Physics of Nanoscale Devices
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Lecture - 02
Introduction and Course Overview

Hello everyone. Welcome to this 2nd lecture on the Physics of Nanoscale Devices. In this lecture we will continue talking about the basics or the introduction of this course and I will also try to give an overview of the entire course or the ideas or the concepts that we will cover in this course.

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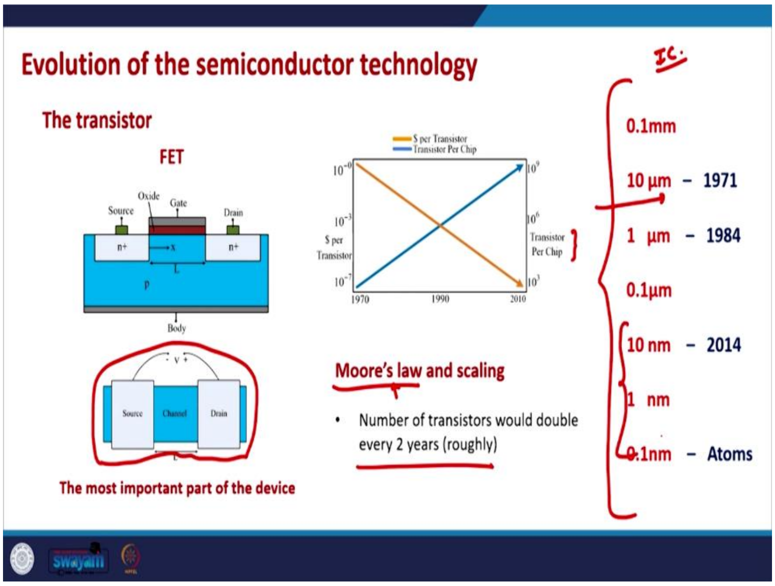

So, as you might recall that this the semiconductor technology is one of the most I would say rapidly progressing technologies around the world and it is actually driving other technologies other fields as well. For example, the revolution in computing technology even revolution in mechanical engineering or revolution in civil engineering or the development of various other engineering disciplines is also being supplemented by the progress in the electronics industry.

And the progress of electronics technologies or electronics industry actually depends essentially depends on the size of the transistor, size of the active region of the transistor and that is captured by the Moore's law. And Moore's law is an empirical sort of observation was an observation by Moore seeing the trends in industry and it says that that the number of transistors per chip will double almost every 2 years and as a consequence of that the cost per transistor will go down.

So, this is roughly the channel length of the transistor since last 40 50 years now. So, in 1970s when this integration of transistors started when the IC technology was getting used was being used or was getting refined and it was used at that time the size of the transistors was in tens of micrometers since last 5 6 years the transistors are in nanometer regime.

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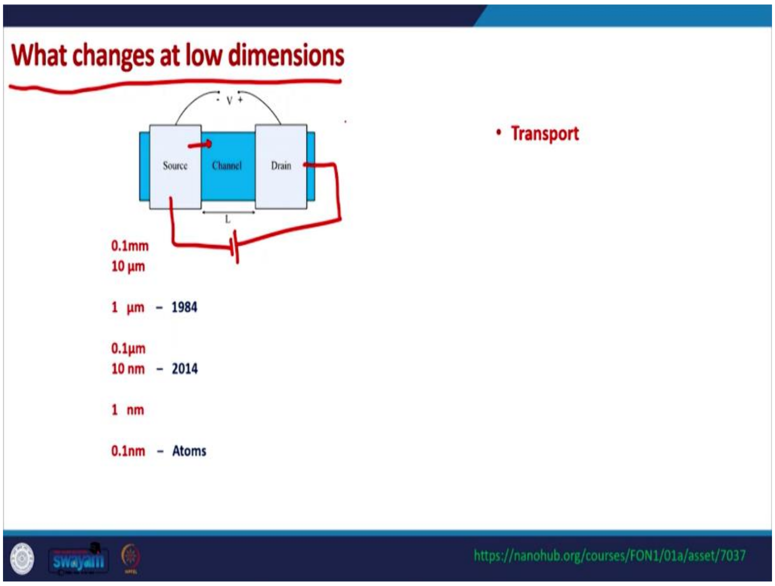

And as a consequence of that the physics or we are facing new questions about the physics of electrons in the transistors ok. And that is the subject matter of this course and as you might recall from the last class that the first question that we sort of pose in this course is what changes at the low dimensions ok.

So, we first look at the electron transport in the device, electron transport means how electrons that start from the left side from the source region. So, generally in transistor we the source there is a battery between the source and the drain .The drain is at high voltage source is at the low voltage. And as a consequence of that the current flows from drain to source the electrons flow from source to drain.

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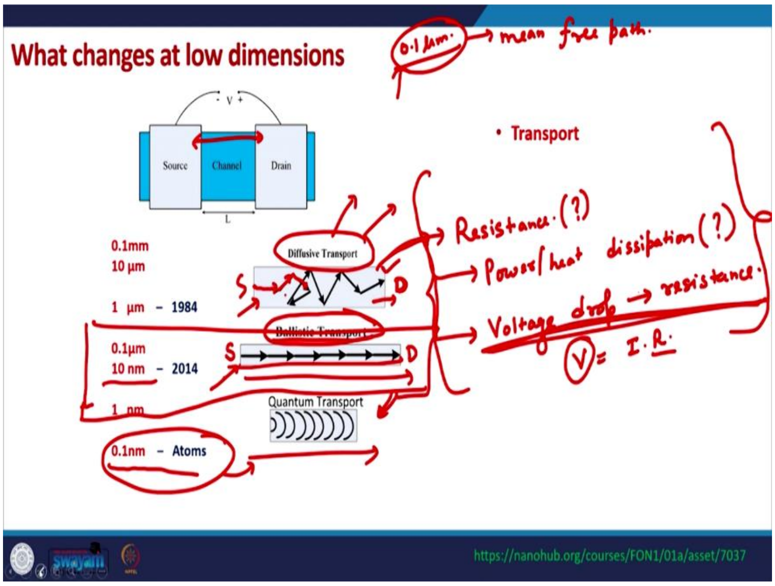

So, when the electrons go from source to drain and the size of the channel is few tens of nanometers in that case what happens is the transport of electron is something like this it starts from the source end it collides with many atoms in between ok. And because of these collisions the path of the electron is as zig zag or very random kind of path and the electrons by the time the electron reaches to the drain side this is the source side to the drain side it has already sort of undergone many collisions.

And that is essentially responsible for the or that is the conventional picture of the resistance that the resistance is because of the collisions in the channel and with resistance the power dissipation or the heat dissipation is also because of this. And even the voltage drop is closely related to the resistance the idea of resistance because according to the Ohm’s law V is equal to I times R. So, with resistance R the voltage drop is also can be also calculated ok.

So, but now the question is what happens to the transport at as we go to tens of nanometers. And generally as is as I also told you in the last class that the average distance between two collisions is around 0.1 micrometer in a typical semiconductor although it depends on the material it also depends on the doping or many other factors, but it is typically in this range.

But if the device length or the channel length is less than the mean free path please remember that this is the mean free path of electrons. If the channel length is lesser than the mean free path in that case the transport might is no longer like this, the transport may happen like this as well. And what does this mean that now the electron starts from the source it does not collide with anything in the channel and it directly goes to the drain side this transport is known as the ballistic transport.

Ballistic essentially means like bullet like transport or without any collision in the channel directly from the source to the drain. The transport where the electron undergoes many collisions in the channel or the transport that happens in the bulk devices is known as the diffusive transport.

But in many modern day devices the transport is no longer diffusive transport it is either ballistic transport, if the transistor is very small or it is on the boundary of the ballistic and diffusive transport which means that the electron might undergo some collisions, but it is not undergoing lot of collisions and things are not averaging out as they were averaging out in the case of diffusive transport.

So, the transport is changing fundamentally as the device size is getting small and smaller as the transistor is getting scaled. And with this now new questions arise the questions are. What would be the resistance in this case? So, the resistance in diffusive transport case were because of the collisions in the channel, but what could be the resistance in the ballistic transport that is an important question that we need to ask so, what is the resistance?

Second question second follow up question is, what is the power dissipation heat dissipation in ballistic transport? If the electron is not colliding with anything in the channel where is actually power getting dissipated or where is the heat getting dissipated is it at all getting dissipated or its or what is happening in this kind of transport?

And on the similar lines what is the voltage drop across the device or what is the resistance of the channel? And these questions cannot be answered from our conventional understanding of the transport from our conventional diffusive transport kind of understanding of the resistance.

Because in that case the resistance was because of the collisions in the channel that is also contributing to heat dissipation or power dissipation and also the voltage drop, but now none of that is happening and we need to fundamentally ask this question in a different way ok.

So, that is why this course is there that is essentially the subject matter of this course we are we would try to ask these basic questions. What is the resistance? What is the power drop? What is the heat dissipation? What is the voltage drop in nanoscale or in the mesoscopic devices where the channel length is few tens of nanometers? ok.

So, if one goes even further if we are sort of we are we scale down thinks even more in that case what happens is or on the exactly atomic dimensions the transport is not ballistic transport as well it is a quantum transport there the wave nature of the electron is quite explicit.

So, at these dimensions where we are dealing with where we deal with individual atoms we need to deal with the electron waves electron wave functions. So, this course is mostly going to be about the transport in the practical devices nowadays so, this course is mostly going to be about the ballistic transport. Towards the end we will also touch upon the quantum transport aspect.

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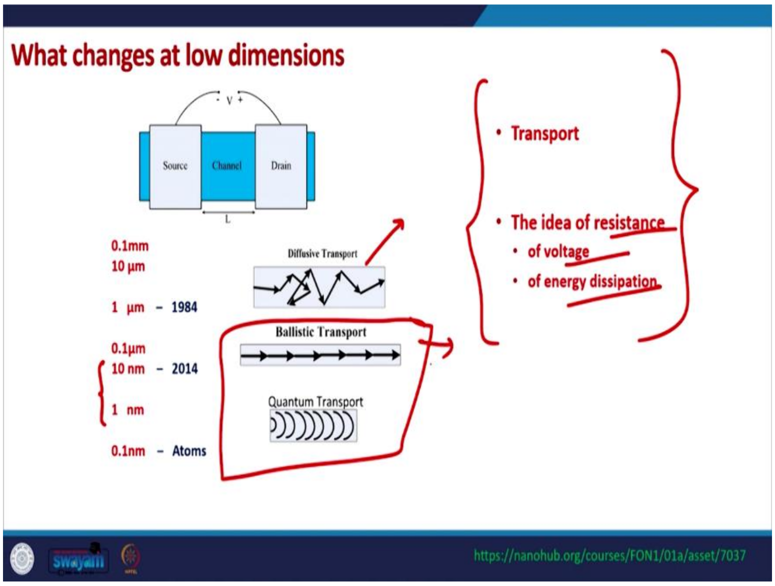

And with this you might have also by now I would say guessed that this is also putting a fundamental limitation to the scaling or fundamental limitation to the Moore's law. Because according to the Moore's law transistors are to double are to sort of the channel length or the transistors are to the number of transistors per unit chip should double every around 2 years for that we need to make transistor small and smaller.

But nowadays we are approaching these dimensions, we are operating around 5 nanometer node and it is extremely difficult to scaling down further and that is essentially posing a great challenge to the continuity of the Moore's law. And that is so, this is the subject matter of the course we will study how the basic ideas of electronics engineering.

The basic ideas for example, the idea of resistance the voltage the energy dissipation power dissipation change at mesoscopic scale ok. And for that we need to contrast or first we need to sort of have a look or we need to contrast the idea of resistance and diffusive transport level to the idea of resistance and the ballistic transport level ok.

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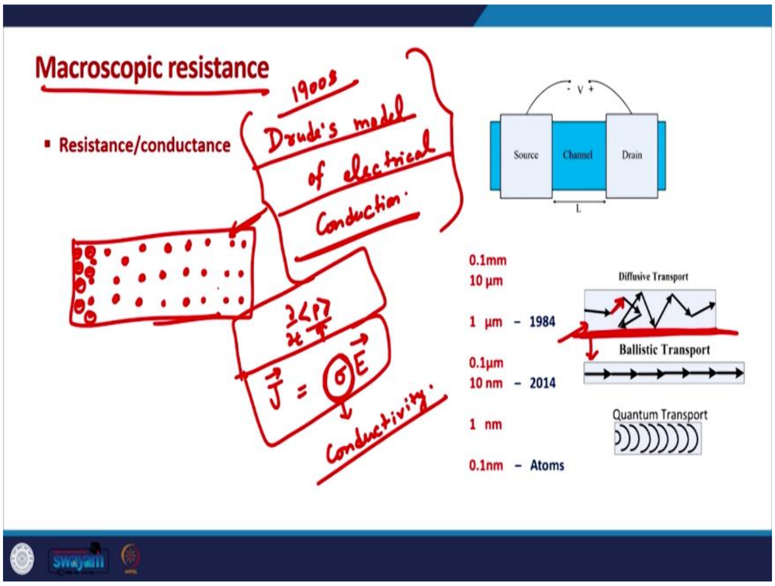

So, the idea of macroscopic resistance or the resistance in diffusive transport this idea is largely due to the Drude's model of electrical conductivity Drude's model of electrical conduction. So, this model of electric electron transport or electron electrical conduction was given by Drude in 1900, exactly 1900 actually and just to sort of put things in perspective that is that was the time when the electron was discovered electron was already discovered, but the structure of the atom was not well known ok.

So, it was the time when the structure of the atom was not known you can forget about quantum mechanics or those things that was quite far away. So, it was the time it was during this time when this electrical conduction model by Drude was given and that is that essentially is the conventional that is where this conventional understanding of the conduction or transport or resistance actually comes up in our minds.

So, this model was essentially inspired from the kinetic theory of the gases where the gas or the gas atoms were identical particles indistinguishable on the identical particles. In this model of Drude it was assumed that we have lot of electrons a sea of electrons so, to say in metals particularly in conductors and we have static charges.

So, in a conductor generally we have the static charges and we have lot of mobile electrons. The exact structure of the atom was not known nothing was very clear, but typically the typical understanding was that we had lot of electrons. So, lot of negative charge carriers are there that can move around in the device in a system in a conductor and the these static atoms are there.

So, when they when the electrons move around in the in this in the material what happens is that they collide with these atoms and the transport is like the diffusive transport say. So, the electron collides with something it gets deflected sometimes the energy may change the momentum may change ok.

So, that way and from there Drude essentially from this model there the two main results actually came up one was about the rate of change of or rate of change of average momentum of the electron $\left[\frac{\partial <p>}{\partial t}\right]$. This p here is the or average p is the average momentum of the electron and the second result was the relationship between the current density and the electric field essentially and they were related to each other by a parameter known as conductivity.

So, the current per unit area in a material or current density is directly proportional to the electric field and the constant of proportionality is the conductivity of the material $\left[J = \sigma\vec{E}\right]$. So, that is essentially the conventional understanding of the conduction or transport. And this was actually quite appropriate for electron conduction in metals where there are.

In fact, a large number of electrons and there are static atoms and it is also it to an extent it also gives decent result about bulk semiconductors where are where we have lot of electrons in the conduction band or lot of holes in the valance band and in that case also these things are alright. And this idea is essentially based on the collision of the electrons with the atoms in the pathway.

But as soon as we reach to this ballistic limit or the limit where the electron does not collide with anything in the channel this idea or the foundation of this idea is no longer true and that is why the results are also no longer true ok.

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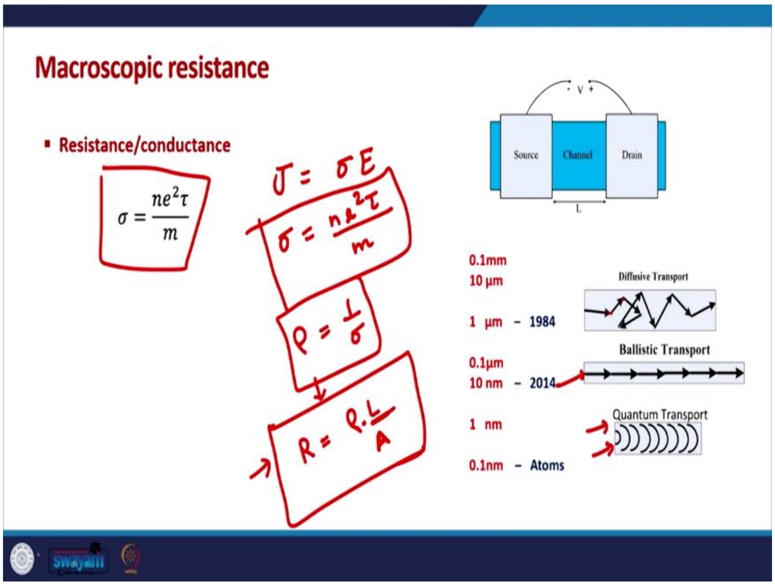

So, the Drude's model says that the conductivity of the material is this the relation or the current density is directly proportional to electric field and this constant of proportionality is the conductivity which is given as ne square tau by m where m is the mass of the electron tau is the average time between two collisions that the electron undergoes n is the number of electrons e is the charge $\left[\sigma = \frac{ne^2\tau}{m}\right]$.

So, this pretty much explains the conductivity and from the conductivity we have the parameter resistivity which is essentially the inverse of the conductivity $\rho = \frac{1}{\sigma}$ and from resistivity we can reduce the resistance of the of a conductor. So, for a 3D conductor the resistance is given as the resistivity times the length of the length of the conductor divided by the area of the cross section of the conductor $R = \frac{\rho L}{A}$.

This is the conventional classical understanding of the electron conduction in the materials ok. But the foundation or the foundational axiom is no longer true in the case of ballistic transport or in the case of quantum transport things are entirely different. Now we the electrons can no longer be treated as balls they can no longer be treated as particles we need to take into account the wave nature of the electrons. Even the ballistic transport will also borrow a lot from the quantum mechanics ok.

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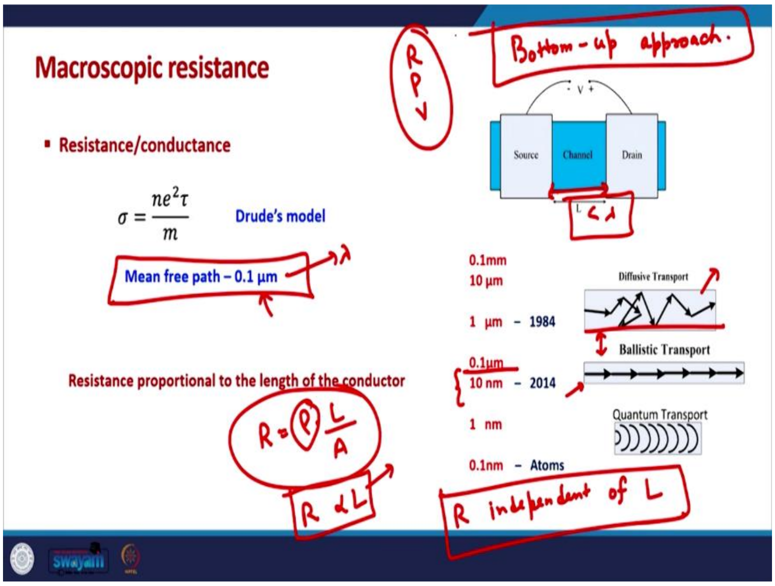

So, the mean free path is 0.1 micrometer as we saw and for the devices that are below the mean free path it is quite possible that the electron will not collide with anything in the channel and then this the transport becomes the ballistic transport specially below these when the channel length L is smaller than the mean free path when L is smaller than the mean free path this mean free path is represented as lambda ok.

So, according to this conventional understanding of or the Drude's understanding of conduction resistances resistivity times length divided by area and this resistivity is a material parameter it depends on the mean free time or the time the mean time between two collisions. And as is clear from this expression the resistance is directly proportional to the length ok, but what we will see in this course is that for ballistic transport this is no longer true actually.

The resistance is for ballistic conductor resistance is independent of the independent of length ok and that is an; that is an very interesting and very fundamentally different result. So, in the nutshell what we can say is that our conventional understanding of conduction comes from the this picture of transport which is essentially electrons colliding with intermediate atoms, but in our modern day devices this is no longer valid.

So, we need to think fundamentally in a fundamental different way. So, in this course we will build from the basics we will start from the bottom so, to say we will start from the fundamental physics ideas and go to the top. So, we will start with the basic physics ideas and try to see what is the resistance in the device what is or where is the power dissipation where is the voltage drop. So, that is why this approach is can be called as bottom up approach ok.

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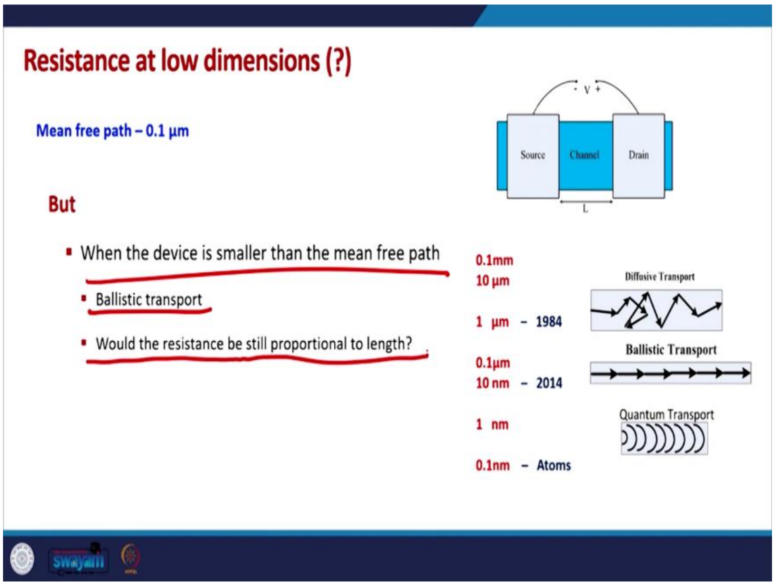

And if we if just to have a glimpse of this when the device is smaller than the mean free path in that case the ballistic transport we are in the ballistic regime and now the question arises would the resistance still be proportional to the length and the answer is in negative.

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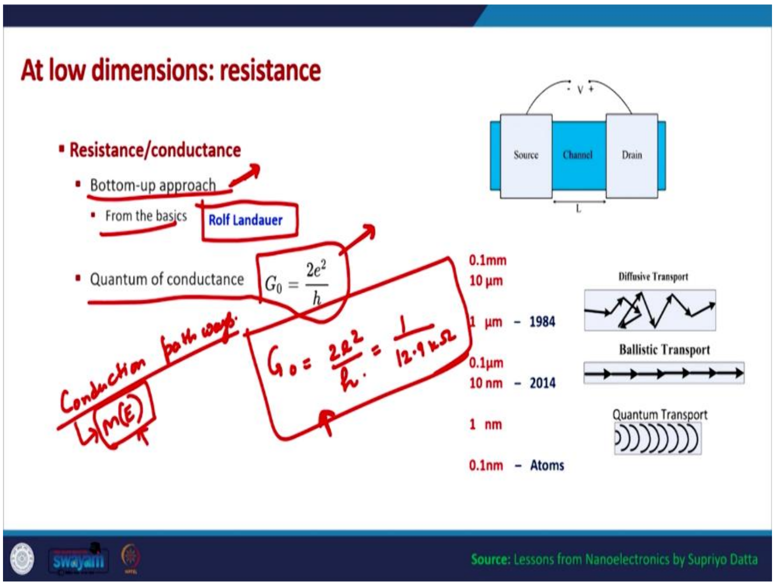

So, from so, in this course we take what is known as the bottom up approach and this basically builds from the basics and this is largely because of the Rolf Landauer because he was the first person who after the invention of or after the discovery of quantum mechanics who essentially started on this thing.

So, later on this was this field was developed by many pioneers and in recent times professor Supriyo Datta and professor Markland Strom are the ones who have given a good formalism or who have given a detailed description of the this bottom up approach in their works ok and this course part of this course borrows from their understanding or their approach ok.

So, according to this bottom up approach we have what is known as the quantum of conductance. And this is given by this G naught is equal to 2 e square by h $\left[G = \frac{2e^2}{h}\right]$ or in or roughly this is around 1 divided by 12.9 kilo ohms. So, that is the conductance of a ballistic conductor when it has one conduction pathway in it.

And this is the fundamental sort of or this is or the conductance of a single conduction pathway is given by this value it is it cannot be less than that it cannot be it or if there are more number of pathways then that this conductance can change. But for a ballistic conductor if the electron is having only one path way in the device that is given by then that the conductance of that pathway is given by this value and this is known as the quantum of conductance.

And along with this we encounter a new idea the idea of conduction pathways. So, we will see these things in greater detail along the course, but just to have a glimpse of the material in this course this new idea of conduction path ways which means this which is also known as number of modes in a device this idea comes up when we do things from in a bottom up way ok.

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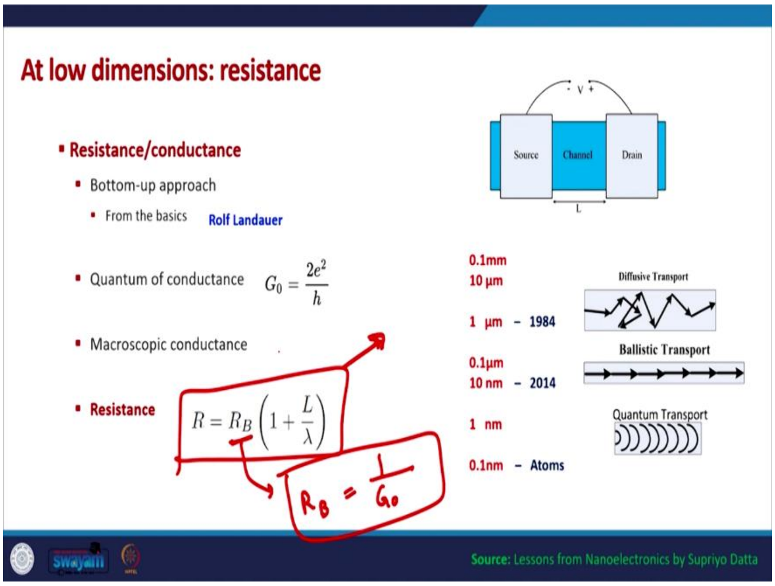

So, building with this the macroscopic resistance can be calculated and the total resistance can be given by this way this expression ok. So, where R_B is the ballistic resistance and it is essentially for a single mode it is 0. So, for a long conductor also we can deduce the resistance and for a ballistic conductor.

So, in total this in general the resistance can be given by in this formula this we will see in greater detail in this course ok.

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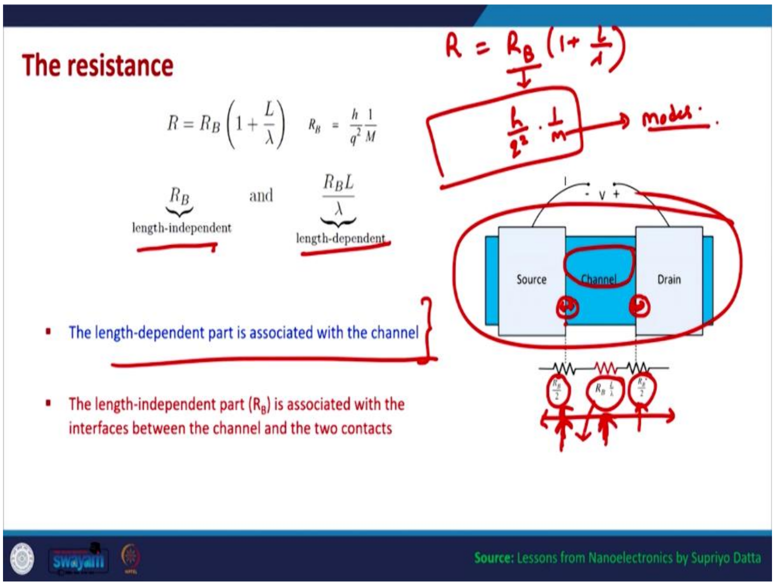

So, this the general resistances R is equal to R_B 1 plus L by lambda $\left[R = \left(1+\frac{L}{\lambda}\right)\right]$ just to sort of have a glimpse on of what how the resistance looks like if we deal with or if we do analysis using bottom up approach. This R_B is the ballistic resistance it is given by h by q square times 1 by m and where m is the number of modes $\left[R_B = \frac{h}{q^2}\frac{1}{M}\right]$.

So, essentially any resistance has two parts one is this R_B which is the length independent part and second is the length dependent part and this length independent part that comes actually this is what we will see later on in this course that this length independent part comes because of the contacts of the channel with the source and the drain.

So, this the resistance of the entire channel can be divided in two components one is the resistance of just of the channel part and the resistance because of the this interface because of the interface with the contacts because of the channel contact with the source and the channel contact with the drain.

Generally, in diffusive transport in our conventional conductors this part dominates. So, this is this becomes negligible as compared to this and that is why this thing is not actually counted. But if we do physics in a bottom up approach using from basic using basic principle of physics we realize that the resistance of this entire device entire two terminal device the active region of the transistor can be written as the sum of or length independent part and a length dependent part ok.

So, as I said this length dependent part is associated with channel and when the channel is ballistic in that case this is this part is not there. So, the only resistance that is there in a in a ballistic conductor is the resistance or the length independent resistor or the resistance because of the interface between the channel and the source and the channel and the drain ok.

And this thing is actually quite nontrivial if we look from the from our conventional understanding of electrical conduction, but this things comes up this these things or these ideas comes up naturally when we do or when we start from the basic physics of the devices as we will see during the course coming course ok.

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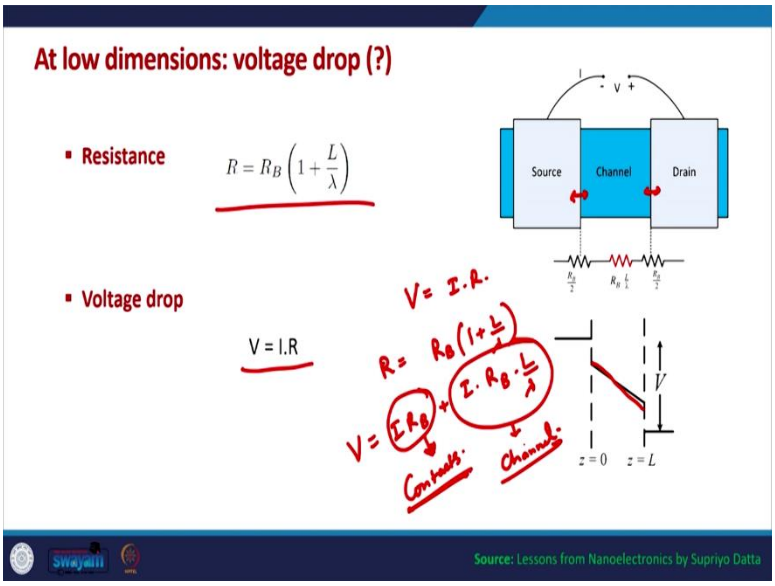

So, as a consequence of this the resistance is fundamentally different than the resistance according to the Drude's model and as a consequence of this the voltage drop is also fundamentally different. So, there is a voltage drop associated with the interface as well and there is a voltage drop associated with the length as well ok. Because the voltage drop is given as I times R and current is constant store the device.

So, if R is R_B times 1 plus L by lambda in that case this voltage drop will also be I times R_B plus I time R_B L by lambda $\left[V = I.R_B + I.R_B.\frac{L}{\lambda}\right]$. So, this part of voltage drop this happens at the contacts and this part of the voltage drop happens in the channel. So, half of this takes place half of this voltage drop happens on the source contact and half of this happens on the drain contact. So, as you can see that the contacts are extremely crucial in especially in the ballistic transport or nanoscale devices.

Similarly, the power dissipation can also be divided in two parts; one is because of the this length independent resistance and one is because of the length dependent resistance and in ballistic conductor since this resistance is not there. So, the only resistance that is there is this R B resistance that is the contact resistance.

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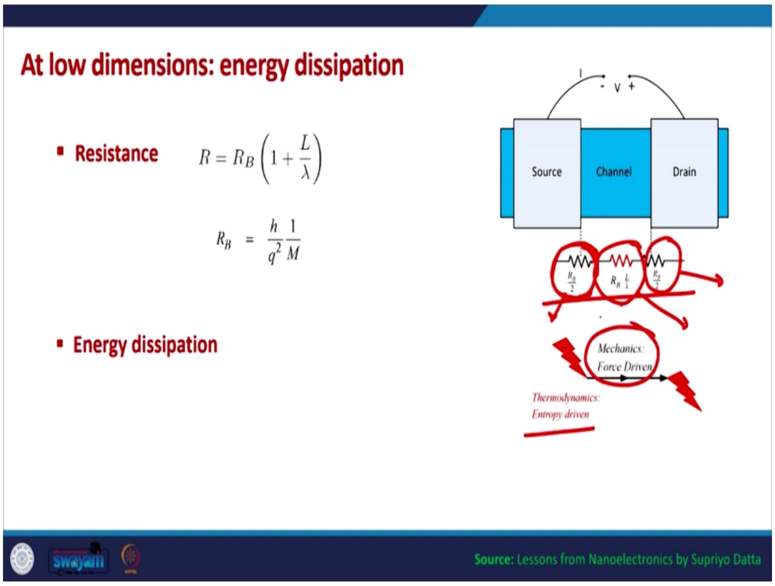

So, the entire voltage drop happens at the contacts or the entire power dissipation happens at the contacts in a ballistic resistor in a ballistic conductor. So, as you can see that things are quite different. So, we need to sort of think entirely differently in the case of in this course ok.

And that is the background that I am trying to sort of build here and this contact the power dissipation at the contact is governed by the thermodynamics of the system and in the channel it is essentially the force driven mechanics because of the; because of the gradient in the Fermi level that we will see later actually.

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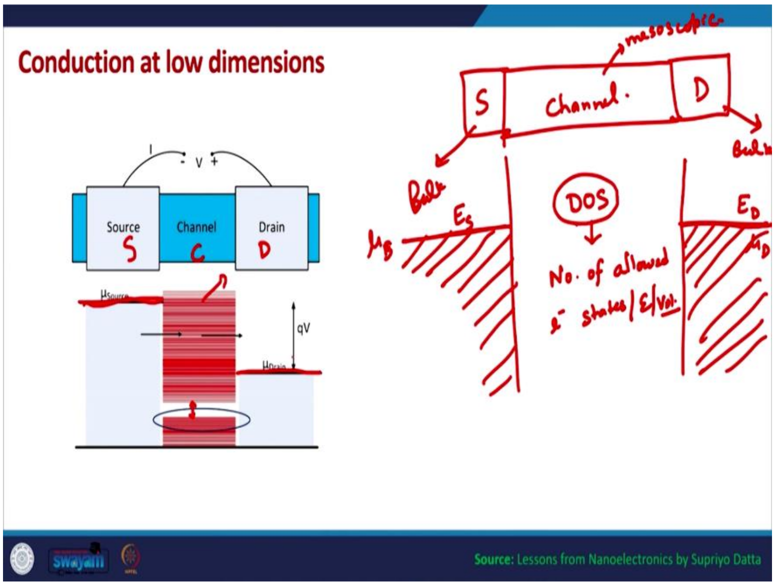

So, finally, at low dimensions this is the picture that we need to we would need to think in terms of in a two terminal device when we have a source, we have a drain and we have a channel region in that device what we have is generally the channel region is extremely small although that is; although that is not obvious from this diagram, but the channel is a mesoscopic channel and the contacts are bulk ok.

So, for the channel we need to we might have discrete energy levels because of the quantum mechanical nature of electrons. So, we need to find the density of states in the channel and we need to see the Fermi levels of the μ_F or sorry μ_S source Fermi level or E_S similarly here E_D or μ_D. The Fermi level is the level below which all energy states are occupied specially at room temperatures and in metals it is the level below which all the electronic states are occupied by the electrons.

The since the channel is small so, we need to see how many so, we need to see or we need to deal with this idea of the density of states which essentially is the number of allowed electronic states per unit energy per unit volume of the material per unit volume in case of 3D material per unit area in case of 2D material and per unit length in case of 1D material ok.

So, this is what we need to see in the in our formalism we first need to understand the density of states of the channel we need to understand the Fermi levels. So, essentially we need to play with the energy levels of the electrons in this entire device and this is typically the picture we have the source Fermi level here and if we apply a voltage on the drain side the drain Fermi level might go down.

In between there might be certain electronic states in the channel and there might be certain energy ranges where there is no electronic state in the channel ok. So, this is typically the picture that we need to deal with while understanding the conduction at low dimensions ok.

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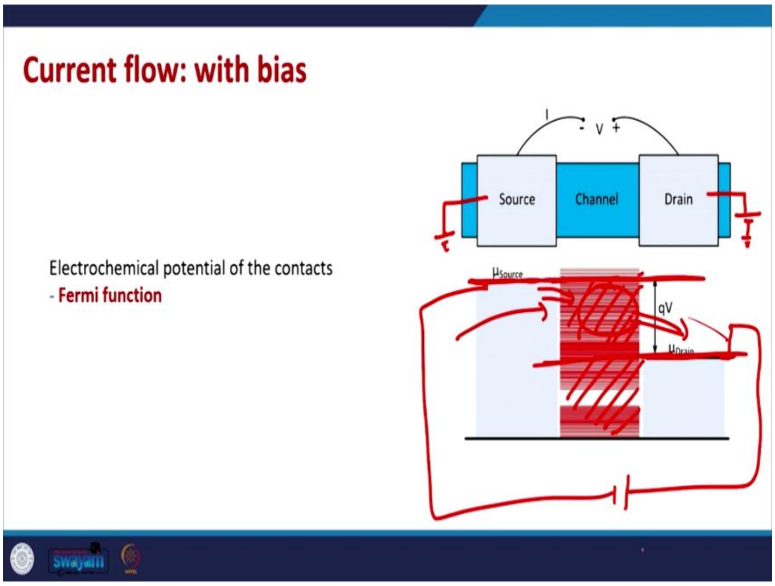

So, we need to see how electrons are distributed in the channel and we need to see how electrons are there in the source and the drain. So, when we apply any voltage for example, in the device for example, on the drain side if we apply a battery if we put a battery here and it is grounded in that case this drain Fermi level goes below source Fermi level is up to this point drain is up to this point.

So, what happens is because of the thermodynamics because of the electron diffusion the source side tries to fill all the electronic states in the channel up to this point. So, it keeps on supplying electrons to the channel until all the states in the channel are filled up to this level.

Similarly, the drain contact will try to fill all the electronic states in the channel up to this point, which means that it will try to fill all these states below the drain Fermi level, but it will also try to empty the states above the drain Fermi level. So, what happens is when the voltage is applied the source is trying to fill these states and the drain is trying to push or trying to sort of take electrons out of these states and that is how a flow of electron is maintained in this system.

Source is continuously giving electron drain is continuously tanking out electron and externally we have a battery through which electrons are getting recirculated in the system ok. So, this is the picture of conduction and when we deal with or specially at low dimensions when we deal with devices of very small sizes.

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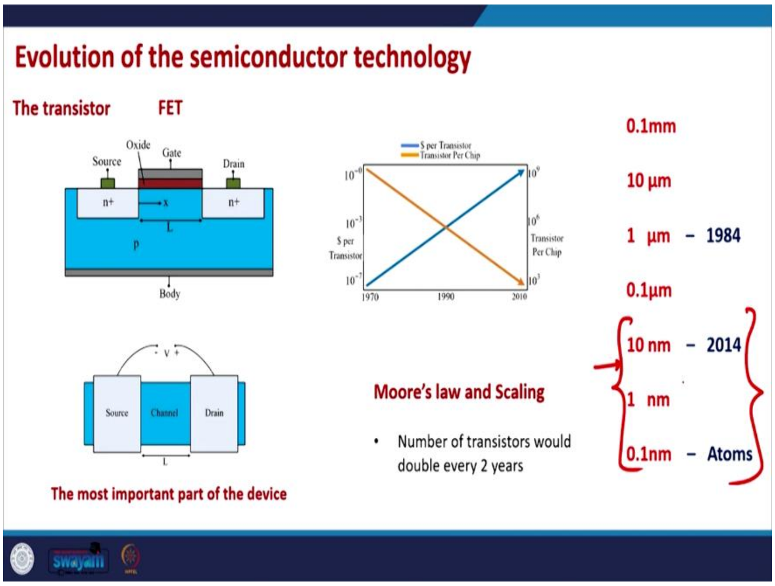

So, finally, this the semi conductor technology is now at a point where we need to deal with the basic physics of the electrons and of the device and after 1920s and 1930s especially after the discovery of quantum mechanics the understanding of electrons and understanding of solid state systems have improved a lot. And that is if we need to understand all this if we need to understand the transistor physics at these scales we need to start from there we need to start with the basics of the quantum mechanics.

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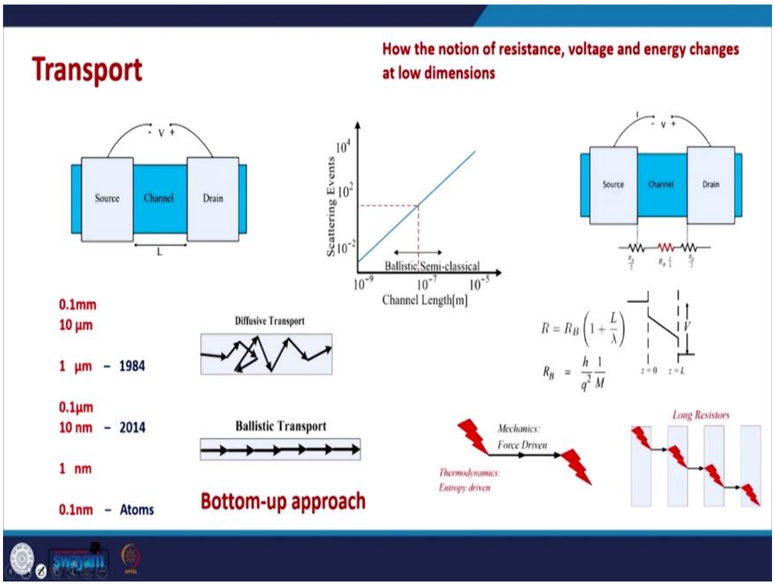

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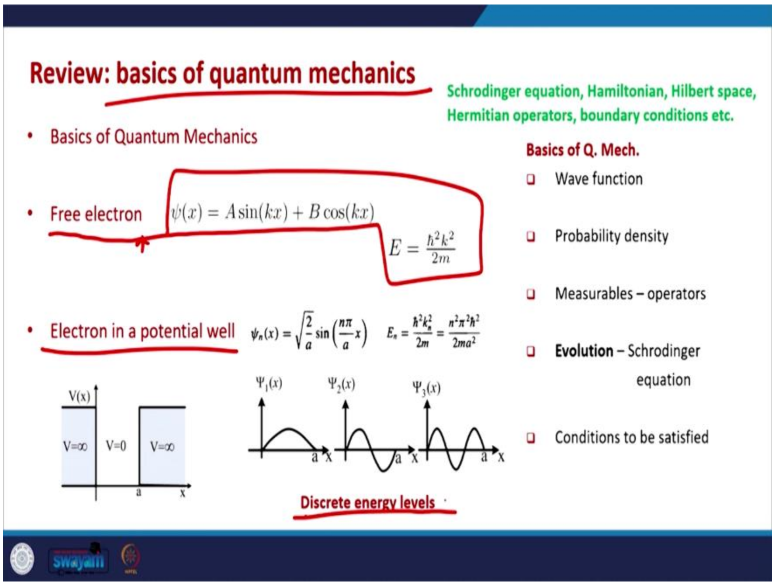

So, that is what essentially we will do in this course in order to understand the transport we will first start with the basics of the quantum mechanics. So, I am not going to go into the details here, I am just giving an overview of the entire course. So, first we will start with the basics of quantum mechanics where first we will see how a free electron behaves.

So, essentially all these electronic devices are about the behavior of electrons in a solid system in a solid state system ok. So, first we will start with the behavior of electron in free space then we will see how electrons behave when the electron is confined and the key result here is that as soon as the electron is confined we obtain discrete energy levels.

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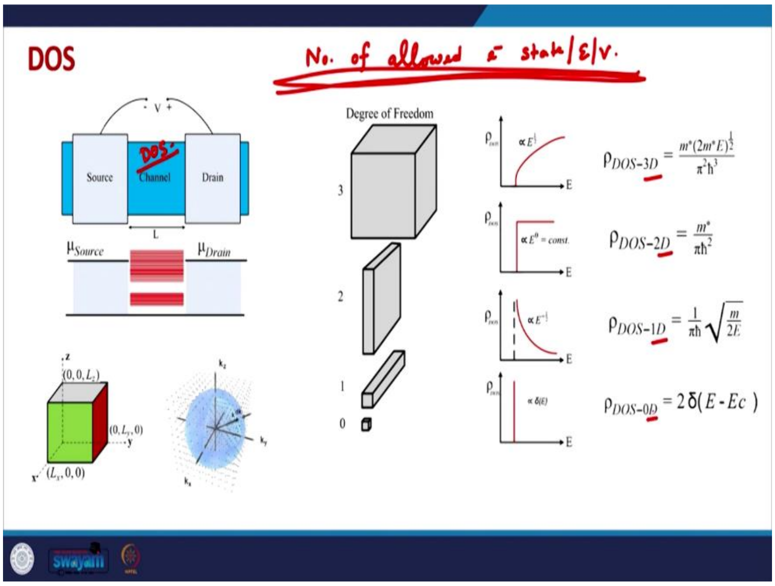

So, from here we will see or we will try to see how electrons behave in solids using K-P model and after that we will study in this course we will study the density of states which is essentially the number of allowed electronic state per unit energy per unit volume. So, that tells us about how many electronic states are there in a system.

So, we try to find out the density of state of the channel that will tell us about the how many that that will tell us about how many electrons can be there in the channel at certain energy. So, we will study the density of states for 3D materials for 2D materials for 1D material and even for 0D materials because these channel can be either 3D 2D 1D or 0D ok.

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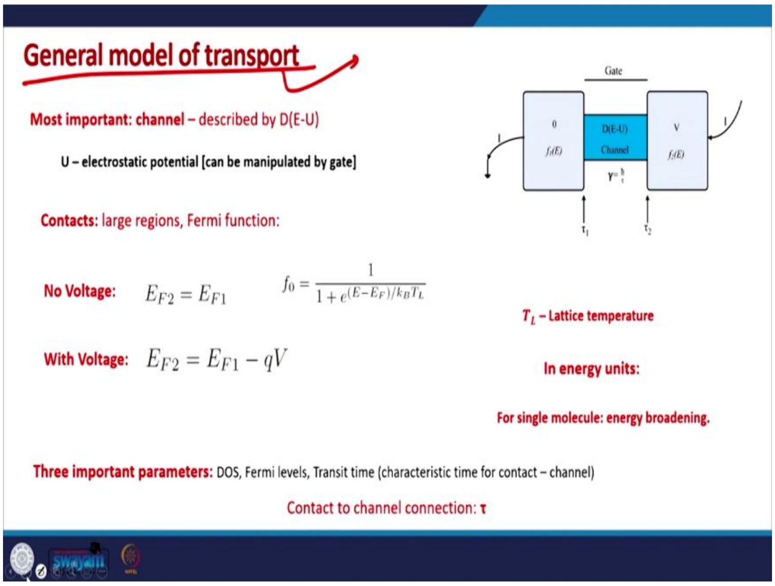

After studying the density of states we will then go to study the general model of transport. So, instead of understanding electrical conduction from a conventional point of view the point of view that was given by Drude now with this understand basic understanding of quantum mechanics and in density of states and using those ideas we will try to formulate a new model of transport and that is known as the general model of transport.

Because it starts with very less number of assumptions and with this model of transport so, again I am not going into the details here because this is going to be the subject matter of many classes.

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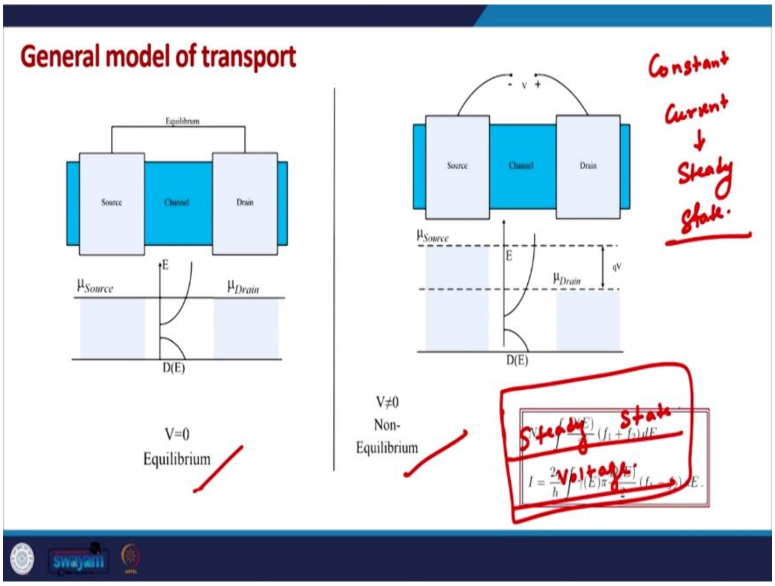

I am just giving an overview we will see how systems behave in equilibrium when we do not have any voltage applied across the system and how systems behave in out of equilibrium or in steady state. Steady state when a voltage is applied.

So, there is an interesting difference between equilibrium and steady state equilibrium is the state of the system when each process has a reverse process exactly of the same magnitude. So, every process is counted by the reverse process so, there is no net flow of anything in the system. In steady state or the steady state of a system is the state in which the flow in one direction is constant or the process in one direction is happening at a constant rate.

So, when there is a constant current in a device that state is known as the steady state. So, most of the times we are interested in equilibrium and in steady state trying to understand those things.

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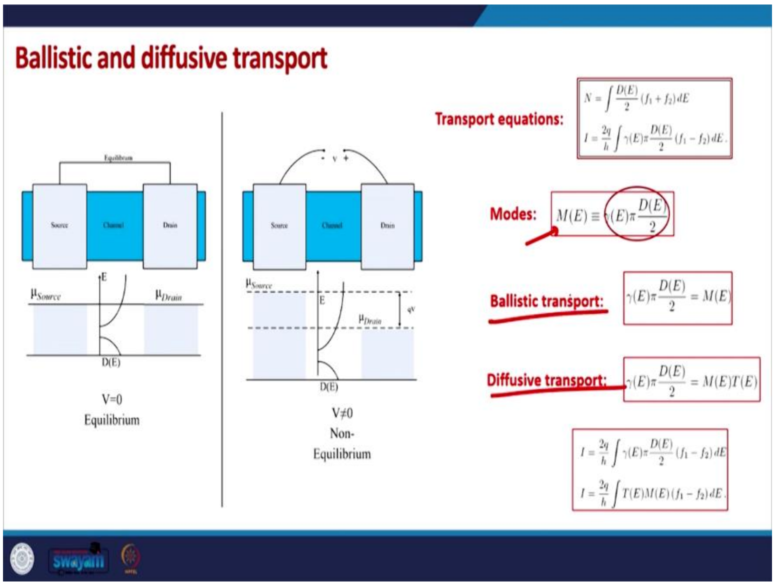

So, this general model of transport will give us the expression for the IV characteristics the conductance the number of modes which is the essentially the conduction pathways both in ballistic case and in diffusive case.

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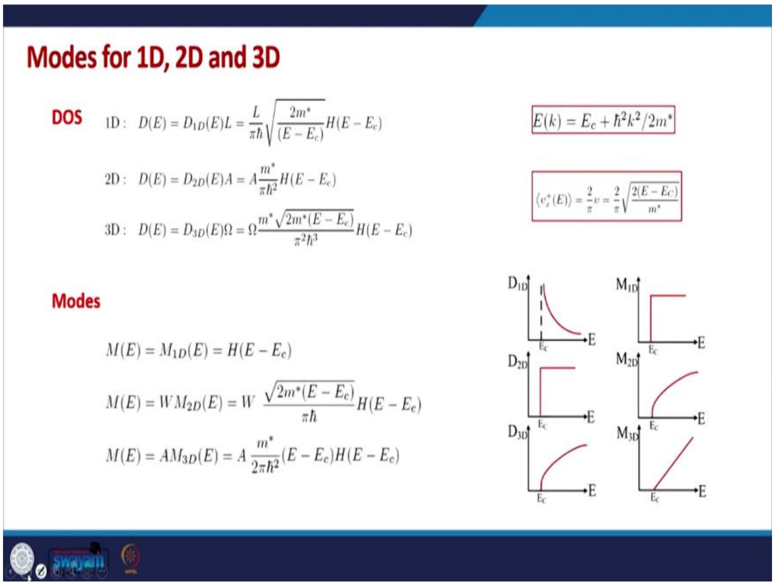

So, that is all that we will see while discussing the general model of transport.

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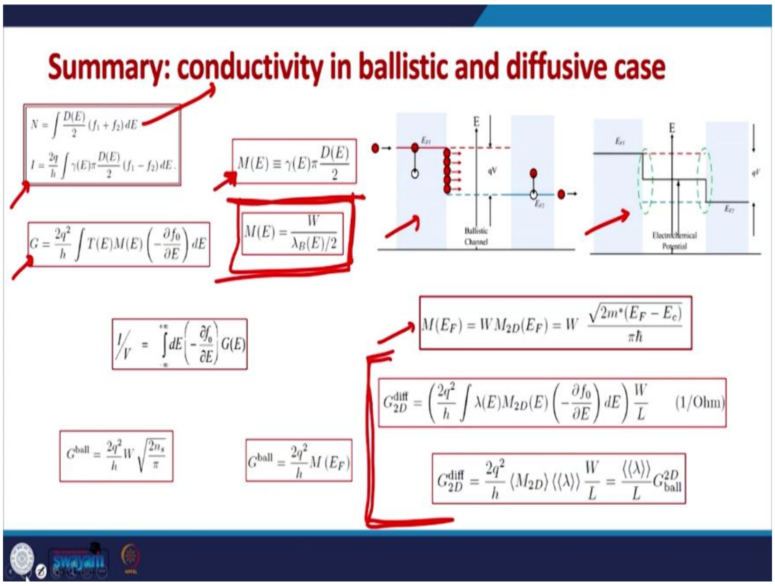

We will discuss the idea of modes in detail and finally, this is all that this general model of transport will tell us about. It will essentially be using this model we will be able to understand where is actually the power dissipation happening, where is the voltage drop happening where is the resistance in a device what are the various expressions what is the expression for the current.

For the in steady state how many electrons are there in the device what is the conductance of the device as a consequence what is the resistance of the device what how many conduction pathways are there in the device. We will also correlate the number of pathways to the de Broglie wavelength of the electrons in the channel and then we will discuss these ideas for practical devices at room temperatures and we will do real calculations of resistance and conductance ok.

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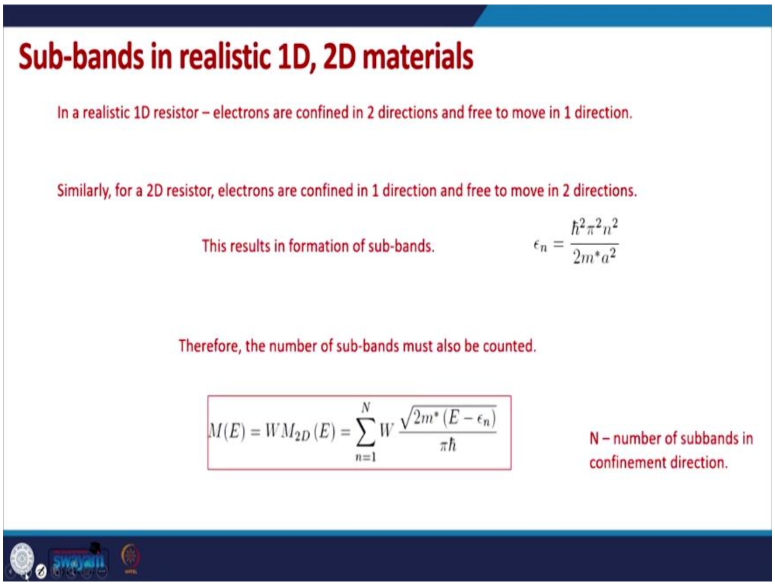

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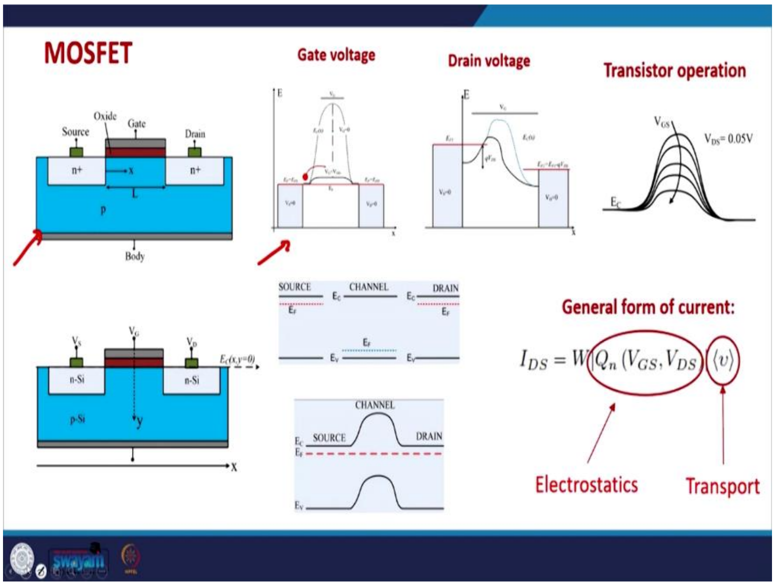

So, all this is what we will be going to do we will also study real practical systems and after understanding all these ideas we will then go to the actual understanding the actual MOSFET. So, in first few classes on MOSFET we will see the basics of MOSFET how MOSFET actually functions.

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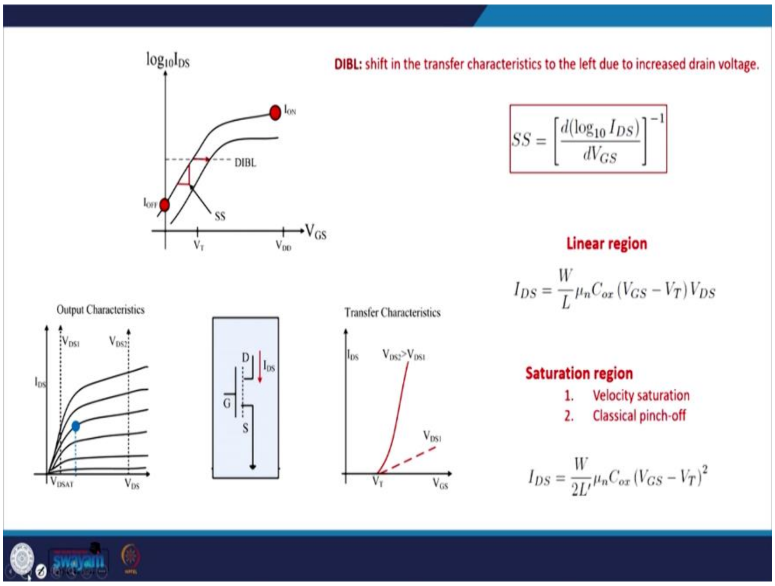

And then we will go to the how we will go to understand how the nanoscale MOSFET actually functions and we will borrow the ideas from the general model of transport and these are various things that we will encounter during our study of the MOSFET ok.

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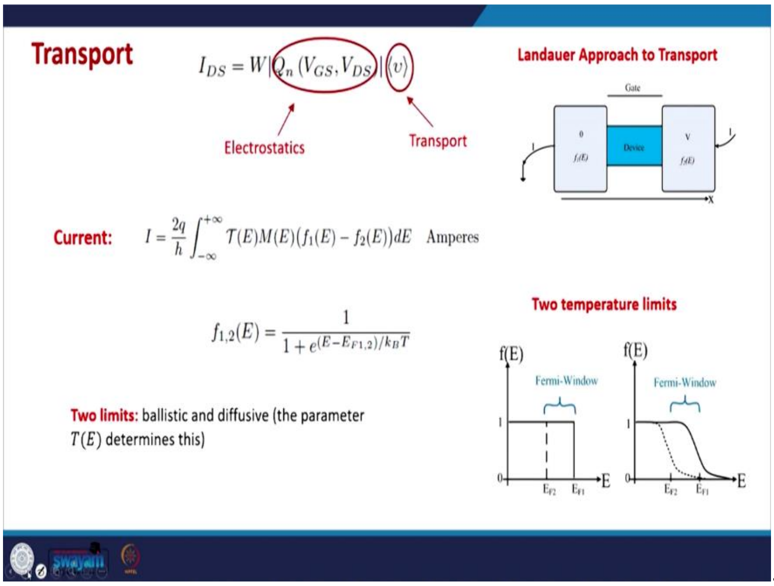

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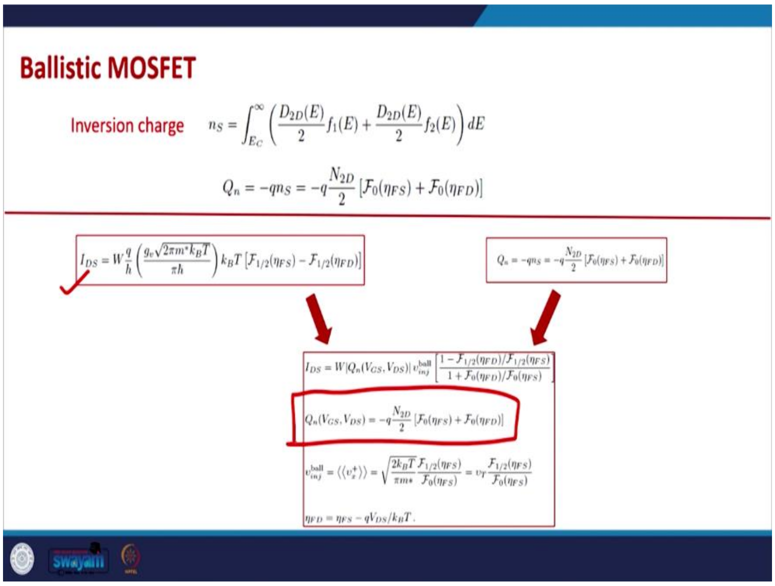

So, we will also study the ballistic MOSFET that is the MOSFET in which the electron does not collide with anything in the channel directly goes from the source to the drain side. And we will see the I-V characteristics for a ballistic MOSFET and the charge for the ballistic MOSFET charge in the channel for ballistic MOSFET.

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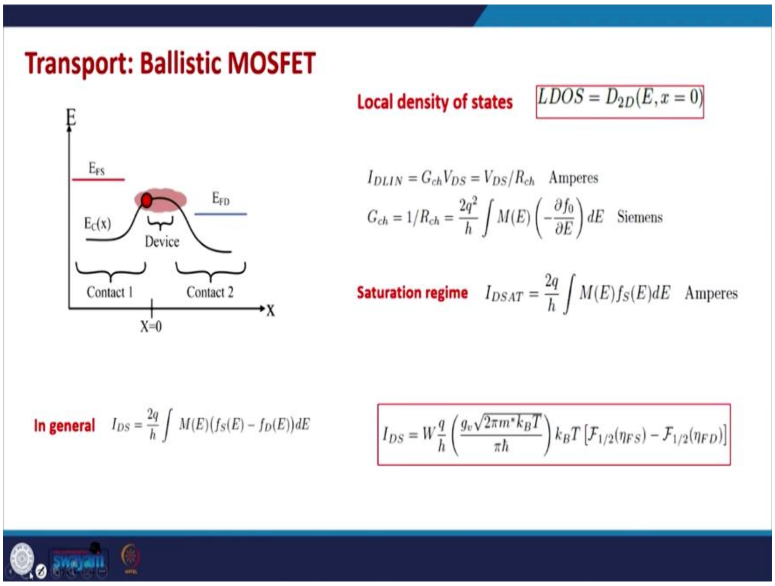

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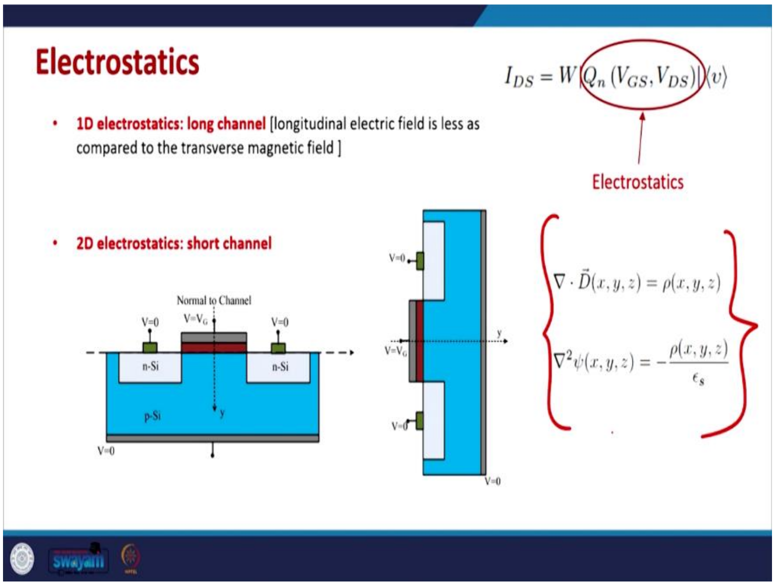

So these are various ides that we will come across then we will also go through the electrostatics of MOSFET and as the MOSFET are scale down we will see how the electrostatics change as well. So, the electrostatics essentially is based on these fundamental equations and we will see how by applying these equations how the electrostatics would change ok.

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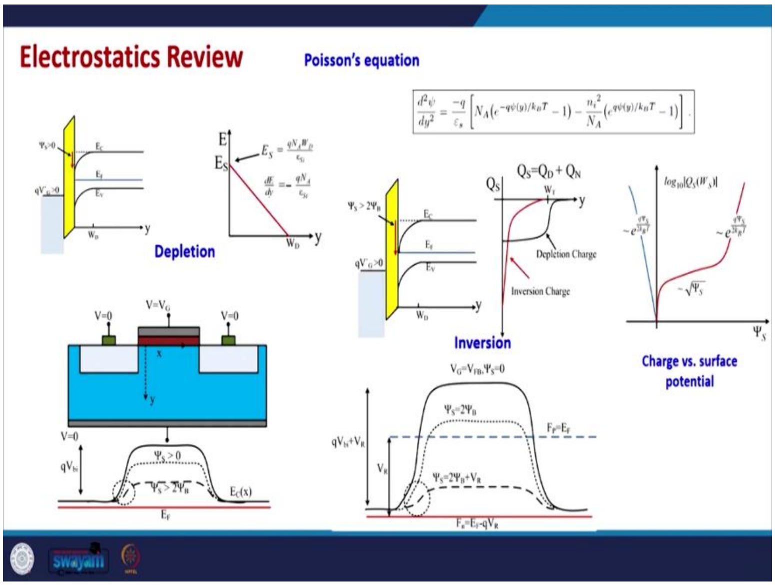

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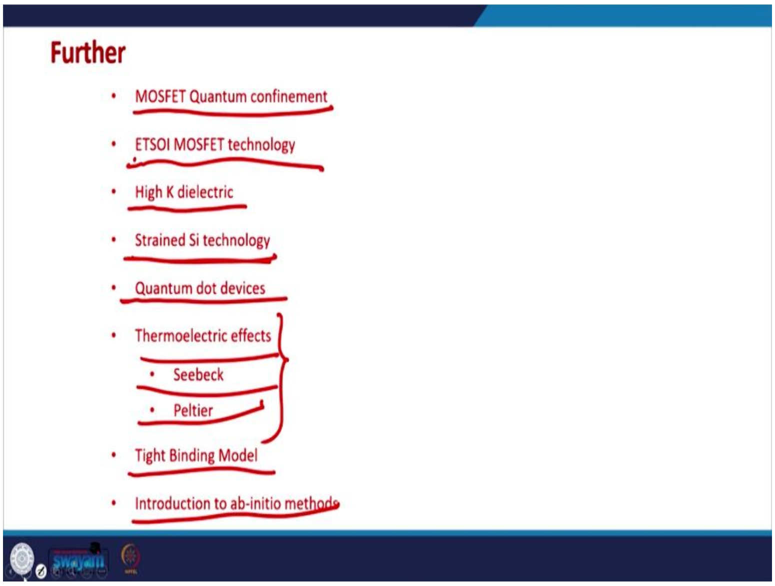

So, we will discuss all these ideas in detail and finally, apart from this the discussion of general model of transport MOSFET transport, electrostatics we will also study the quantum confinement in MOSFET. We will also study the ETSOI MOSFET technology extremely thin silicon on insulator MOSFET technology which are quite popular nowadays.

We will see how high K dielectrics are useful or are used in modern day transistors; we will also go through a little bit in the strained silicon technology. Then we will go beyond MOSFET technologies we will see how quantum dot devices work some basic ideas on them.

And finally, we will also briefly study the thermoelectric effects in solid state devices we will and this essentially consists of studying seebeck effect and peltier effect and finally, in very briefly we will also try to study the tight binding model and introduction to the ab initio methods in the in solid state devices. So, this is essentially the entire overview of this course and I hope you would enjoy the content of this course.

Thank you for your attention. see you in the next class.