Semiconductor Device Modeling

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Lecture - 01
Motivation, Contents and Learning Outcomes

Welcome to the course on semiconductor device modeling. I am Shreepad Karmalkar. I have about 25 years of experience in the area of semiconductor devices. I have been doing teaching and research in this area. It will be my pleasure to share with you the enthusiasm and expertise I have gained in this area over 2 decades of research work. I believe that as a teacher, my job is to remove any fear you may have about the subject, dispel confusions bring about intellectual clarity and arose curiosity.

So please feel free to raise doubts, ask questions or make comments whenever they arise in your mind. The first 2 lectures will be introduction. In this first lecture, we shall answer the question what and why. What is a device model and why I study device modeling? Then this brief discussion will clarify what is the target audience of this course and what is the background preparation required to go through this lectures.

After this, we will discuss the contents in detail. We will point out what will be the take away from this course. What skills will you develop at the end of this course? In other words, these are called learning outcomes. We shall look at some of the unique features of the approach adopted in this course and then we will close the lecture with a set of reference books.

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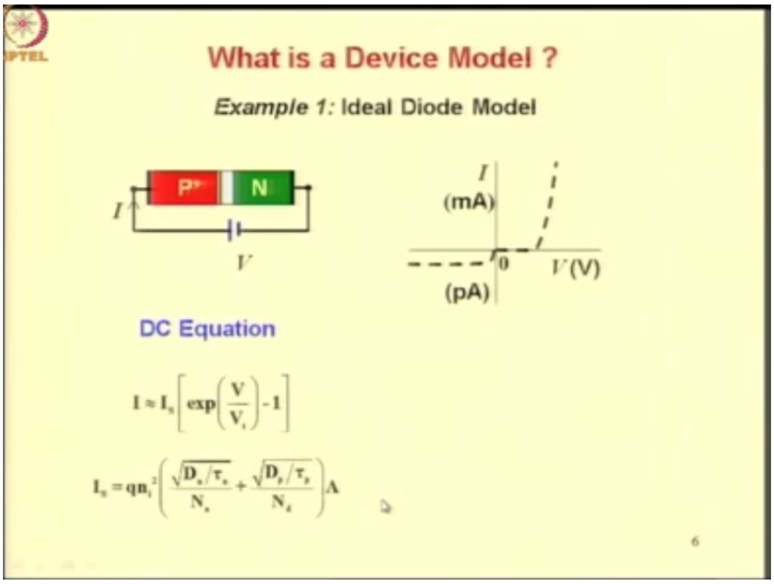

Now let us look at the question what is a device model? We shall consider several examples. Example 1, you would have come across what is called the ideal diode model in the first level course on solid state devices. What is this model? Let us look at the static model. You apply a voltage V to the diode and as a result you have a current I. This is the plot of the DC current I as a function of voltage.

You can express these current voltage characteristics in terms of an equation, which is called the DC equation. I=IS into exponential of V/Vt-1 where IS = q times ni square into square root of Dn/tau n/Na+ square root of Dp/tau p/Nd into the area of the diode. Dn and Dp are the diffusion coefficients, tau n and tau p are the minority carrier lifetimes and Na and Nd are the doping levels on the 2 sides of the junction, ni is the intrinsic concentration and q is the electronic charge.

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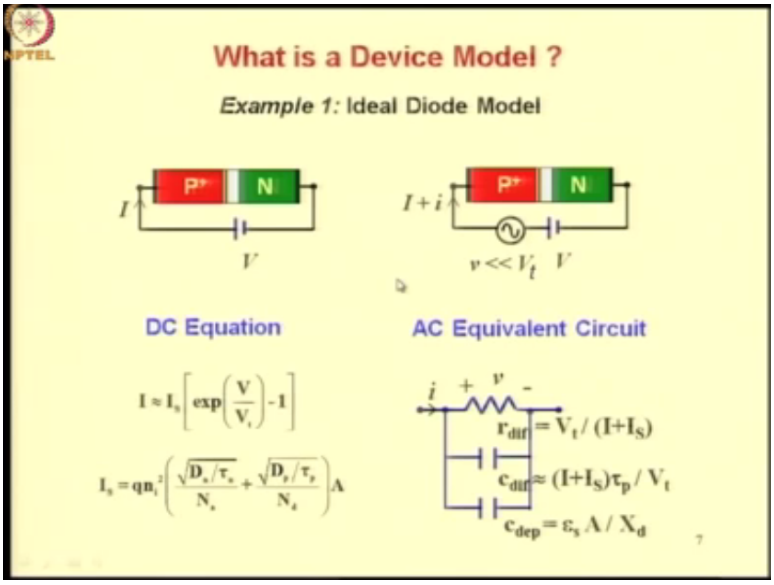

Let us look at the AC model. So here you have applied a DC voltage in series with the small signal AC voltage. Consequently, you get a DC current I and a small signal current i. The AC equivalent circuit expresses the relation between i and v. This relation is expressed in terms of an equivalent circuit. So if you apply a voltage across this combination of resistance and capacitances, then whatever current result is the small signal AC current.

The resistance component of this equivalent circuit is the so called diffusion resistance. It is = the thermal voltage / the DC current I+IS which is referred to as the reverse saturation current. Similarly, one component of the capacitance is diffusion capacitance, which is approximately = DC current I + reverse saturation current IS multiplied by tau p, which is the lifetime of holes in the N type region so called like a dope region, which governs the DC characteristics.

And also the AC characteristics divided by the thermal voltage. The depletion capacitance on the other hand is given by the permittivity of silicon epsilon S into the area that is the area of cross section of this device divided by the depletion width Xd so width of this region.

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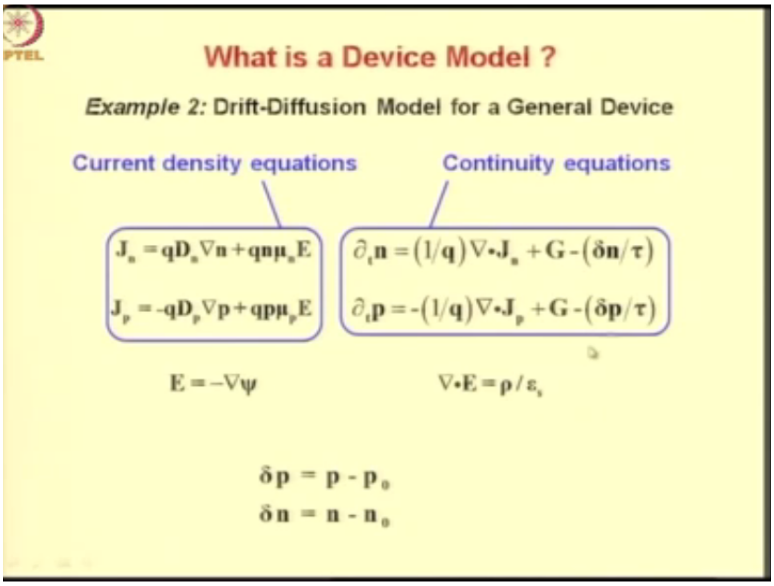

Let us look at another example, the drift diffusion model of a general device. The model that we discussed just now for a diode was such that it can only be used for that particular device namely the diode. Now we are going to look at a set of equations using which we can derive the current voltage characteristics of any device. You would have come across these 6 equations out of which these 2 are referred to as a current density equation.

For example, this is current density of electors Jn = q times the diffusion coefficient of electrons into gradient of n, this quantity is the diffusion current plus this quantity is the drift current, which is q into electron concentration into mobility of electrons into the electric field. Similarly, this is the equation for the whole current density. Since this model is based on drift and diffusion currents it is called drift diffusion model.

Look at these equations here, these 2 equations are called continuity equations. For example, for electrons it is dou n/dou t = 1/q into diversions of Jn+G which is the volume generation rate, this is excess generation because of light because of avalanche multiplication and so on minus the excess electron concentration by the lifetime of the region in which we are applying this continuity equation is the lifetime of minority carriers.

The excess electron concentration is equal to the electron concentration minus the equilibrium value of the electron concentration at that point in the device. Similarly, this is the whole continuity equation.

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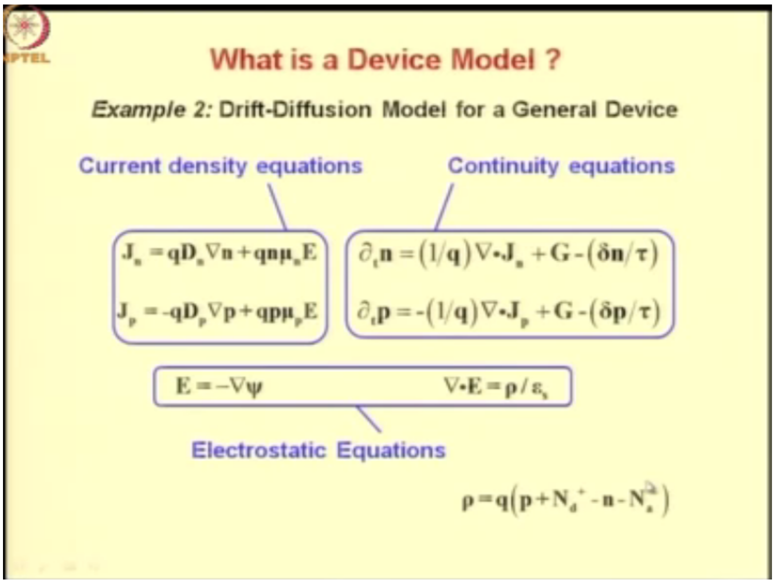

These 2 are the electrostatic equations, E= - gradient of psi and diversions of E=rho/epsilon S, rho is the space charge given by q times the hole concentration + the concentration of ionized donors - the electron concentration - the concentration of ionized acceptors. Psi here is the potential. Now using these equations, you can derive the current voltage characteristics of any device.

In the first level course, you would have used these equations, made some approximations and then derived the characteristics of diodes, bipolar transistors, MOSFETs and so on.

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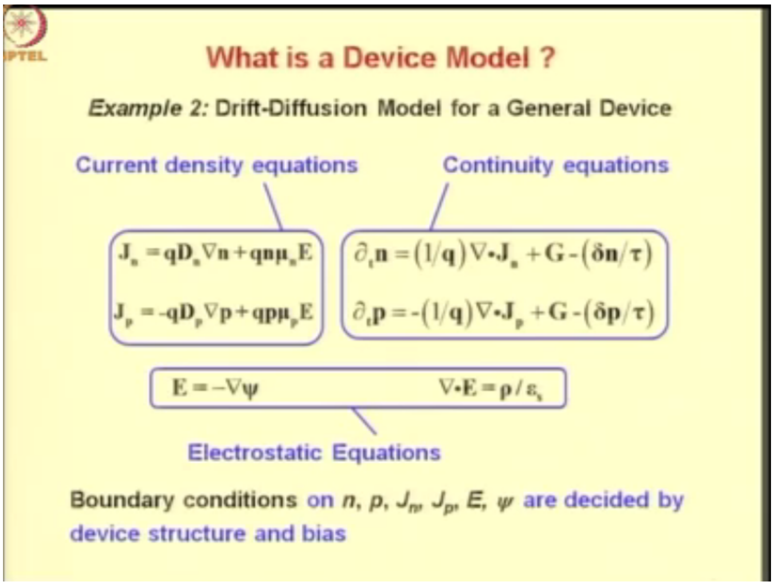

Now while solving these equations, you need boundary conditions on 6 variables because there are 6 equations, there are 6 variables, electron and hole concentrations, electron and hole current densities, the electric field and the electrostatic potential. So these boundary conditions are decided by device structure and applied bias.

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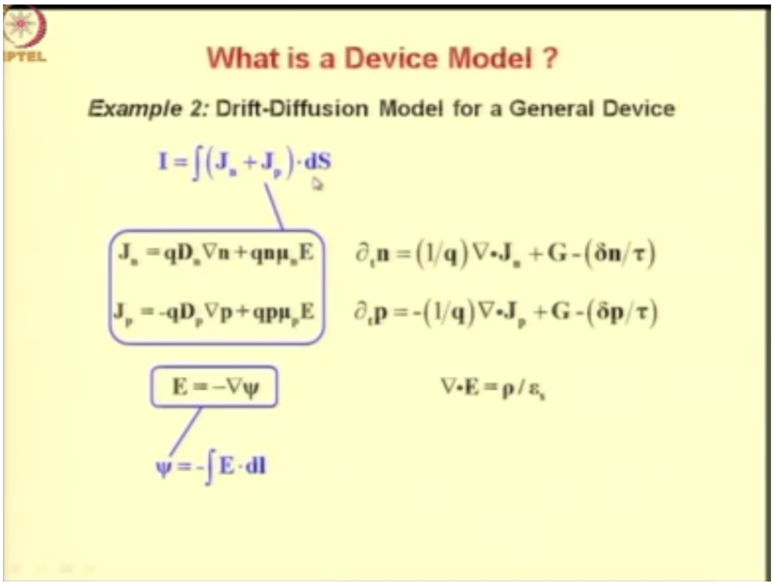

Now how do you get the current? The current is obtained by integrating Jn+Jp over the contact area, which is dS, there is a dot product here because you must consider the current flow perpendicular to the contact area to find out the total current from the current density. Similarly, the potential applied across the 2 terminals can be calculated using this formula negative of the integral of E dot dl so this is how you can get the current I for any voltage psi.

So in this approach you will take different values of psi and for each value of psi you will solve these 6 equations as a function of space and time and then at any instant you will find out the current for that psi using this formula.

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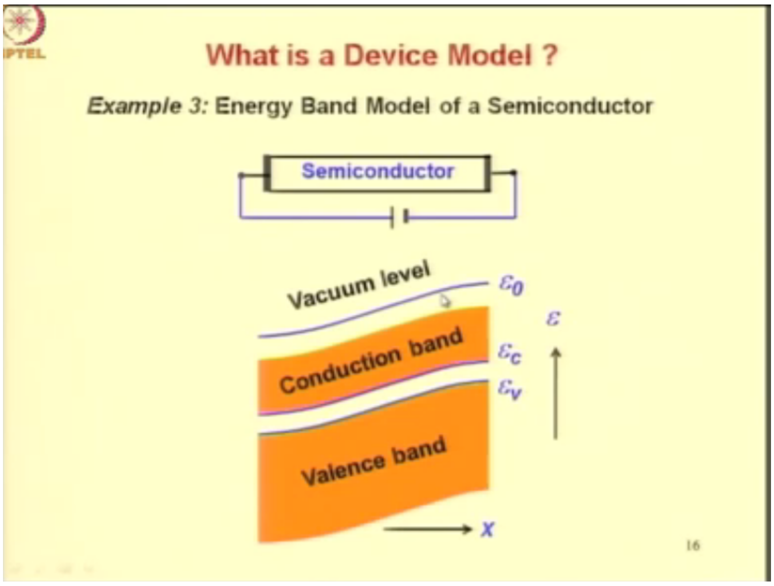

Let us look at one more example. The energy band model of a semiconductor. Here is the semiconductor across which a voltage has been applied, now the conditions within the semiconductor can be represented using this diagram which is called the energy band diagram where this E0 is the vacuum level, Ec is the conduction bandage and Ev is the valence bandage.

So this diagram plots the electronic energy in the y direction as a function of distance. This is the 1-dimensional energy band diagram. Now you find that the lines are somewhat curved because the conditions in the semiconductor are not uniform. So even a diagram is a kind of a model, graph also is a kind of model. Similarly, a table could also represent the model of a device.

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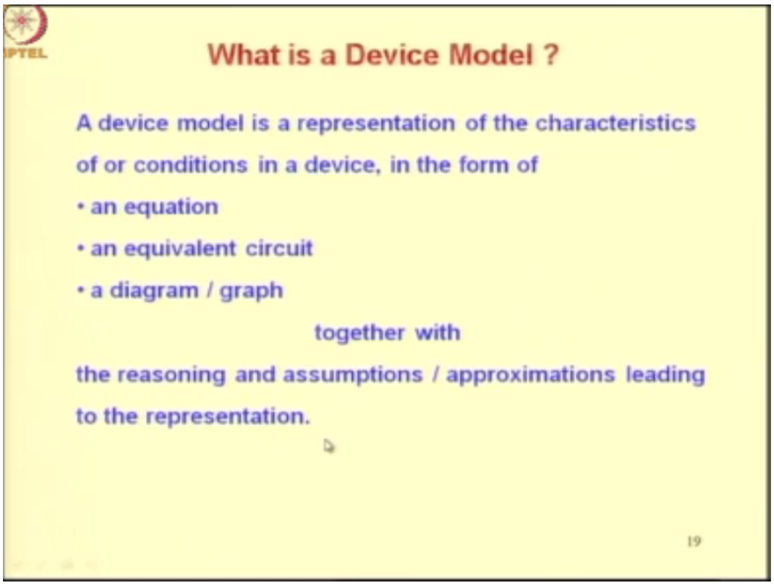

Therefore, we can summarize by saying that a device model is a representation of the characteristics of or conditions in the device in the form of an equation, an equivalent circuit or a diagram or graph. One could also include table in this category. However, please note that while the equation or the equivalent circuit or diagram or graph is the face of the model the model contains more than this face just as a body is not nearly the face.

So what is that something more that is the reasoning and assumptions or approximations leading to the representation. So you must remember this very important point that the representation together with the reasoning and approximations that lead to the representation constitute the model. This point about the approximations and the reasoning we shall elaborate in the second lecture.

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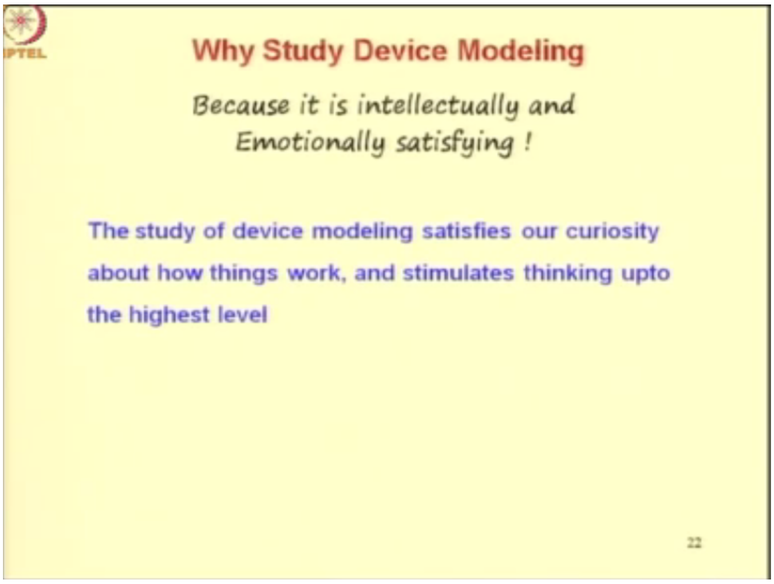

Let us address the question why study device modeling? Different people have different motivations for doing things. Let us list some of the motivations. One motivation I think for studying device modeling is that it is intellectually and emotionally satisfying. The study of device modeling satisfies our curiosity about how things work and stimulates thinking up to the highest level.

Now you might say well I am a more practical person. Can you tell me what are the practical reasons for studying device modeling?

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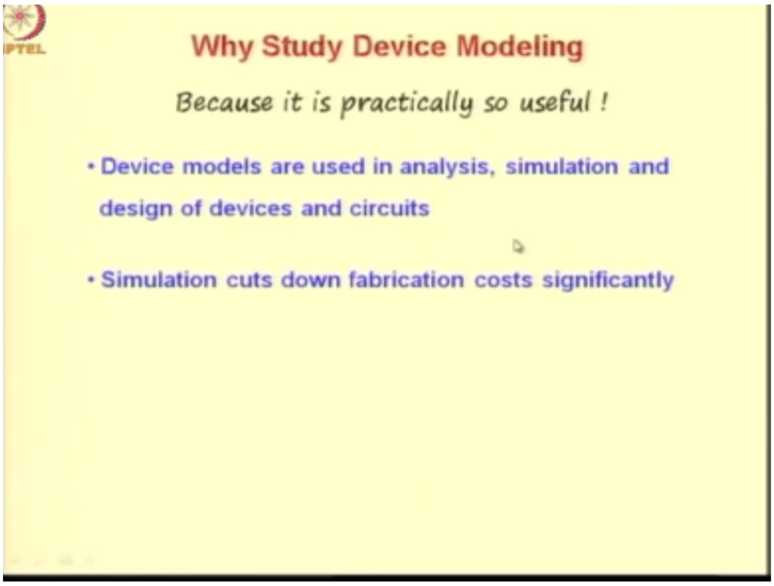

So device modeling is also practically useful. Example, device models are used in analysis, simulation and design of devices and circuits. In the next lecture, we shall clearly understand the difference between analysis, simulation, design and modeling. Simulation cuts down fabrication costs significantly. So you are using models in simulation and the reason why one must study simulation is because simulation cuts down the fabrication cost.

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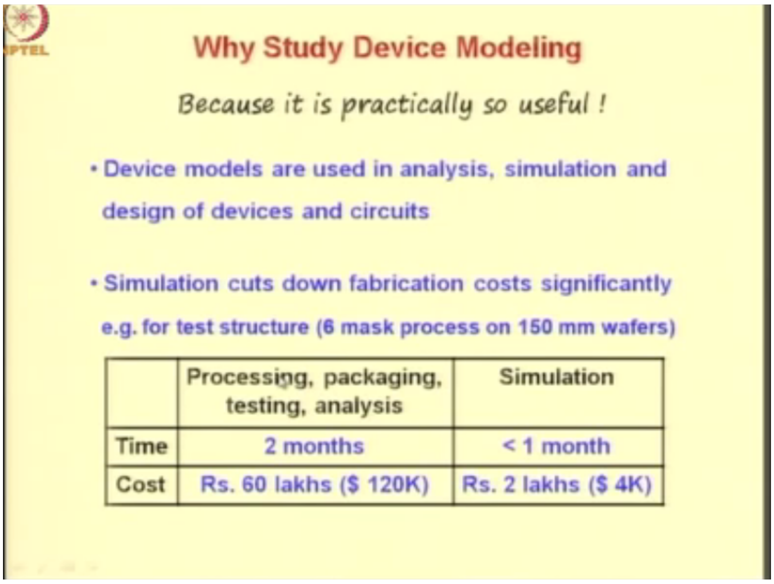

For example, for fabricating a test structure, which consists of a 6 mask process on a 150 mm diameter silicon wafer. Let us look at the 2 approaches and compare them. If you do a physical fabrication involving processing, packaging, testing and analysis, actually go through the steps then the time required is 2 months and the cost is about rupees 60 lakhs, which is equivalent to in US dollars about 120K.

On the other hand, you can get the same information that you get out of fabricating this test structure and then doing a testing and analysis using simulation. You replicate the working of the test structure in a computer that is what a simulation. For doing this and getting the same information as you get out of this physical exercise you take less than a month and you just end of paying about rupees 2 lakhs or US dollars 4K.

Because these 60 lakhs is the cost of material processing, energy and so on. This 2 lakhs is actually the cost of employing 2 device engineers right for about a month.

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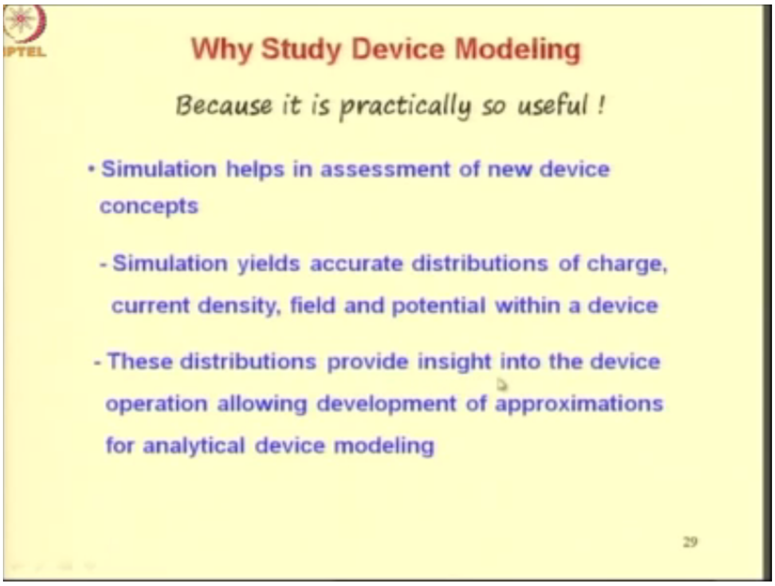

Let us look at importance of simulation apart from cost efficiency. Simulation helps in assessment of new device concepts. Now how does it do that? Simulation yields accurate distributions of charge, current density, field and potential within a device. These distributions provide insight into the device operation allowing development of approximations for analytical device modeling.

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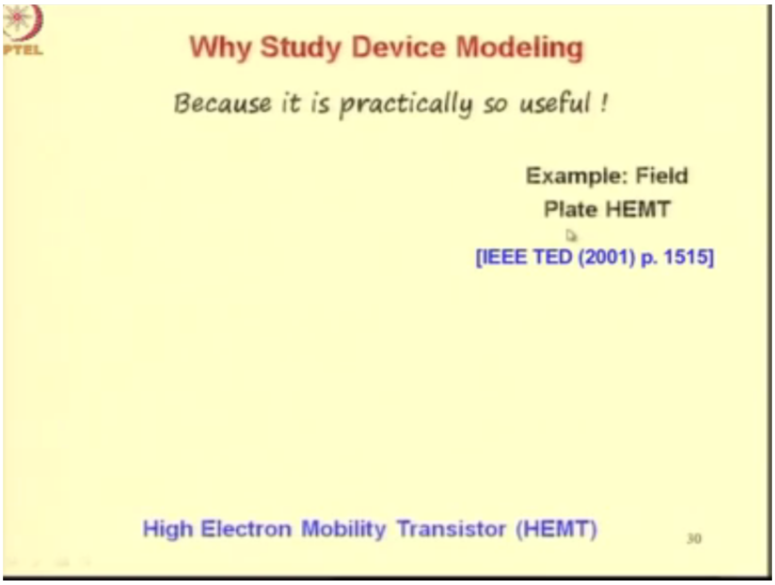

Let us look at an example, a recent example a practical example, this regarding a high electron mobility transistor. The particular type of high electron mobility transistor that we are considering in this example is called field plate HEMT. Will explain what a field plate HEMT means. Now you might wonder how will I understand this example if I do not understand the operation of a HEMT.

Well to understand what I am going to talk about you do not need to know the operation of a high electron mobility transistor in grade depth. You have been exposed to a field effect transistor in your first level course. HEMT is another field effect transistor okay.

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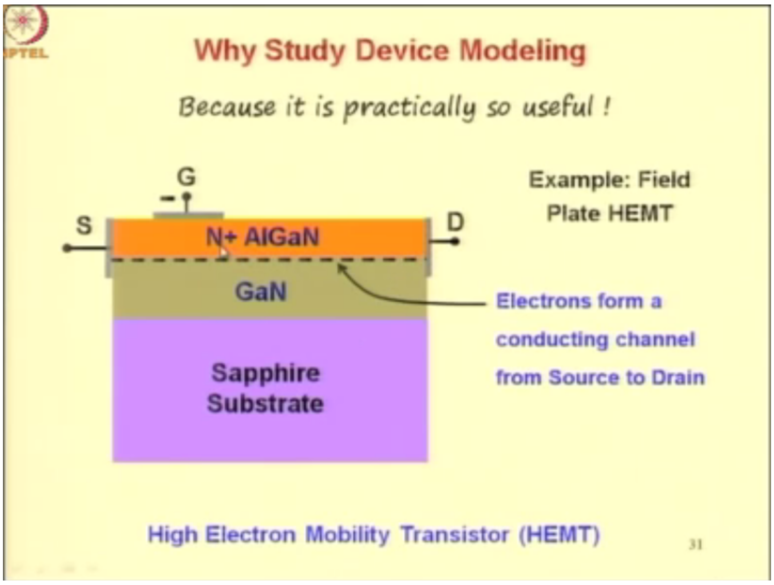

Let us look at its structure. It consists of a heavily doped N-type aluminium gallium nitride, a thin layer deposited over a gallium nitride substrate, which is relative with it, but since the thickness of this gallium nitride is still not several tens of micron, which is required from mechanical handling reasons. You deposit this gallium nitride on a thick sapphire substrate, which can help you handle the whole device mechanically.

Now electrons are transferred from this heavily doped region aluminium gallium nitride into the gallium nitride region. As it happens in any junction and this high concentrations of electron at this surface forms a channel from source to drain. If want an analogy of this device to the MOSFET, this would be the oxide of the MOSFET right, this would be the gate and these 2 would be the source and drain. You can look at it in that form.

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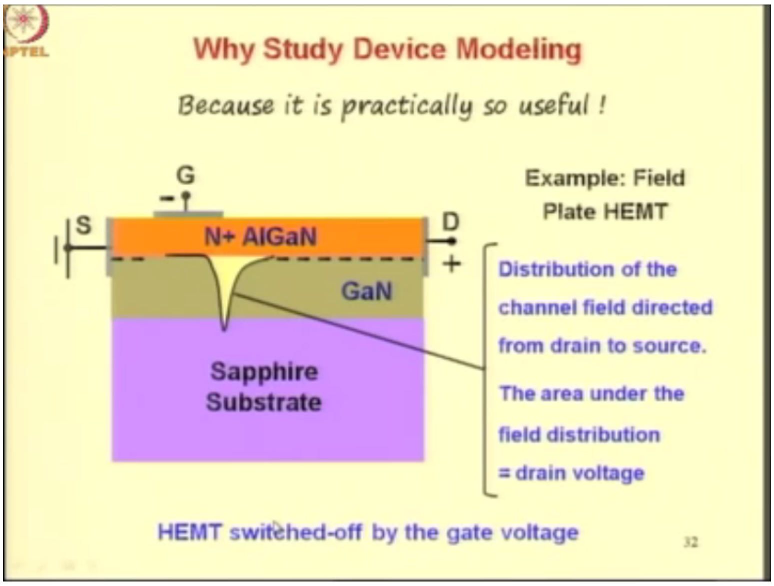

Now let us look at the half state operation of this device. You know that any field effect transistor nowadays is used for either switching or amplification. So we are looking at the high electron mobility transistor as a switch. Now what should a switch do. It should be able to withstand as high a voltage as possible in the off state. In the on state, it should be able to conduct as much current as possible.

Let us look at the off state and let us see how we can increase the breakdown voltage of this structure. So this is where the simulation helps so what you do is you get the field distribution within the device by simulation. It will look something like this. You might have come across a field distribution like this in your first level course near the drain end of the gate in a MOSFET.

So this electric field distribution, this is the end of the gate and this is the drain. It is directed from drain to source. So you know that the electric field can have a vertical direction and also it can be horizontal because you are applying a voltage in this direction because of the gate and you are also applying a voltage from this contact to this contact so there is a field in this direction as well as vertical direction, horizontal and vertical.

And so the relevant component of the field here is the field in the horizontal direction. Area under this horizontal component of the electric field gives you the drain voltage. Now if you want to improve the breakdown voltage of the device so that this device can withstand a high off state voltage, then the way to go about doing it is to reduce the peak electric field because if the peak is high, the device will breakdown for a lower voltage.

So the issue is how do you reduce the peak? The way to reduce the peak is to spread the field over a wider distance. So that since the area under the field distribution is the applied voltage for the same voltage or for a same area if the base of this triangular like region is wide, the height which is the peak will reduce.

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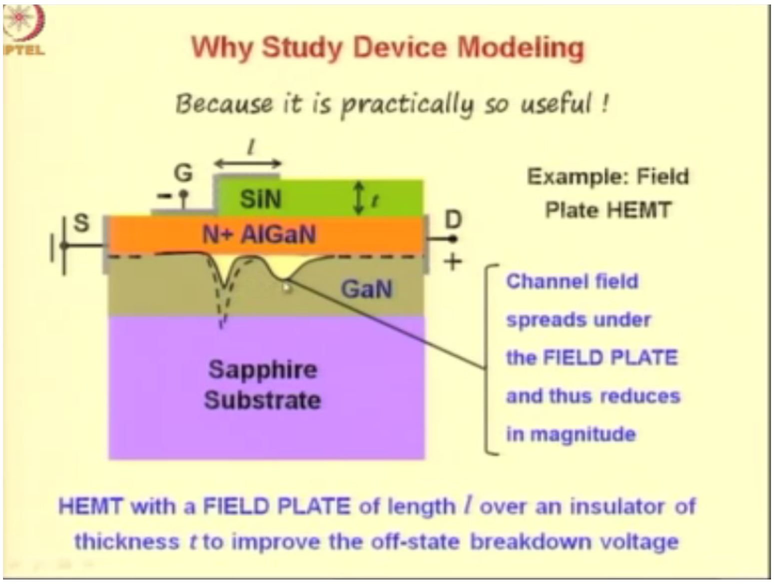

Now one way to do that is to use a field plate that is use a protrusion of the gate over an insulator such as silicon nitride in this fashion. This protrusion is called the field plate because a field from this particular plate modulates the electric field in the channel. Now you see what happens is that the electric field gets distributed and it develops 2 peaks.

It is easy to understand that if you have a protrusion of the gate and you expand it in this direction, stretch it here, then the field will get distributed. And at the 2 edges the field will be maximum there is this edge and this edge. Therefore, you get 2 peaks. Now the area under this expanded field distribution is the same as the area under the dotted field distribution, which was the distribution in the absence of this protrusion or absence of the field plate.

So clearly the peak has reduced. Now this feature can be exposed very nicely in a simulation. So you take the device structure and you simulate and then you see how much is the reduction in the peak. Now in fact this idea of field plate was conceived intuitively, but at the time it was applied to the high electron mobility transistor it was not clear just how much enhancement in breakdown voltage it will give.

So since first people did not do a simulation of this device structure and they started fabricating the new structure to see the enhancement in breakdown voltage, it turned out that they got only about 20% to 30% enhancement in breakdown voltage. They were quite happy about it, but they could not figure out just how much more they can improve. Now the technology which was available at the time this field plate idea was applied to the HEMT allowed you to deposit only thin silicon nitride insulators.

And with that thin silicon nitride insulator and some intuitive idea of this length, people got about 20% to 30% enhancement. It is only a simulation which showed that by proper choice of this thickness of the insulator and the length one could enhance the breakdown voltage by a factor of 2 or 3 so rather than 20% or 30% it could be 200% or 300%. Now this could not have been possible by fabrication because the technology at that time did not permit you to deposit a thick silicon nitride insulator on this particular device structure.

However, when the simulation showed that you can get 200% to 300% enhancement then there was a motivation to develop the technology of depositing this silicon nitride film of sufficiently large thickness to get the required or to get the maximum potential out of this particular structural modification okay. So these are examples where the simulation helps you to work on the technology and improve the technology right so as to achieve an improved device performance.

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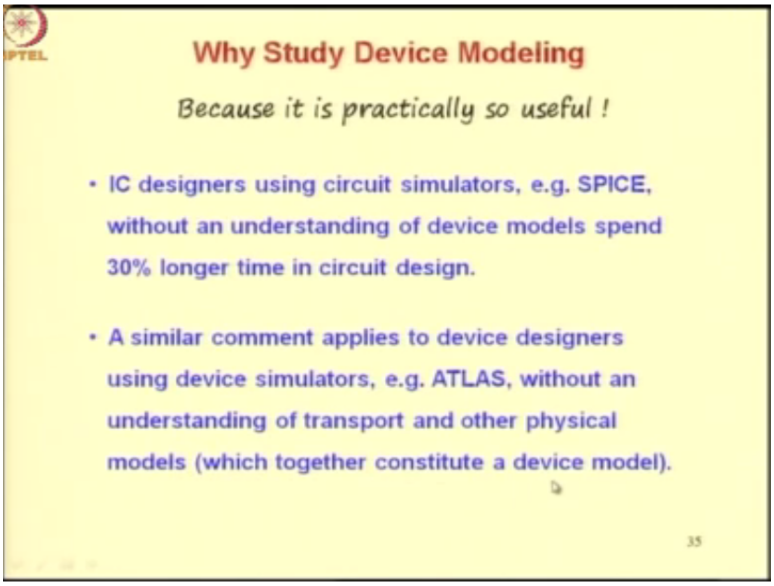

Let us look at a few more practical reasons for studying device modeling. IC designers using circuit simulators, example SPICE, without an understanding of device models spend 30% longer time in circuit design. A similar comment applies to device designers using device simulators, example ATLAS, without an understanding of the transport and other physical models, which together constitute a device model.

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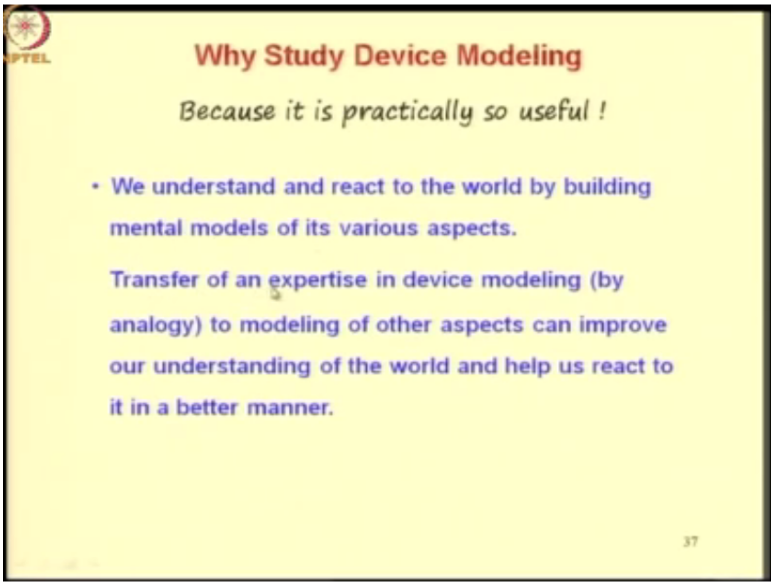

Finally, a very important practical reason is that we understand and react to the world by building mental models of its various aspects. So you can regard the human being also as a device right and you want to model human behavior so here also you are getting your encountering the activity of modeling. So when we react to the world we react by building mental models of its various aspects.

So our relation with others depends on our models of how others are likely to behave with us. Transfer of an expertise in device modeling by analogy to modeling of other aspects can improve our understanding of the world and help us react to it in a better manner. So this is a very, very important offshoot of studying about modeling in general and device modeling in particular.

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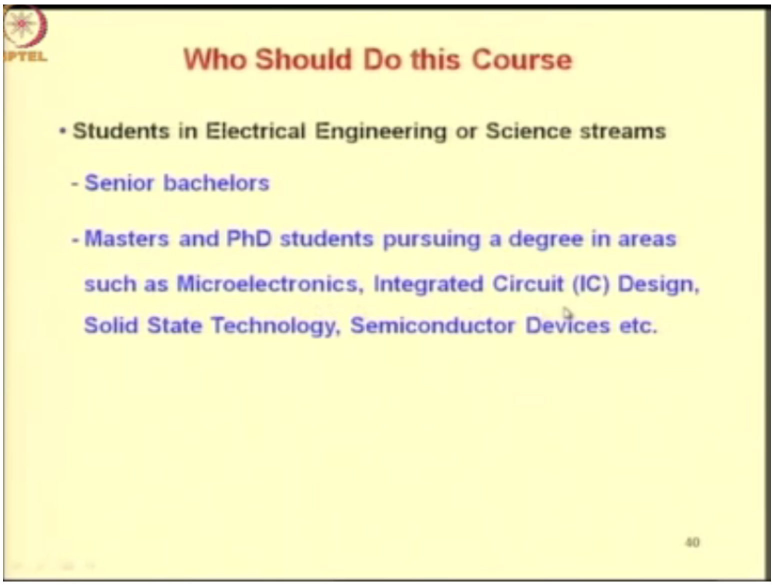

Now this description should clarify the target audience for this course. Who should do this course? So the first set of people who should do this course are students in electrical engineering or science streams such as senior bachelors, masters and PhD students pursuing a degree in area such as microelectronics, integrated circuit design, solid state technology and semiconductor devices.

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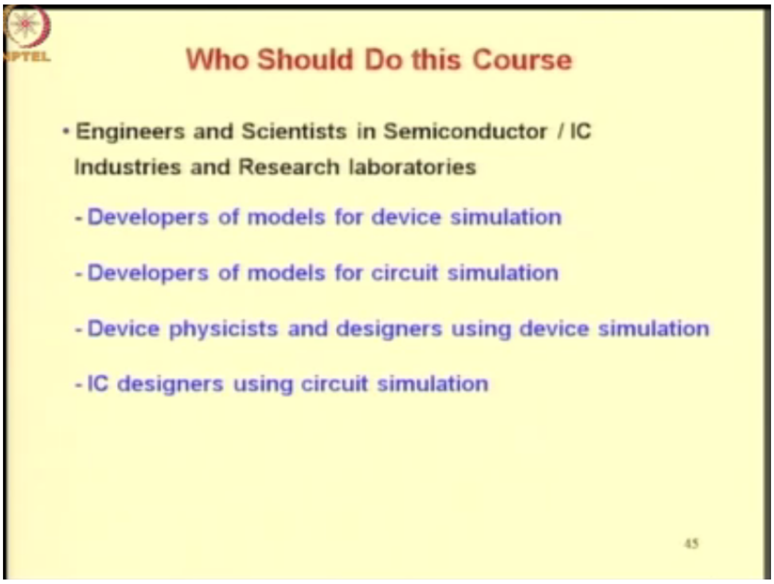

Then engineers and scientists in semiconductor and IC industries and research laboratories such as developers of models for device simulation, developers of models for circuit simulation, device physicists and designers using device simulation and IC designers using circuit simulation. So all these kinds of people working in industry can benefit by studying about device modeling.

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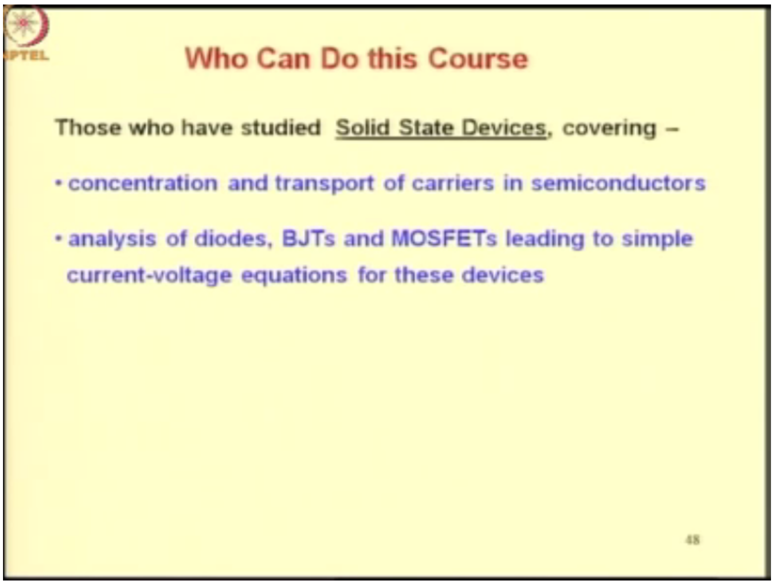

Now let us look at the background preparation required. Who can do this course? So all those who have studied solid state devices covering these topics, concentration and transport of carriers in semiconductors, analysis of diodes, BJTs and MOSFETs leading to simple current-voltage equations for these devices.

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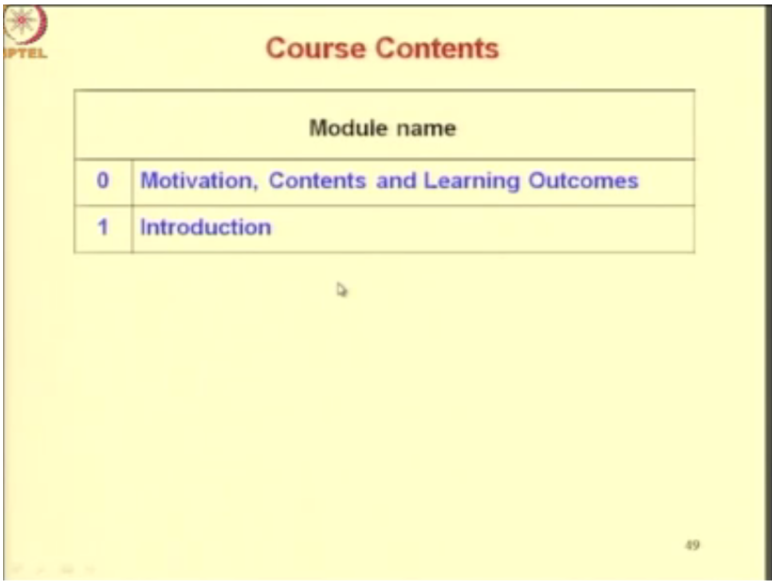

Now we come to the course contents. This course is actually a modular series of lectures. So the lectures are organized into various modules. The module 0 which consist of just one lecture that is the present lecture, it talks about motivation, contents and learning outcomes of the course and module 1 will introduce the course and its remaining contents.

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Qualitative model of semi-classical bulk transport is what we are going to discuss in module 2. In module 3, we shall discuss the electromagnetic field and transport equations of this semi-classical bulk transport. Now any modeling exercise starts with a qualitative aspect and then goes on to quantitative aspects that is why here we are first discussing the qualitative model of transport and then quantitative model. Further we are going to restrict our self to semi-classical transport.

We shall elaborately explain what is the meaning of the word semi-classical? Basically, it means that we do not consider current such as tunneling okay. We restrict ourselves to drift diffusion maybe little bit of thermoelectric current and so on. Then we shall look at the drift-diffusion transport model, equations, boundary conditions, mobility and generation/recombination.

Now if you would like to know what are the various things that will be covered in these modules, the simple approach for you would be to go to the very first lecture of the module and look at the first couple of minutes of the lecture. These couple of minutes will give you in detail what are the learning outcomes of the particular module. Similarly, each module has a summary at the end, which is fairly detailed for example in some modules almost the entire lecture is devoted to the module summary.

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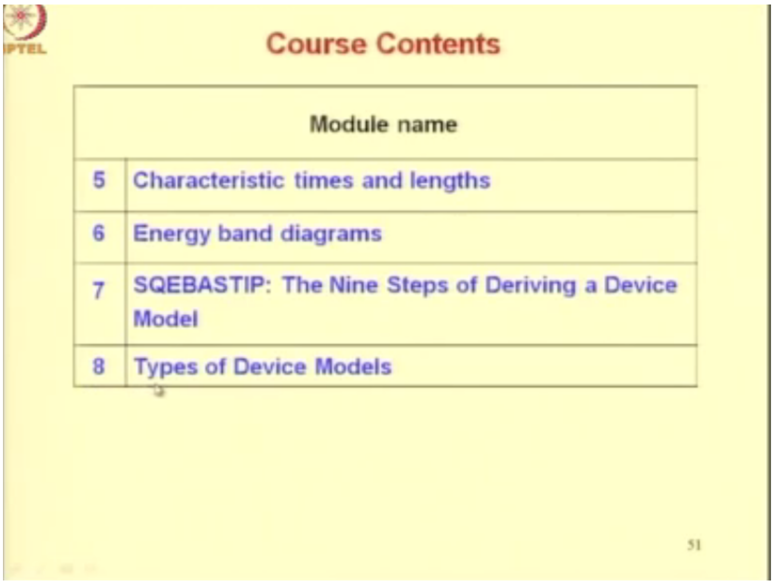

In module 5, we shall look at the characteristic times and lengths, which are used in device modeling. In module 6, we look at the energy band diagrams, which is a very, very important tool both for representing conditions in a device and for analyzing conditions in a device. In 7th module, we shall look at the 9 steps of deriving a device model and these are abbreviated in terms of this 9 letters, which can be spelled as SQEBASTIP.

So here S stands for structure and characteristics of the device that is the first step, you should know the structure and device characteristics, the next step is qualitative physics or qualitative understanding, then comes equations and boundary conditions E and B, then you summarize all the approximations that you have made during your qualitative model development and any other approximation that you may make to equations and boundary conditions.

So after that you have summarized all the approximations that are possible in the given situation, then you go on to solve the equations under the given boundary conditions. So S stands for solution, then T stands for testing, you check the solution whether it is right or not, there are several ways of testing the solution. After a testing, if you see a scope for improvement then the next step is I that is improving the model.

And finally after your model is complete then you extract the parameter so P stands for parameter extraction. So extract the parameters of the model for the given device so that you can use this model to make calculations about circuit performance or any other thing. In module 8, we shall discuss types of device models.

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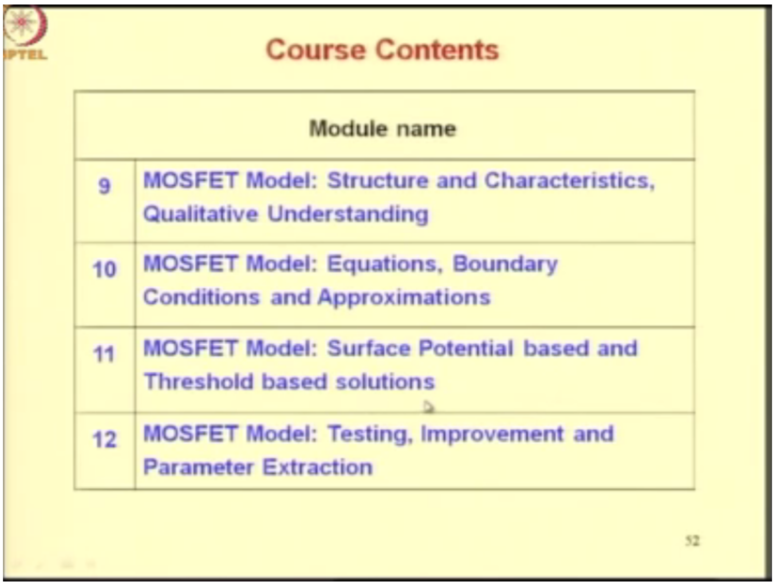

Next we shall discuss modeling of the MOSFET in detail. In this module 9, will discuss structure and characteristics and qualitative understanding of the operation of a MOSFET. In the tenth module, we shall look at the equations and boundary conditions together with the approximations that are used in modeling of MOSFETs. Then we shall look at 2 broad approaches of modeling of MOSFETs namely surface potential based and threshold based solutions.

And then finally we shall look at testing, improvement and parameter extraction steps of the MOSFET model. So here we are going to take you through all the 9 steps for the MOSFET. Now this is the modular series of lectures, right now what will be uploaded will be up to models of the MOSFET. Later on, we may record more lectures on models of other devices like BJTs, then passive devices and so on and then we will go on expanding this modular series on semiconductor device modeling.

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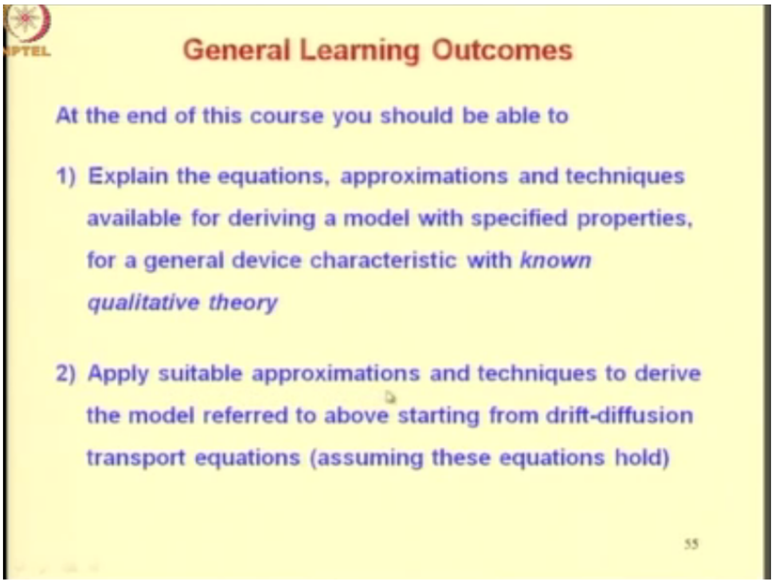

General learning outcomes, now apart from specific outcomes related to each of the modules, we expect that a student undergoing this entire series of lectures will develop some general abilities. Now what are those general abilities? This is what is listed here, so at the end of this course you should be able to explain the equations, approximations, and techniques available for deriving a model with specified properties for a general device characteristic with known qualitative theory.

So suppose you are given a device and then you know its qualitative operation. How do you derive a model, set of equations and so on right? For any device you must know a road map to derive the equations starting from a knowledge of the qualitative theory. Another ability you should develop is apply suitable approximations and techniques to derive the model referred to above starting from the drift-diffusion transport equations assuming these equations to hold.

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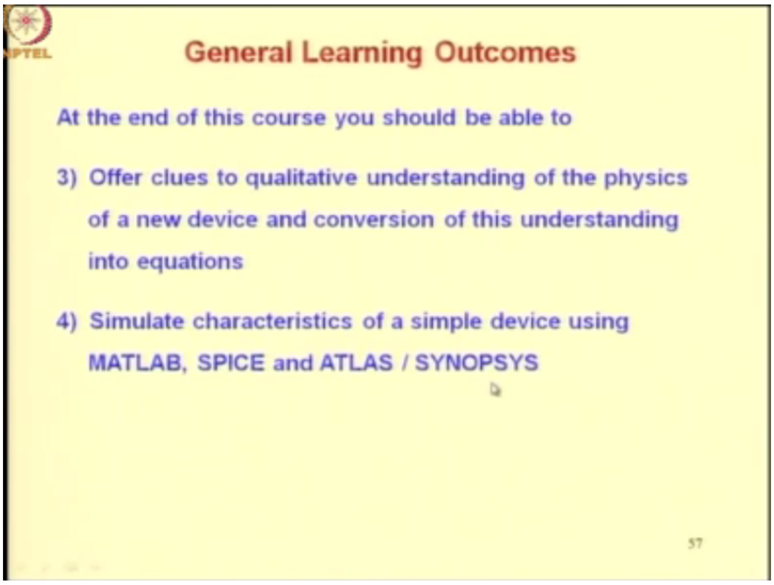

We have already remarked that our course will be based on the drift-diffusion model. Next, offer clues to qualitative understanding of the physics of a new device and conversion of this understanding into equations. So this is a fairly advanced ability right. The first 2 abilities that we discussed were related to converting a known qualitative theory into equations, but now what we are saying is suppose there is a new device right.

And you want to develop its theory right from beginning then if you have done this device modeling course perhaps you would be able to offer some clues as to how to start developing the model. Another ability you would develop is to simulate characteristics of a simple device using MATLAB, SPICE, and ATLAS or SYNOPSIS. So SPICE is a circuit simulator and ATLAS/SYNOPSIS is a device simulator and MATLAB is a program you know it can be used to make calculations using any set of equations.

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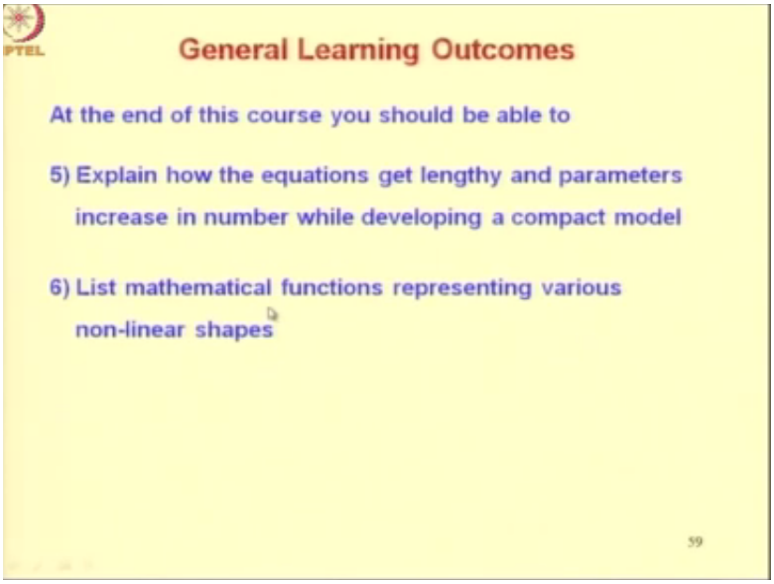

Now you will be able to explain at the end of the course how equations get lengthy and parameters increase in number while developing a compact model. A compact model is a model of a device used in circuit simulation right. What are the details of this kind of a model? What are the features? We shall discuss them in this course okay, but you will know why the equations are lengthy and large number of parameters are used okay in a compact model.

For example, MOSFET model right used in circuit simulation so called BSIM model has a few 100 parameters. Why should there be so many parameters right? How do so many parameters arise? So this is something that you will be able to appreciate by the end of this course and finally you will be able to list mathematical functions representing various nonlinear shapes.

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Let me highlight some unique features of the approach adopted in this lectures. Problem solving or theory development? What are we talking about here? We are talking about both. Now let me give you an example. Now you are aware of the kind of the preparation you do for entrance exam such as the joint entrance exam to the bachelor's program in IITs or the GATE examination, which is an examination which helps you to enter into the post graduate programs in IIT.

Now the kind of preparation you do there is we can call as problem solving preparation. So preparation to solve problems. So this kind of preparation involves understanding the key principles in a sufficient depth so that you can apply these principles to solve problems; however, how those principles are developed from scratch is not something that you bother about much how those principles are developed from scratch so that is called theory development.

The goal of this particular series of lectures is to cover both these aspects, problem solving as well as theory development. So therefore our approach will start from scratch and develop some of the equations that are used in device model and it will also discuss how the equations can be applied to develop the models for different devices. As a result, we are going to talk about both foundations and developments.

What does this mean? Let me give you an analogy, analogy of a building supposing you think the first level course on solid state devices, which you have undergone is the ground floor of the building then in this course we shall talk about both the higher floors of the building as well as the basement and foundations on which the first floor stands right. So we are going to go a little bit deeper down as well as move up okay.

So both these aspects will be covered. So starting from drift-diffusion model developing the equations for IV characteristics of MOSFET would constitute developments right. It is like the higher floors of a building whereas looking at how the drift-diffusion model is obtained starting from electron as a particle or a wave is analogous to or it amounts to exploring the foundations of the drift-diffusion model.

Physics or modeling? Now you might say why this should be an issue? This is the course on device modeling. In fact, if you see all of physics is also some sort of modeling. It is arriving at some sort of the representation for various phenomena in the world okay. So therefore this course has a lot of physics right, a lot of material that people would call as physics though it all comes in modeling.

So in other words, the so called foundations maybe likened by people to the physics and these developments could be liking to modeling; however, please note that both foundations and developments are some sort of modeling just as the physics is also some sort of modeling. Now is it a course of some 3 or 4 credits or is it a modular series? This is an important issue.

The way the course is fashioned as I have remarked earlier, it is an expanding series of several modules. We have given importance to explanations of some key ideas and therefore we have not tried to put restriction on the time. For example, if I take a topic such as energy band diagram, I do not put restriction that I must cover this topic let us say in 3 hours so that the entire course is restricted to about 42 hours or say 52 hours okay.

So this set of video lectures is like an aide for understanding this area. Teachers who would like to use these lectures to teach a time bound course should use these lectures to get explanations of many key ideas and then they can decide what portion of the course they would like to actually teach in the classes. So the focus is on explaining a concept in sufficient detail and the time constraint has been relaxed a little bit.

Therefore, the number of lectures is going to be large. Another aspect of the course is related to explanation and organization of materials. So here we are providing some explanations, which are not readily available elsewhere. Similarly, we have organized the material in a fashion that is not available in the same form in many of the texts. The material as such is available, but the explanations and organization maybe somewhat different, for example characteristic lengths and time.

One set of lectures discussing all the characteristic lengths and time, which are used in modeling. Now this kind of a module or a set of lectures you will not find in books, but in modeling use of characteristics lengths and time is very important that is why we have chosen to devote a module for this topic. So this is how some of the organization of the material is different and the topics the way they are covered are also different. About 6 lectures are devoted to energy band diagram okay.

Now you may not find in books a separate chapter such as energy band diagrams. They might cover different devices and while developing models of different devices, they might include a discussion of the energy band diagram of that device; however, here we have discussed several energy band diagrams in one place and how the energy band diagram arises first of all from first principles right.

So both foundations and developments because we feel that ability to draw energy band diagram of a general device is an important skill that a person who wants to become a good device model developer should have. Video lectures versus book, many books are available on device modeling so why would one look at the video lectures? One reason why people like to look at video lectures is because nowadays they are readily available on internet where much of the other information is available.

So since the computer is the window to the world nowadays many people would like to look at whatever is available on the internet and work with it as far as possible. So this is one of the reasons why video lectures are preferred over books. Another reason people might view video lectures is to get the feel of a classroom. When you read a book it is you who has to pay attention to what is being read there.

In a video lecture; however, there is a teacher, there is an audio visual effect and so on to help you understand the subject and therefore learning becomes somewhat more easy and more comfortable. Another reason for video lectures is that if you compare it to a live class, in a live class if you do not understand a subject or a topic or a small part of the class, you might hesitate to ask the teacher to repeat okay.

Whereas a recorded video lecture, you can pause at any point and then you can repeat that portion which you would to like to go through again and again. So this freedom is available. It is one more reason why people like video lectures. Finally, I would like to mention that we have extensively used slides in the video lectures. It is true that students like blackboard because things can be developed in a very nice way starting from some simple things on the board.

However, when we want to impart a large amount of material efficiently, slides can be very useful. There are certain diagrams and so on which take a long time to draw on the board, but that much of time need not be spent in imparting the knowledge about that diagram to the student. So that amount of time that is spent on drawing the diagram on the board and giving as an example can be saved if the same thing is developed quickly in a slide.

So in this manner, the information transfer becomes much more efficient, you can transfer more information in the same time that is why slides have been used apart from blackboard.

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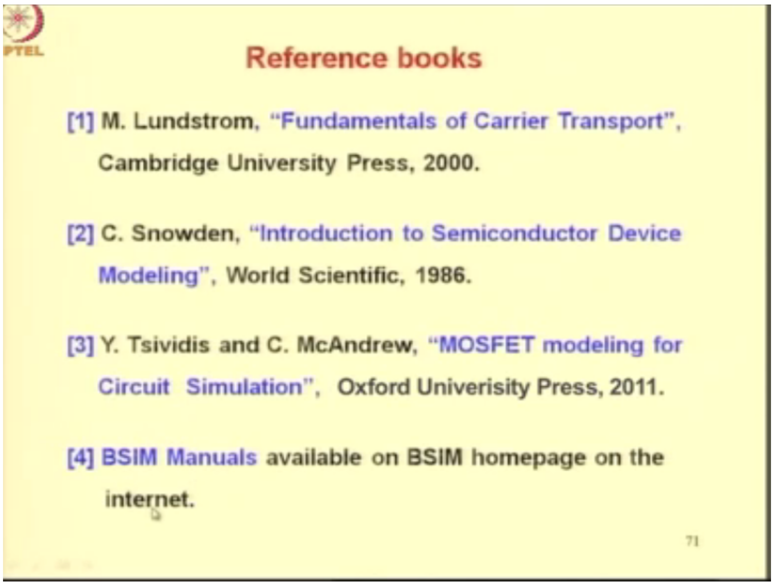

Let me end the lecture with the set of reference books. One nice book for this course or rather the transport phenomena part of the course is the book by Lundstrom on Fundamentals of Carrier Transport. Many people might think that this topic falls in the area device physics rather than modeling, but as I mentioned physics is also about modeling. Another point is today the device sizes have shrunk a lot okay.

And many types of devices are coming where lot of different types of phenomena occur and therefore it is very important to get a good thorough understanding of electron transport and therefore apart from drift-diffusion model, there are other models, which are required to understand the modern devices such as balance equations and in fact some of the cases you have to go to as basic equations as Schrodinger’s equation or Boltzmann transport equations and so on.

And therefore discussion of these topics is very important so that a person who is exposed to this topic can then branch off to modeling in any direction nano or high frequency or high power or anything of the sort. Therefore, a good idea of carrier transport is important and this is a good book. Then coming to applications, device simulation, Christopher Snowden, this book introduction to semiconductor device modeling discusses how devices can be simulated, how models are used for device simulation.

Coming to circuit simulation, Tsividis and McAndrew MOSFET modeling for circuit simulation, this book is very good for understanding the MOSFET models employed in circuit simulation, compact models. Finally, really coming to the application and BSIM Manuals available on BSIM homepage. So here we are starting from foundation and going to applications right.

So this is a fundamental book and this is simulation, this is further moving towards application, this device simulation and this circuit simulation and finally this really about the model used in circuit simulation, the practical aspects of the model right. If this is theoretical aspects of the model, these are really practical aspects of the model.

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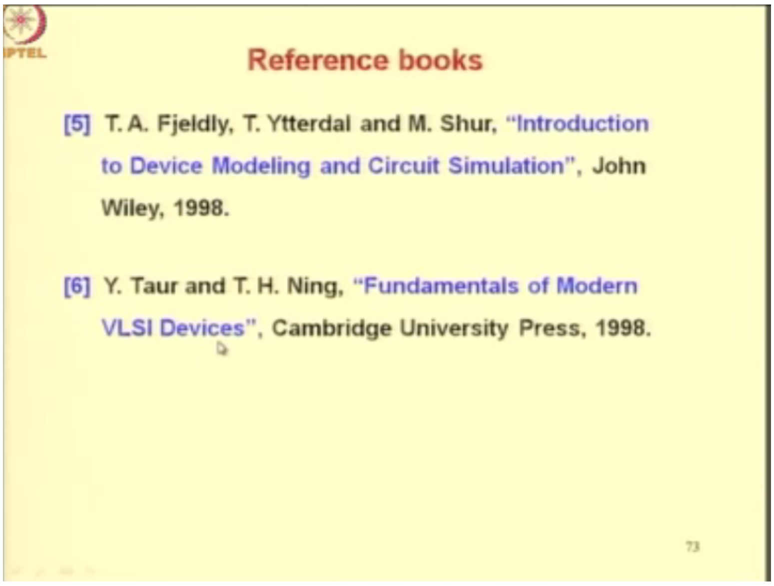

I would also like you to look at 2 other books one of which is a book by Fjeldly Ytterdal and Shur on introduction device modeling and circuit simulation. This book gives models of various devices for circuit simulation whereas the book by Tsividis concentrates on MOSFET, this considers various devices and another book Taur and Ning talks about Fundamentals of Modern VLSI Devices.

So with that we come to the end of the first lecture of this course to quickly summarize what we have discussed. We first answered the what and why question. What is a device model and why study device modeling? Then we looked at the contents of the course. We looked at what abilities you will develop as a consequence of going through these set of video lectures and then we pointed out some unique features of the course and finally a set of reference books.

In the next lecture, we shall give a more formal introduction to this course or this modular series of lectures on semiconductor device modeling.