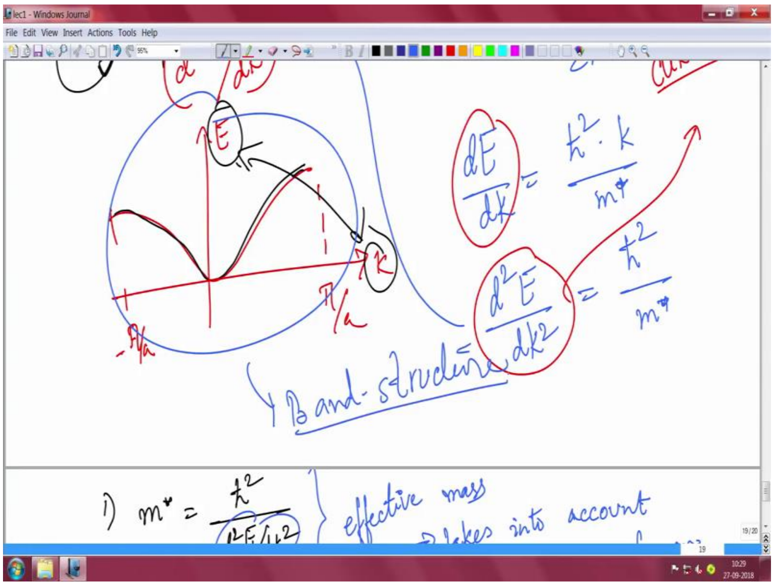

This E-k diagram that I told you that E-k diagram that I have been telling you here. This E-k diagram actually it is sort of a it is actually it is called a band structure this E-k diagram it iself is called band structure. How energy of electron changes its momentum that is actually call band structure. It comes from quantum mechanics. I told you it is very heavy physics. But the entire band structure information is actually condensed and you know crisply put into this d^2E/dk^2 expression.

So, when you have this effective mass defined this way, you do not have to solve any quantum mechanical equation separately. This particular expression of the derivative second derivative of the E-k diagram takes into account entire physics and quantum mechanics that is inside that is inside the band structure. So, what does it mean? It means that all the classical sorry all the classical physics equation all the classical physics equations. For example, you know f-ma hat is the Newton's second law of motion right;

for example, ma=F. All these classical physics equation can be applied now can be applied to electron.

See electron is a subatomic particles, quantum mechanical properties have to be included when we study transport of electron, because electron is a subatomic particle. And you know the Schrodinger's equation has to be inherently used all this becomes highly mathematical. And in day-to-day understanding of your devices, if you understand a LED for example, how an LED works, or how a MOSFET works that makes your transistors you know processors, your Intel everything. If you want to understand all these day-to-day devices, then solving the Schrodinger's equation or doing a quantum mechanical analysis every time becomes tedious. It will need supercomputer and all these things. So, lot of mathematical work.

But if you can apply classical physics equation like f=ma you know thinks like that very simple equation you know then life becomes easier. So, all classical physics equation can be applied two electron, all though ideally you should not be able to apply classical if you try to understand classical physics equation should not be applied or cannot be applied to subatomic particles like electrons, they can only apply to bigger particle microscopic things like a like a table, a chair, a cosco ball a football and all these thing you can apply classical.

But you talk about electrons and you know all this things subatomic particle you should not be able to apply classical physics equation. But because you have taken all the quantum mechanical information in d^2E/dk^2 , we can use classical physics equations to electrons in semiconductor crystal as long as we use as long as we use effective mass effective mass. So, as long as you use effective mass ok, as long as you use effective mass, you are going to include the quantum mechanical information inside this particular term which you do not have to solve or do anything, it will be given ok.

So, as long as you use a effective mass, we are free to use classical physics equation on a subatomic particle like electron and still get fairly accurate results or mathematical understanding of the devices. So, this is one beauty of the E-k diagram that it condenses all the information into this, and then it allows you to use the very simple high school classical physics equation even on particles like electrons that is the beauty of the equation ok. Now, these things you do not have to solve typically this effective mass will be given.

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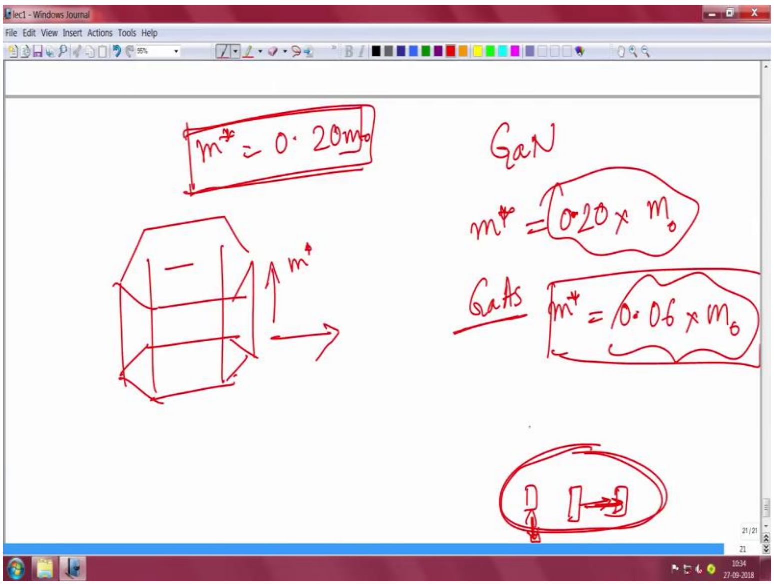

For example, the effective mass of electron inside semiconductor crystal for example gallium nitride is a semiconductor, and effective mass of electron inside the crystal will be 0.2 times the effect the free electron mass. So, it actually lower in a way; it can be higher also. But for example, you know you know you know this in a material like gallium arsenide, it is another semiconductor that is used to make your very high speed transistors, your effective mass of electron will be 0.06 times free electron mass.

So, this particular information this particular information basically captures all the quantum mechanical picture you do not have to bother about it. So, as long as we use $m^*=.20m^o$ for gallium nitrate for example, different materials have different effective masses by the way ok, different materials have different effective masses of electron that is one thing. So, as long as we use these effective masses, you can freely use classical equation to understand the electron transport that is the beauty ok.

Of course, I told you different materials havr different electron effective masses. And another thing is if you take a crystal for example, if I take this hexagonal crystal of gallium nitride right, I keep telling you this if I keep taking this you know crystal then it is possible that whether you are looking at this direction or whether you are looking at this direction your effective mass may change which is what to say the effective mass can be anisotropic.

You have a crystal right. You have a crystal semiconductor crystal, but whether you are looking towards the top you are looking towards the side, your effective mass might be different in different material. It is called anisotropic effective mass. It is not universal. Some materials may not have that property; some materials may have that property. So, what I am saying is if you take a wafer semiconductor wafer like that right, whether you are looking at a transport this way like there is a metal pad here, there is a metal pad here looking at transport this way, or you have a metal pad here and metal on the back side. So, the electron is moving in this direction.

Depending on whether is lateral or vertical effective mass might be different; it is called anisotropic effective mass. We will not consider it here, but it is made even possible that in effective mass might be anisotropic. For example, in silicon you have different direction and you can have different effective masses ok. I was take you telling you here number one thing right. What is the number two thing; the number two thing is that for effective mass ok. The number two thing for effective these are important concepts that is why I am spending time to understand that.

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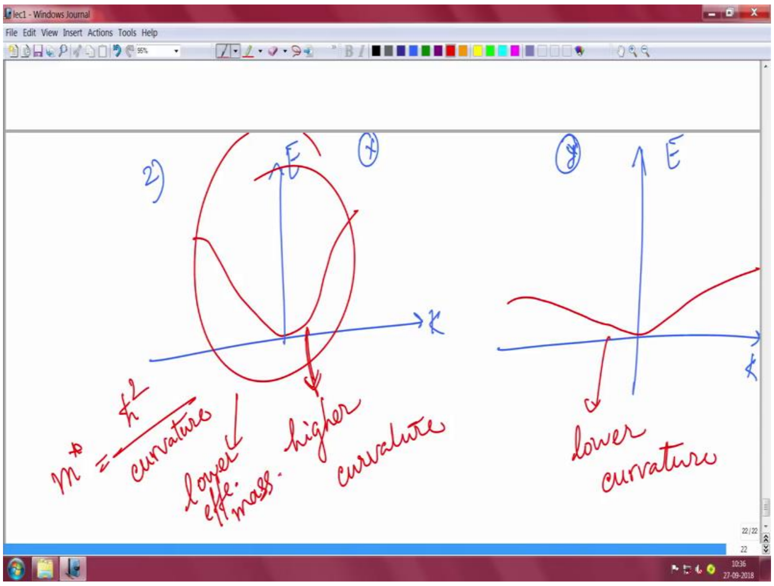

Number two thing I told you that it is it is inversely proportional to curvature. So, suppose I have a material whose E-k diagram whose E-k diagram say looks like this.

And then I have another material E-k diagram. Suppose, this is suppose this is one material semiconductor x, and this is another semiconductor y ok. Now, this E-k diagram here, it looks like this it is also parabola sort of thing, but it looks like that. You can see that this has a higher curvature does not it looks like. It has a higher curvature, because it is curving sharply here. And this is a lower curvature; this is a lower curvature right. I told you the effective mass of electron m* is inversely proportional to the curvature right is inversely proportional to the curvature ok. So, if this as a higher curvature, then this means this material will have a what it is higher curvature know, it will have a lower effective mass ok.

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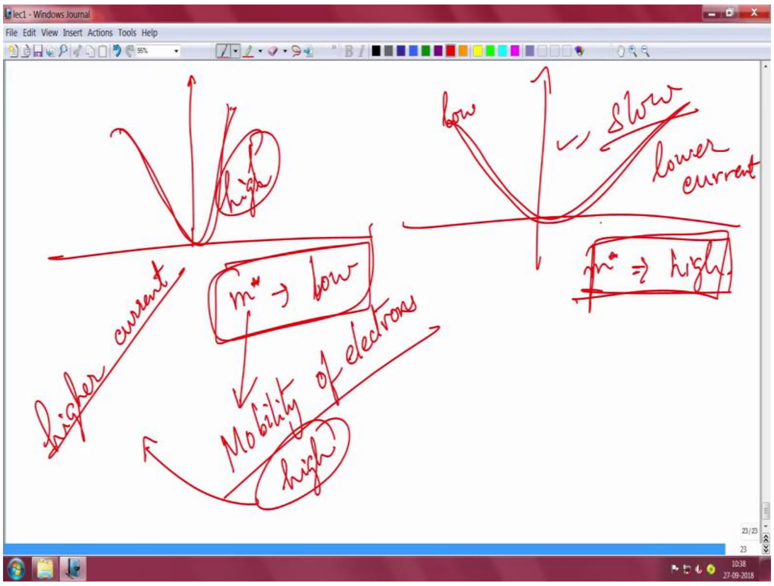

What I am trying to say is that of course, your E-k diagram can keep changing although it will looks almost like parabola, but it is very possible that you know sorry it is very possible that one material has an E-k diagram which looks like this very high curvature. And another E-k diagram has a material which E-k diagram looks like this sorry ok. So, the curvature here is high very high curvature, the curvature here is very low.

So, if you have a higher curvature, then effective mass will be higher curvature will have low effective mass; and lower curvature will have higher effective mass. Now, you may ask so how does this effective mass being higher or lower matter it matters tremendously it matters tremendously in your devices. If your effective mass is low, if your effective mass is low, then there is something called mobility? I will come to that may be few classes later. There is something called mobility of electron there is something called mobility of electron. If your effective mass is low, then mobility of electron is high.

If you have a higher electron mobility, then you get higher current. You get higher current in a device, you get superior transport, you can carry very high current densities very useful for high power, high speed electronics for example so you want a low effective mass material. You do not want a material with high effective mass. So, this E-k diagram actually this E-k diagram actually tells you so many things right. See it has a lower curvature right, because it has a lower curvature it has a high effective mass right and that is why it is this material will basically slow. It will also be carrying lower current it is not a good material right. So, this kind of things can be inferred for making devices from the E-k diagram so that is a very important concept we have learnt.

So, what do we learned so far that electrons move in a periodic crystal and because they move in a periodic crystal their parabola is distorted. And because their parabola is distorted, you have you know this E-k diagram that that basically fragments into different distorted forms.

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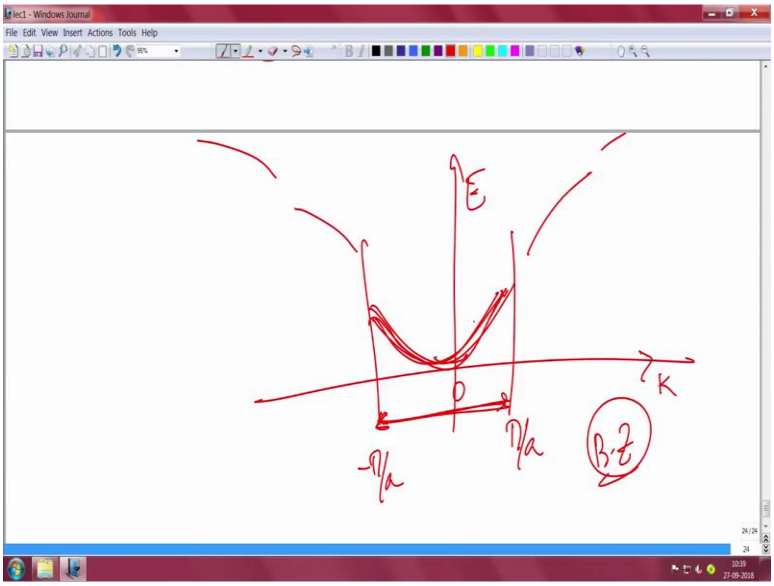

So, you have something like that; then like that right, high order bands keep coming. I said the first look at the first zone here it is called first Brillouin zone between -π/a to π/a. And most of the physics and most of the electron transport will consider only this band.

So, we called as the first Brillouin zone B-Z Brillouin zone we first considered the first Brillouin zone. And we confine ourselves to the discussions here ok.

There are many things associated with a periodic potential, how to solve the Schrodinger equation, and the periodicity of the potential also helps solving the Schrodinger's equation by putting some boundary conditions there are things like block oscillation, block equation like this because of this periodicity that comes there you know you can you can put the some boundary conditions there.

We have not you know covered those these are not very essential from this course point of view, we have this course is actually does not need a prerequisite. So, we cannot going too much details here, but you know the first zone basically will be enough ok, the first zone will be enough to understand all the physics all the devices that we will talk about in the course.

So, I told you the curvature of this zone E-k diagram very importantly basically capture the effective mass of the electron, and it is not exactly a parabola. It is slightly it is not a parabola, but close to 0, it still a parabola and the effective mass can be derived from the second derivative, so that we know and the effective mass is huge role to play in how you device the devices you know design the devices. So, that is very important. And I told you the effective mass can be different in different directions in the same crystal in some materials right.

Effective mass values typically it is a lowered and the free electron mass and space. It can also be a higher in certain materials it is all depend on the crystal structure in a way right. So, this is quiet essentially about the E-k diagram was. And now going ahead we shall introduce a very fundamental concept actually, the very fundamental see we were talking about electrons right.

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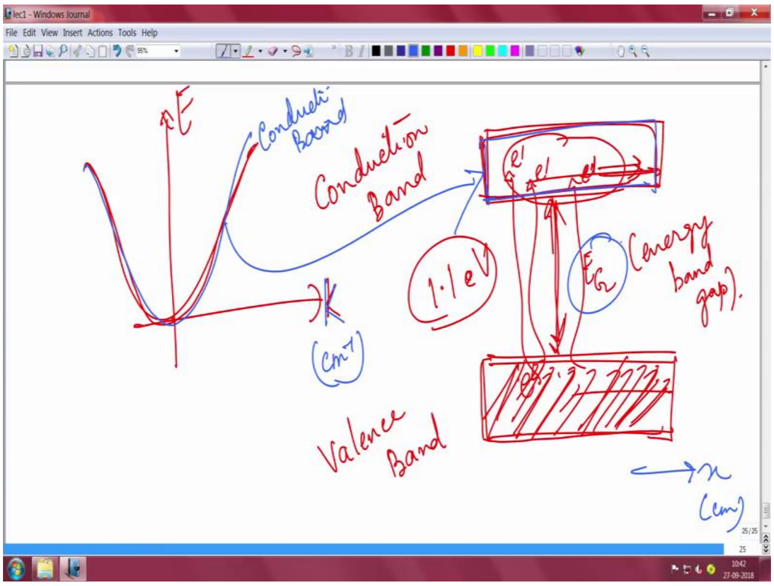

We are talking about electrons. Remember this is E-k diagram, but I will if I talk a realistic diagram I told you in the last lecture you know there is a conduction band here which is nearly empty if you recall and then there is a valence band here. I told you how bands are form a free if you recall you remember how bands are formed do you remember how bands are formed. These bands are formed when discrete energy levels of atoms they split into continuum of many, many discrete levels when you bring the atoms close together.

And eventually when you have large number of atoms coming close together to each other to form a crystal, then this discrete energy levels will form into a band ok. It looks like a band. And this band is completely filled with electrons. This is mostly empty of electrons, but there is a gap here between them two it is called the energy band gap we denote it with E_G right, and then this is called energy band gap. It is a fundamental material property of every semiconductor. Every semiconductor has a band gap. This band gap it is gap between this two can have values that you can range from 0.1 eV or even lower to even up to 6 eV.

The lot of range of band gaps available, but typically semiconductor like silicon have a range of say one point as a value of 1.1 e V right, 1.1 electron volt is a energy separation between the fully field conduction valence band and the empty conduction band. You can actually excite this is filled with electrons. You can actually excite electrons from here to here to here you can put, and this electrons are now free to move because this band is empty. So, energy states are empty.

When the energy states are empty, electrons can easily move if it is packed here, then electrons cannot move right. If it is packed with electrons, then how can they move they cannot, but here this is empty? So, if you can excite electrons from here, then the electrons can move and that is how they can carry current. And this electron movement in the conduction band was what actually we had described in the E-k diagram right, the E-k diagram and I am not a very good drawing person, but this is E-k diagram it is a it is you know.

And this E-k diagram this particular energy that I had drawn this band you know what this band actually is a conduction band ok, is actually the conduction band, is actually the conduction band which is this. This is in real space the x-axis is distance in centimeter ok. This is in reciprocal space x-axis is k momentum which is cm^{-1} you can say right, this is centimeter meter. So, this is real space. This is conduction band right. And this is actually what I had drawn here. This E-k diagram actually replace the conduction band in the K space which in real space the straight line here of course, right. So, that is actually how you relate it.

This energy band gap by the way changes with temperature it is very strongly depend on temperature. Now, if you increase the temperature, decrease the temperature, this will shrink or become you know large and so on. Now, the most important thing that I will introduce very quickly and as you going to the next lecture now we will stop and we will going to the next lecture, but the next lecture we will discuss about what happens when electron goes from the conduction band the valence band which is fully filled goes from the valence band to the conduction band where it can carry current.

When it goes what it what does it leave behind it leaves behind a hole, electron has gone to conduction bands so it leave behind a hole. So, that concept will introduce in the next lecture after this. And from there we will take forward to the statistics and how electrons and holes are distributed in the bands, and then we are ready to understand devices ok. So, here we end the class.