Semiconductor Device Modeling
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Lecture - 02
Introduction

In the very first lecture of this course, which was also the module 0, we discussed the motivation, contents and learning outcomes. We briefly discussed what is a model? and explained in detail why the study of device modeling is important. We pointed out that this course would be useful for model users such as IC designers, device designers and device physicists as well as for those who want to develop models for circuit and device simulation.

Then we pointed out some of the unique features of the approach that we have adopted in this course or modular series of lectures.

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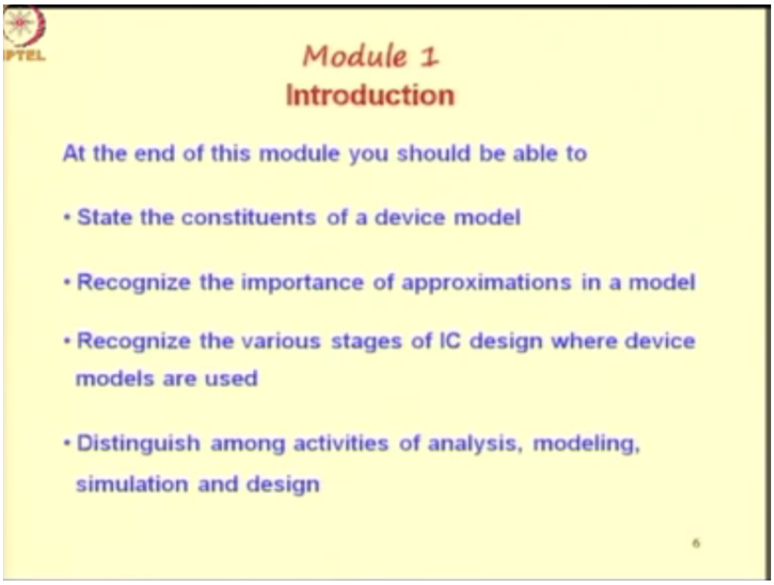

Now at the end of this module, so this module is also 1 lecture module, you should be able to state the constituents of a device model, recognize the importance of approximations in a model, recognize the various stages of IC design where device models are used and distinguish among activities of analysis, modeling, simulation and design.

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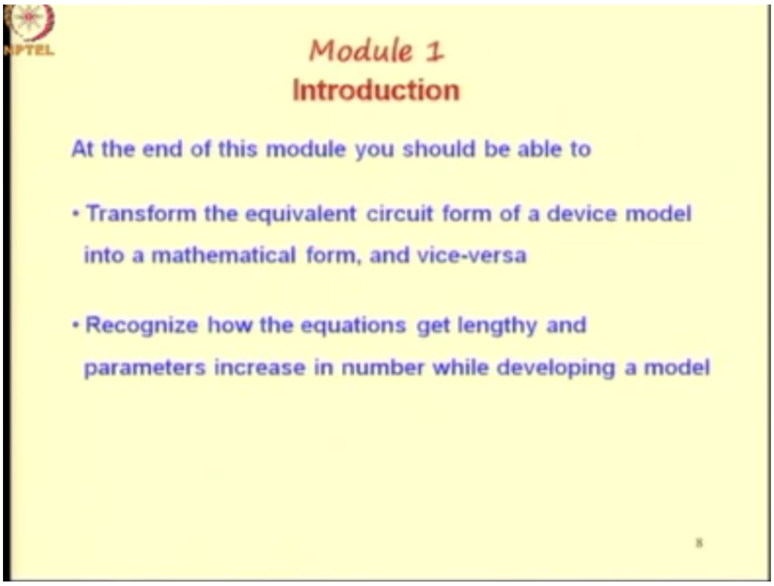

You should also be able to transform the equivalent circuit form of a device model into a mathematical form and vice versa and finally recognize how the equations get lengthy and parameters increase in number while developing a model. So this lecture is a formal introduction to the course.

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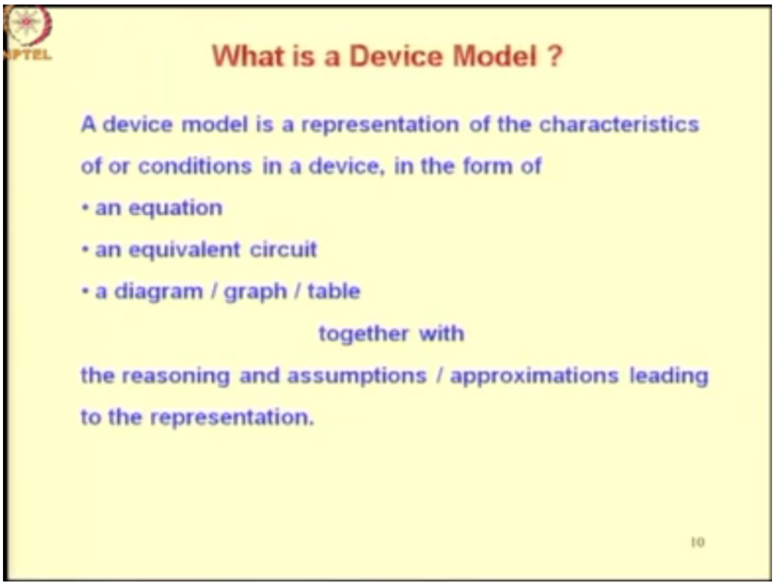

Let me repeat a slide from the previous lecture regarding what is a device model? So we said a device model is a representation of the characteristics of or conditions in a device in the form of an equation and equivalent circuit or a diagram, graph or table together with the reasoning and assumptions or approximations leading to the representation.

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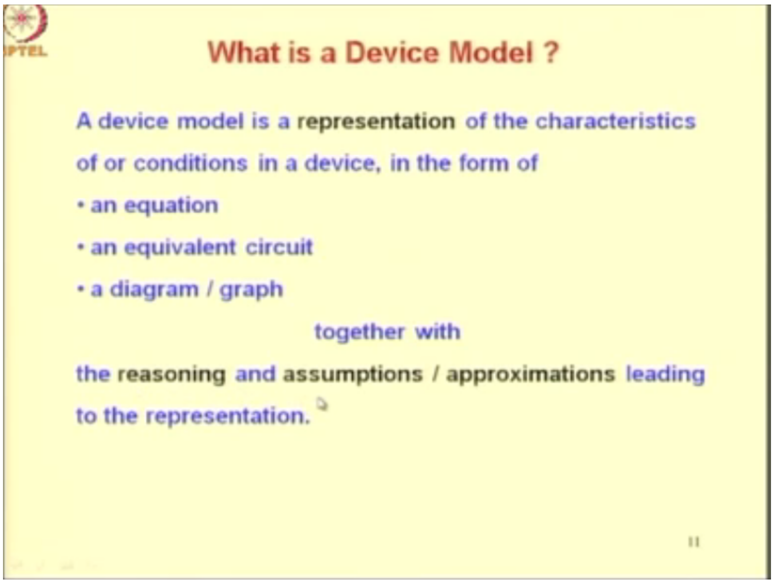

Let us highlight 3 important words in this definition namely the representation, the reasoning and assumptions or approximations. These are the 3 constituents of a device model. We know that we can remember a diagram much longer in the memory than a definition made up of words.

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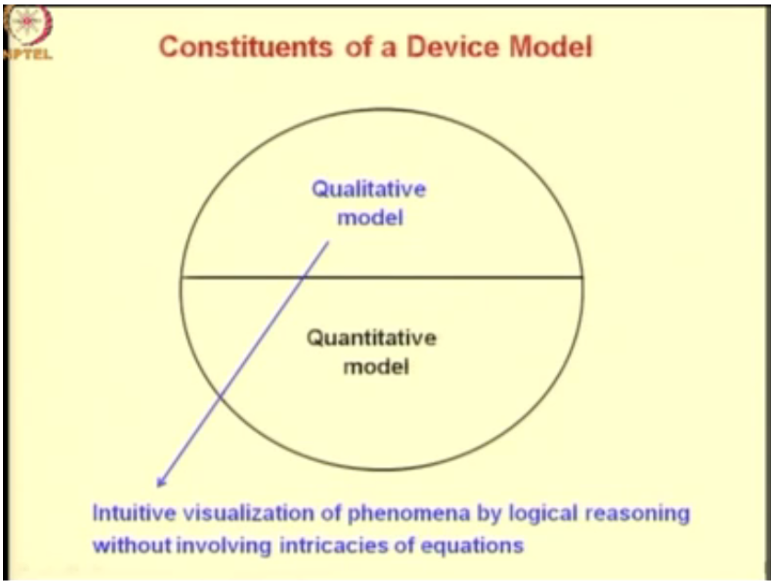

Therefore, let us convert this information into a diagram. So if the circle shows the body of the model, then it has 2 important parts namely qualitative model and quantitative model. The qualitative model is intuitive to visualization of phenomena by logical reasoning without involving intricacies of the equations.

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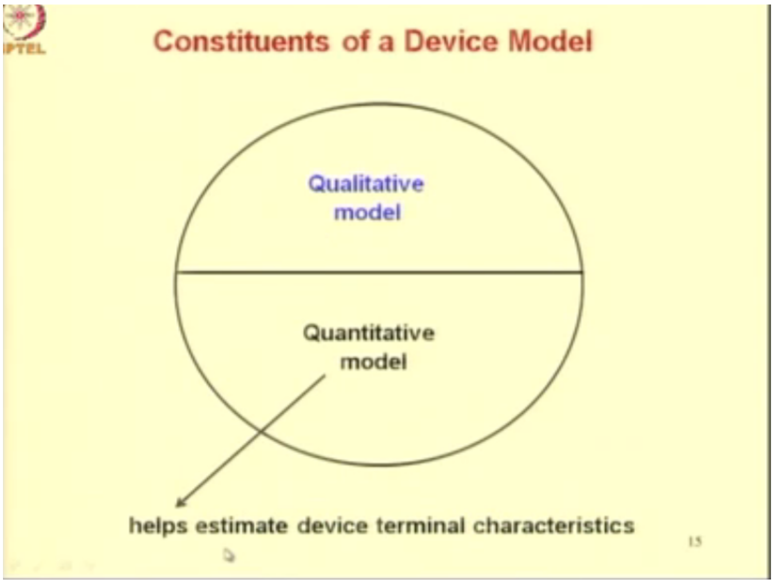

On the other hand, the quantitative model which is the face of the model helps us estimate device terminal characteristics.

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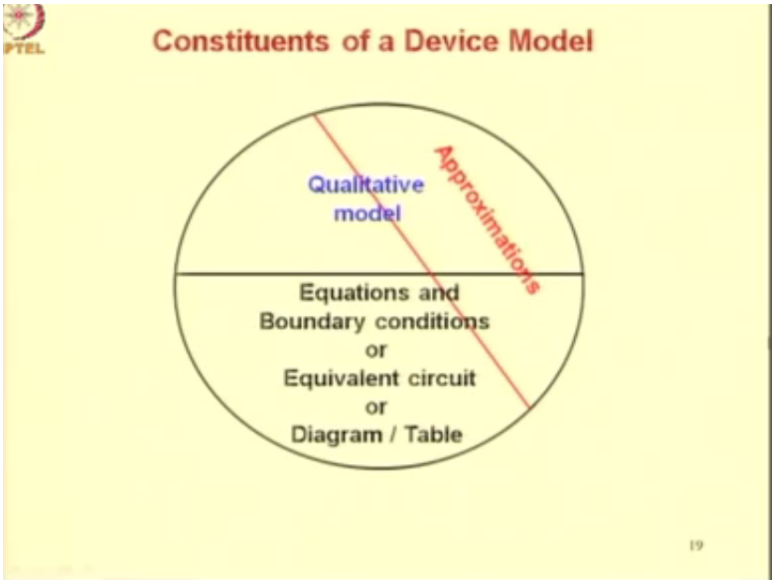

The quantitative model could be in the form of equations and boundary conditions or equivalent circuit or diagram or a table. Here we are including graphs also in diagrams. The important part of a device model is a set of approximations, which are employed both in the qualitative part of the model as well as quantitative part. So device modeling begins with approximations.

In fact, any model development begins with approximations. After the qualitative part is converted into equations, the equations maybe simplified to get the final form of the model.

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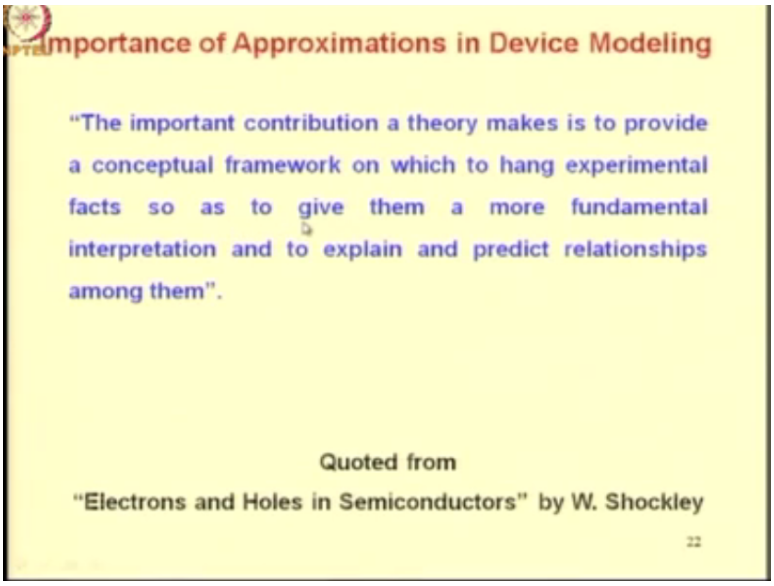

Since approximations are important let us dwell a little bit on the importance of approximations in device modeling. Here is a quote from the book electrons and holes in semiconductors by Shockley. The important contribution a theory makes is to provide a conceptual framework on which to hang experimental facts so as to give them a more fundamental interpretation and to explain and predict relationships among them.

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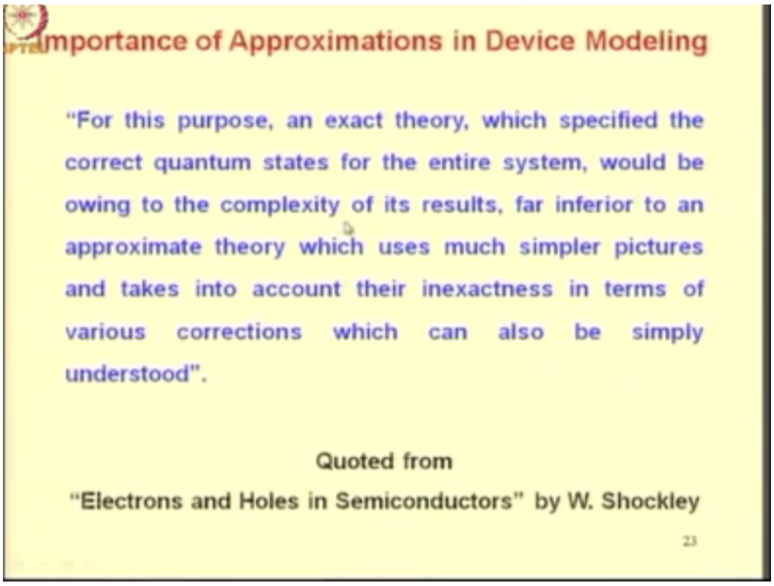

For this purpose, an exact theory which specified the correct quantum states for the entire system would be owing to the complexity of its results far inferior to an approximate theory which uses much simpler pictures and takes into account their inexactness in terms of various corrections which can also be simply understood. So the importance of approximations in any theory or model development cannot be over emphasized right.

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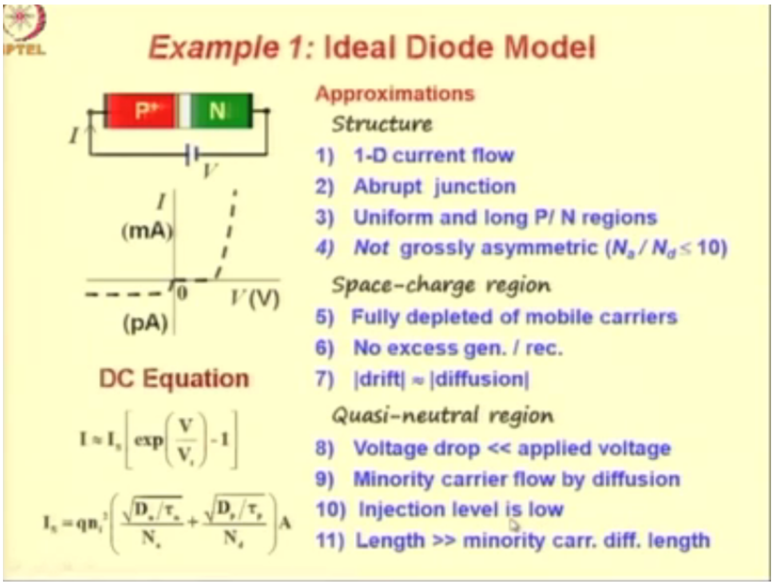

Let us consider the approximations in some of the models we are familiar with. Let us look at the ideal diode model, which we presented in the very first lecture of the course. This was the DC equation meaning equation between the current I and the voltage V. This is the biasing arrangement. This graph shows the current voltage relation predicted by this equation. Now what are the approximations in this model?

You can divide the set of approximations into 3 parts, one set related to the structure of the device, another set related to the space-charge region so this is the space-charge region and a third set related to the quasi-neutral region so this green N region and the red P+ region, these are the quasi-neutral regions. So a device can be separated into space charge and quasi-neutral region.

Related to the structure the approximations are 1-dimensional current flow and abrupt junction. This means the doping changes abruptly from P-type at the junction to N type when you move to the other side. The 2 other approximations related to the structure are uniform and long P/N regions so these P and N regions are long. Now what is the scaling length with respect to which we decide whether the regions are long or not will come to that shortly.

Another approximation related to the structure is related to the doping, so the junction is not grossly asymmetric. In other words, Na/Nd <= 10, so the doping on one side of the junction should not be too high as compared to the other side okay, factor of 10 being the kind of rough limit. So the ideal diode model is valid only under these structural restrictions.

The space-charge region, we assume that the space-charge region is fully depleted of mobile carriers. So this region here is the space-charge, which is fully depleted of mobile carriers. Further no excess generation or recombination in the space-charge region. A very important approximation that leads to exponential relation of the current with respect to the voltage is the fact that the drift current is assumed to be approximately equal to the diffusion current in magnitude.

Now this approximate equality can also be stated in another form namely that the magnitude of the drift and the magnitude of the diffusion currents are much larger than the difference between them. It is the difference between drift and diffusion that contribute to the total current. The drift and diffusion in the space-charge region, this is very important. Quasi-neutral region, we assume that the voltage drop across the quasi-neutral region is much less than the applied voltage.

This means that this N region and this P+ region do not experience much of a voltage drop and therefore the applied voltage V falls almost entirely across the space-charge region. Then minority carrier flow occurs by diffusion alone. So in both N and P neutral regions, the minority carriers are flowing because of diffusion alone and finally the injection level in the quasi-neutral regions is low and the length of the quasi-neutral regions is much greater than minority carrier diffusion length.

So when we said uniform and long P+N regions, so the long P+N regions here, this is the expression giving you an idea of what is meant by long so the length is much more than minority carrier diffusion length.

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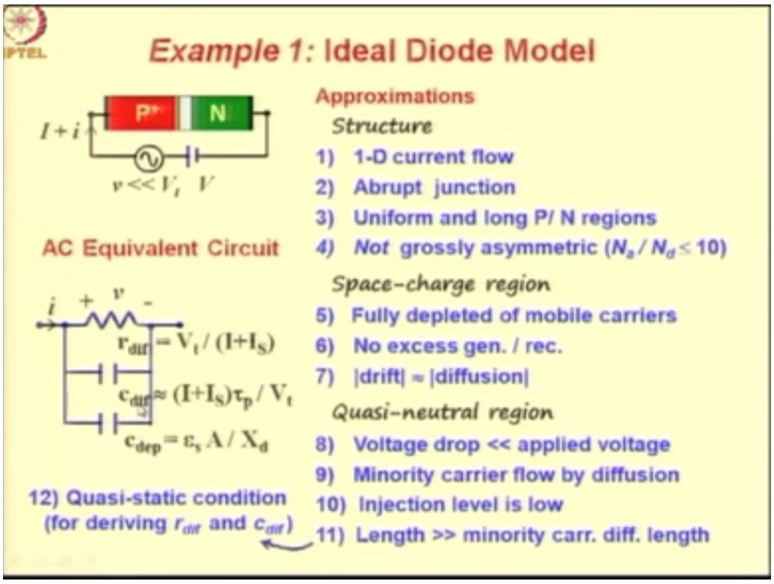

Let us look at the AC equivalent circuit based on the same diode model. So in this case, you are applying a small signal voltage, which is much less than the thermal voltage and this small signal voltage is superimposed over DC voltage. You have a DC current or which a small signal current is superimposed. The relation between small signal current I and small signal voltage V is given by this equivalent circuit, which has a resistance in parallel width, two capacitances.

Now you see the expressions here are independent of frequency, you must have encountered these expressions in your first level course, so you know that these expressions are based on a very important approximation namely the quasi-static approximation. So the conditions are assumed to be quasi-static for deriving the diffusion resistance and the diffusion capacitance. If this quasi-static assumption is not made then the diffusion resistance and diffusion capacitance would become a function of frequency.

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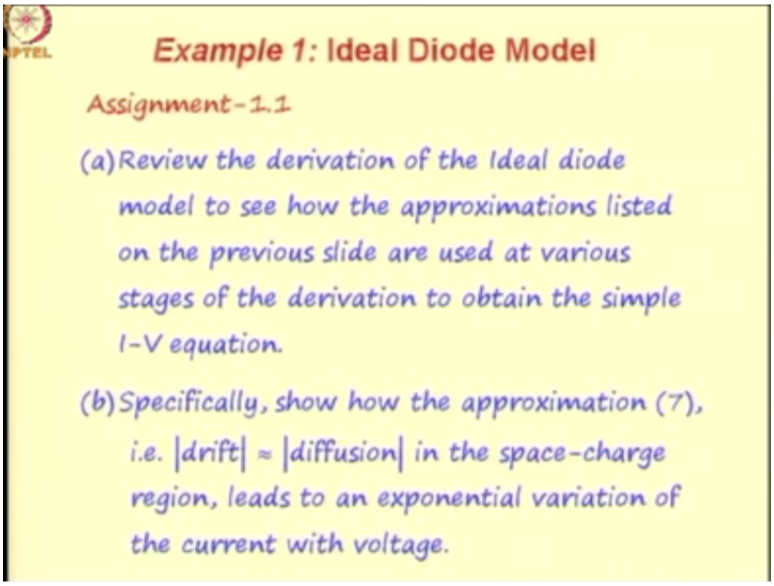

Here is an assignment for you. Review the derivation of the ideal diode model to see how the approximations listed on the previous slide are used at various stages of the derivation to obtain the simple I-V equation and part b specifically show how the approximation 7 that is the magnitude of drift is approximately equal to the magnitude of diffusion current density in the space-charge region leads to an exponential variation of the current with voltage.

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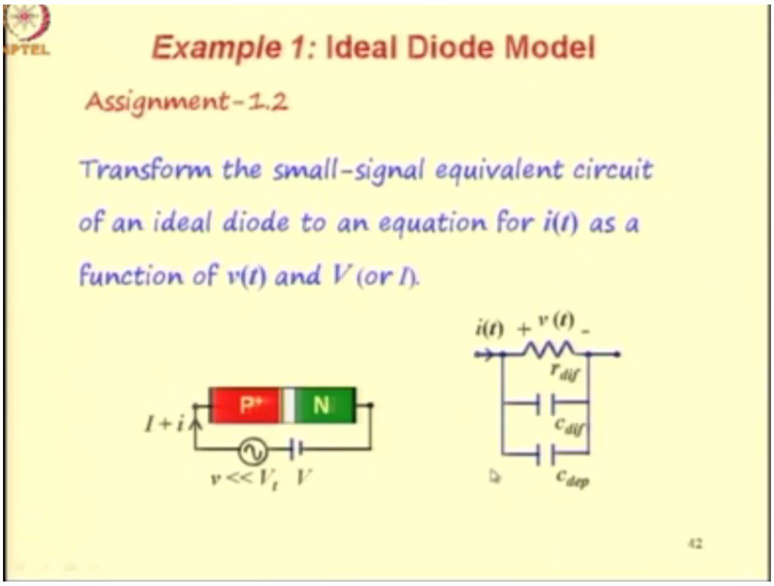

Another assignment transforms the small-signal equivalent circuit of an ideal diode to an equation for small-signal current as a function of time as a function of small signal voltage as a function of time and the DC voltage V or the DC current I. So these are the equivalent circuit components. You have to convert this equivalent circuit into relation for i of t as a function of v of t.

So this will tell you how the equivalent circuit form of the model of a device can be converted into a mathematical expression.

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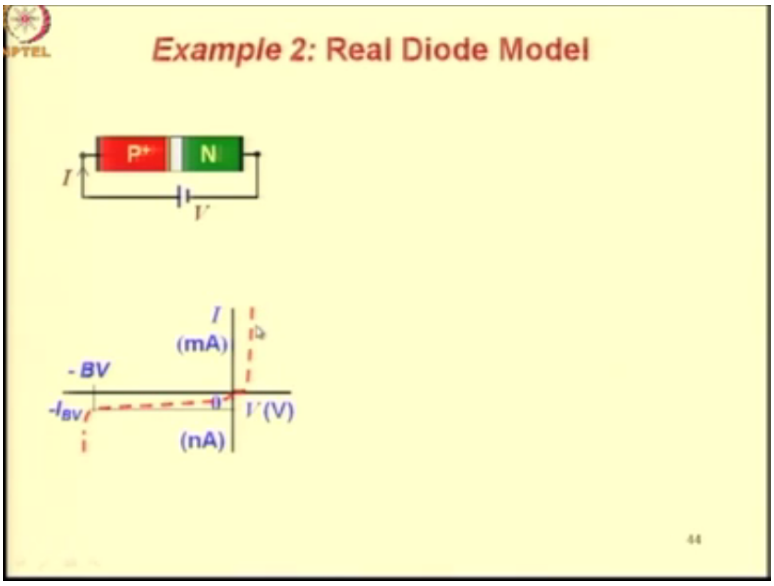

Let us look at a real diode model. Now this model that we are discussing it is possible that you may not have done in your first level course because it tries to take into account a number of phenomena and the equation that you see will ultimately be much more complex than the ideal diode model. However, to understand the fact that a set of approximations are associated with any model, you do not need to know the derivation of the model.

So here we are only trying to emphasize how the mathematical expression of the model is related to the set of approximations. So a real diode model tries to capture this particular current voltage relation. Let us identify some differences from the ideal current voltage characteristics. Firstly, there is a breakdown voltage right. So the breakdown is not included in ideal diode model.

Secondly and very important the reverse current scale, which was pico amperes in ideal diode model is nano amperes here. We are considering a small signal diode. There are some variations in the shape of the forward characteristics, which are not so evident here. We will be including the effect such as generation recombination for small voltages and high injection level and voltage drops across the quasi-neutral regions under high voltage conditions.

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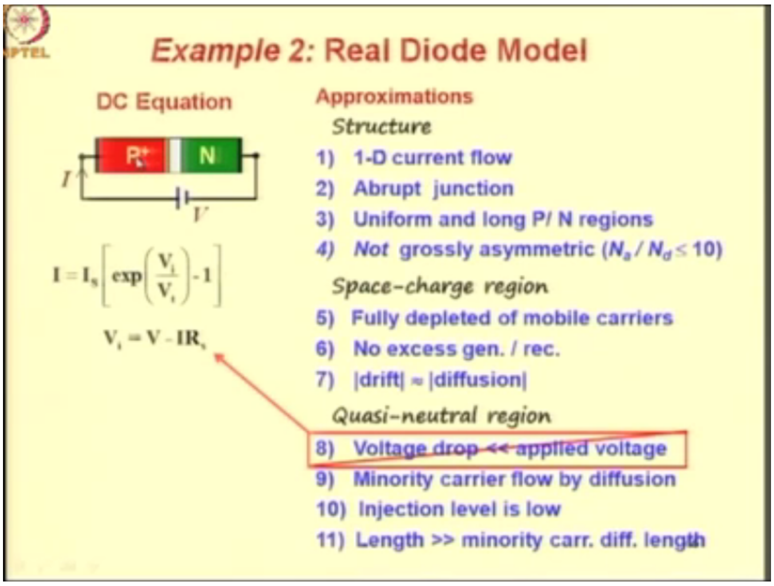

To look at the approximations associated with the real diode model let us begin with the ideal model. So this is an ideal diode equation and these are the set of approximations associated with an ideal DC equation. The real diode model is obtained by dropping the various approximations one by one. For example, if you drop the approximation that there is no voltage drop across the quasi-neutral region then the modification that happens to the ideal diode equation is as follows.

You replace the DC voltage V which was the DC applied bias by V suffix i which is the internal voltage or the voltage across the space-charge region. So here we are using the symbols employed by the SPICE diode model. V suffix i = the applied bias V - the DC current I multiplied by a series resistance which represents the voltage drop across the quasi-neutral N and P regions.

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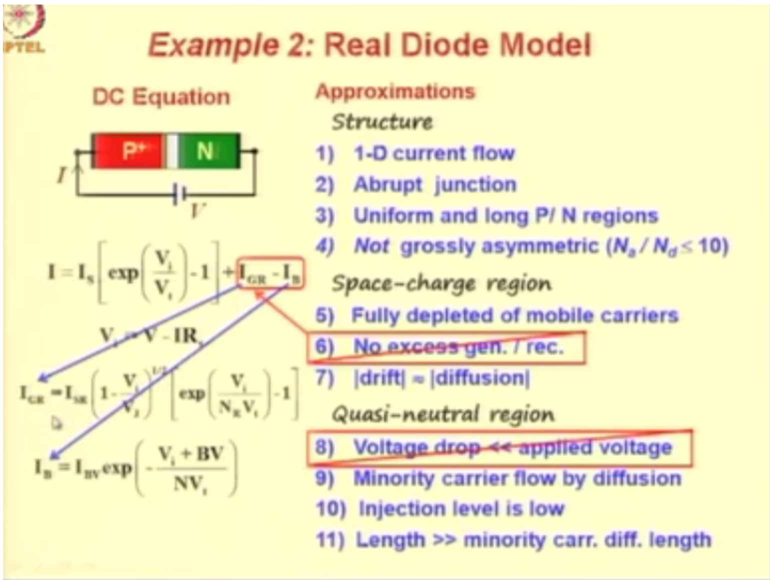

If you drop the approximation that there is no excess generation or recombination. In other words, we include excess generation and recombination in the space-charge region then you get 2 additional current terms. This is the thermal generation recombination current term and this one is the breakdown current term because of breakdown happens in the reverse bias you have a negative sign here.

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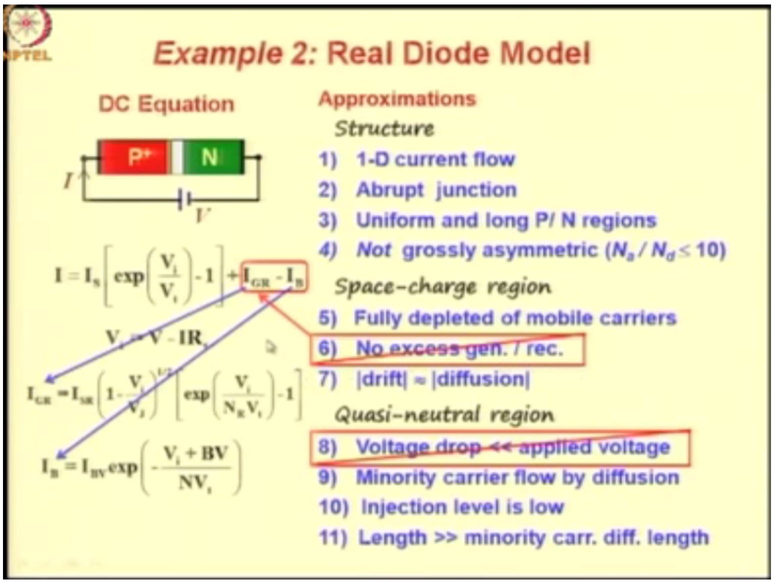

The thermal generation recombination is given by IGR = ISR which is reverse current due to generation recombination multiplied by 1 - the internal voltage that is the voltage across the space-charge region divided by the built in potential of the junction that is V suffix j multiplied by exponential of Vi divided by NR Vt where NR is an ideality factor related to generation recombination -1.

I would like to emphasize that here we are using the symbols employed by the SPICE diode model. The breakdown current on the other hand is given by IBV which is the current when Vi = minus of BV multiplied by exponential of minus of Vi +BV/N Vt where N is an ideality factor different from this NR.

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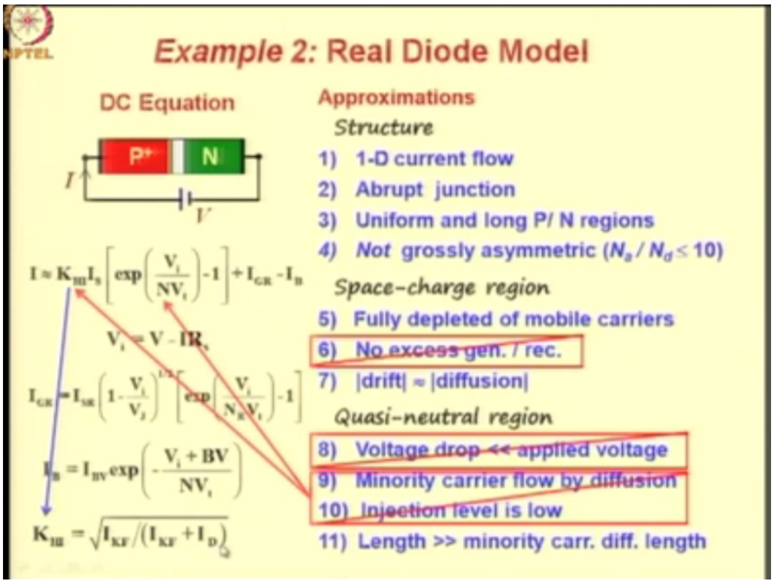

If you drop 2 more approximations namely minority carrier flow occurs not only by diffusion, but also by drift rather you drop the approximation that minority carrier flow occurs by diffusion alone and assume that drift will also be included and that the injection level is not necessarily low, it could be high. Then you get 2 additional terms, so you introduce an ideality factor in the main exponential term of this equation and you introduce the factor K suffix HI, HI stands for high injection level.

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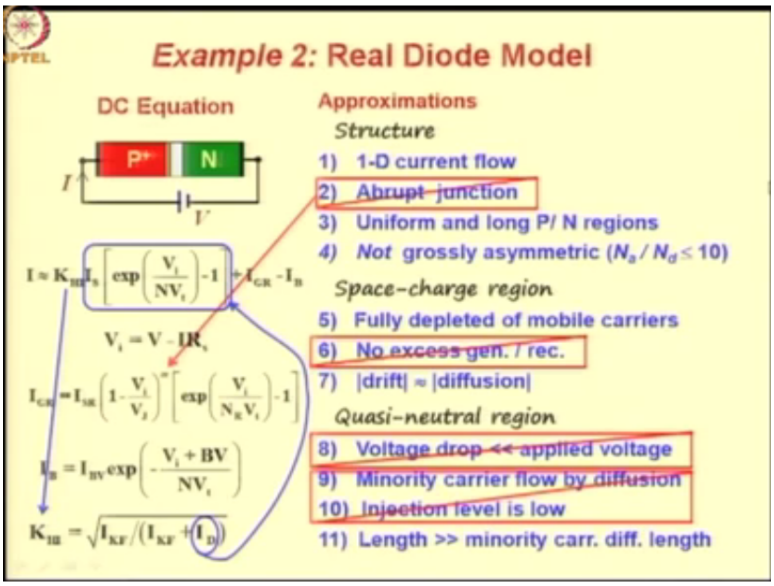

So this K HI is given by the formulas square root of IKF divided by IKF+ID so IKF is another parameter and ID is nothing, but the current IS into this exponential factor. Now if you relax the assumption that the junction is abrupt, which means you assume a graded junction. So a doping profile is not varying abruptly at the junction, but somewhat slowly right.

Then the modification that you have to do is to change this factor here to m which is the fitting parameter. The value of m depends on the extent of grading of the doping. So in this manner you can see that by dropping the approximations one by one you can develop a model for the real diode and the consequence of dropping the approximations is that more and more terms get added in the equation.

So what you find is lesser the number of approximations more complex the model equation. On the other hand, if you encounter a simple equation, a simple model, you must always be aware that there will be a number of approximations associated with the equation and unless you are aware of the approximations you may commit the mistake of using the simple equation in regions where the model is not valid.

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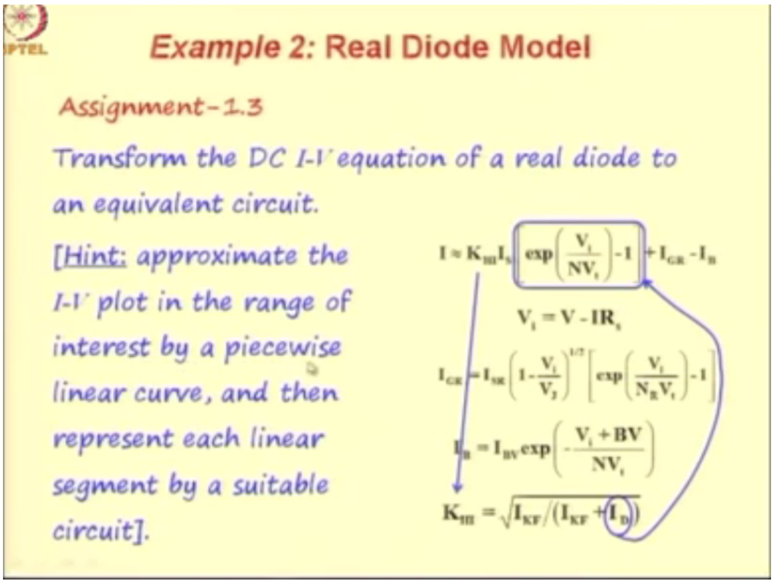

Here is an assignment, transform the DC I-V equation of a real diode to an equivalent circuit. So far one assignment involved converting an equivalent into a mathematical equation. This is the reverse. So you have an equation you convert it into an equivalent circuit to see what would happen if you were to use an equivalent circuit instead of an equation to represent the DC I-V characteristics.

So this is your equation which looks somewhat more complex and I admit that you may not have derived this equation in the first level course, but I want to emphasize that you need not have derived this equation. Just take a close look at the equation for a few minutes and identify the terms with various phenomena. This you can very easily do by going through the discussion that we just now had where we showed how dropping of approximations one by one introduce these turns.

Then you will find that this current voltage relation is a nonlinear relation and you will have to approximate this nonlinear relation by something like a piecewise linear relation and convert each segment of the current voltage characteristics in this piecewise linear relation into an equivalent circuit. So this is the hint, approximate the I-V plot in the range of interest by a piecewise linear curve and then represent each linear segment by a suitable circuit.

So this assignment is basically meant to drive home the point that while for certain situations the equivalent circuit form of the model maybe the best one to use, some other situation the mathematical equation would be the best one to use. Although, in any situation for a device characteristics both forms of models are available, equivalent circuit and equation form. So it is convenient to use one of them okay.

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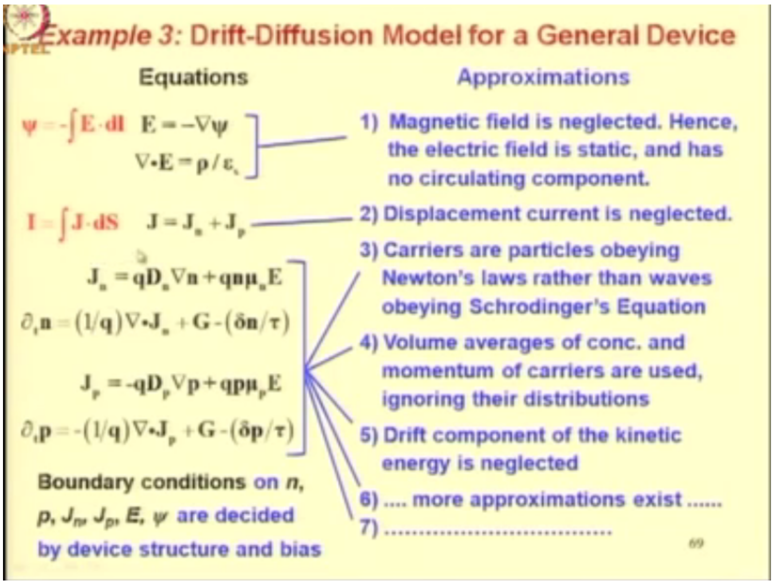

Let us look another example, drift-diffusion model for a general device. This example was also considered in the first lecture. Let us list the equations and then every time we list some equations we also tabulate the approximation that has led to that equation. E= - grad psi and diversions of E = rho/epsilon s where rho is the space-charge and epsilon s is the permittivity of the semiconductor.

Now when you write these equations the approximation involved is that magnetic field is neglected hence the electric field is static and has no circulating component, J=JN+JP. When you write this equation the approximation is that the displacement current is neglected. Consider the current density and continuity equations for electrons and holes.

When you write these forms of equations, there are a few approximations that are made of which the first is carriers are particles obeying Newton's laws rather than waves obeying Schrodinger's equation. Then volume average is of concentration and momentum of carriers are used ignoring the distributions and drift component of kinetic energy is neglected. Now when you heard these approximations you might wonder where did I come across these.

In the first level course, a discussion may not have taken place about these various approximations that we have listed so far. In the present course, we are going to discuss about these approximations in detail. So all these ideas will get clarified. Right now, our goal is to list the approximations and show how each equation that we use in a device model is associated with some approximation or the other.

There are more approximations associated with these equations. The boundary conditions on n, p, Jn, Jp, E and psi, which are the variables associated with these 1, 2, 3, 4, 5, 6 equations are decided by device structure and bias. From these equations for any given voltage or potential different psi, you can find out the current I in this approach. So apply the psi which fixes the boundary conditions and then solve these equations to get the various quantities n, p, Jn, Jp, E and psi as a function of space and time.

And then at any instant you can put together the current densities of electrons and holes and integrate the current density over the contact area to get the current.

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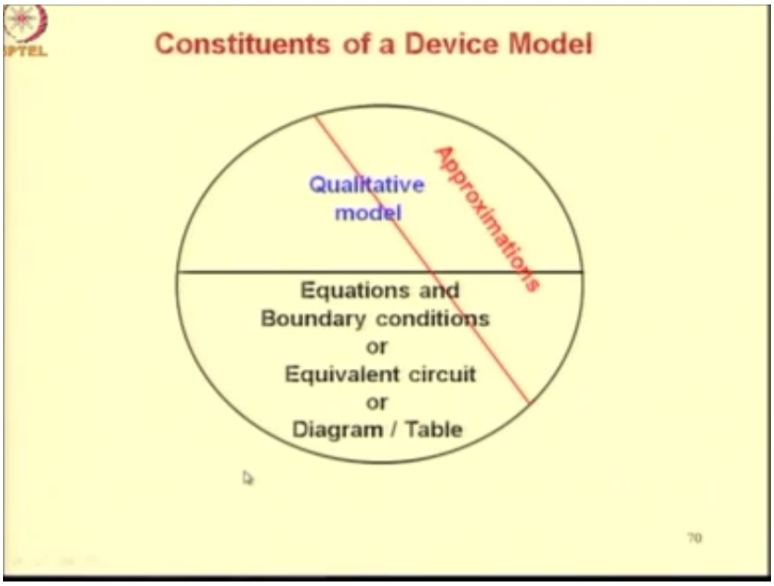

Let me repeat the slide about constituents of the device model, which said that the body of the model consists of qualitative part, a quantitative part which could be equations in boundary conditions or equivalent circuit or diagram, graph and table and an important part of both qualitative and quantitative models is the set of approximations. So this is the diagram that you should commit to memory about a model and you should not assume that only the equation equivalent circuit or diagram or table is the model.

So I want to repeat the quantitative part of the model is the face which is very, very evident, but the entire body should not be forgotten, which consists of all the approximations and the qualitative reasoning, which is actually the starting point of development of any model.

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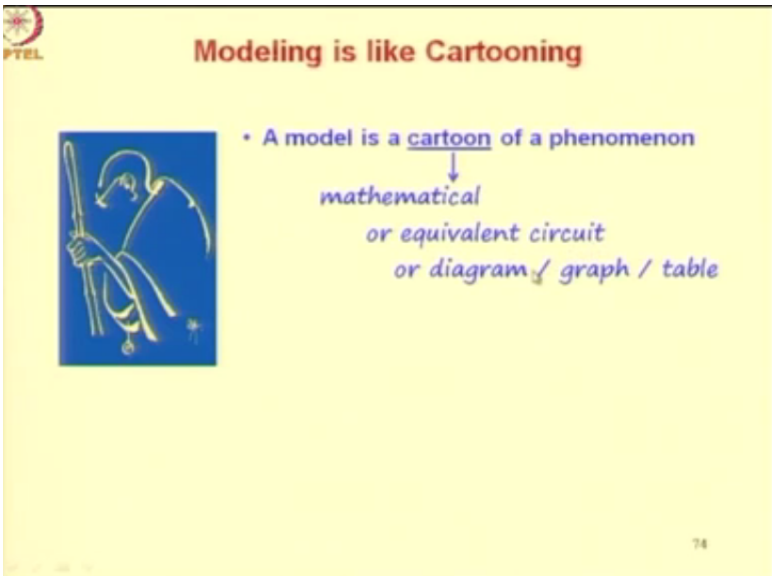

Let us look at modeling activity a little bit philosophically. So modeling is like cartooning. Let us look at a cartoon. All of you are familiar with this cartoon. There are just a few lines in this which capture the personality of the person whose cartoon is depicted here. From this few lines, you can figure out that the cartoon represents the well-known figure namely Gandhiji. So the art of cartooning is to just find out those few set of lines, which can capture the personality.

Cartoon is not a photograph. So cartoon is a model. In modeling also, the philosophy is same. Can you just identify those dominant phenomena and those few equations, which will represent the actual operation of the device. So model is a cartoon of a phenomenon where the cartoon could be a mathematical form, equivalent circuit form, diagram, graph or a table. Now how do you decide how many lines are required in a cartoon?

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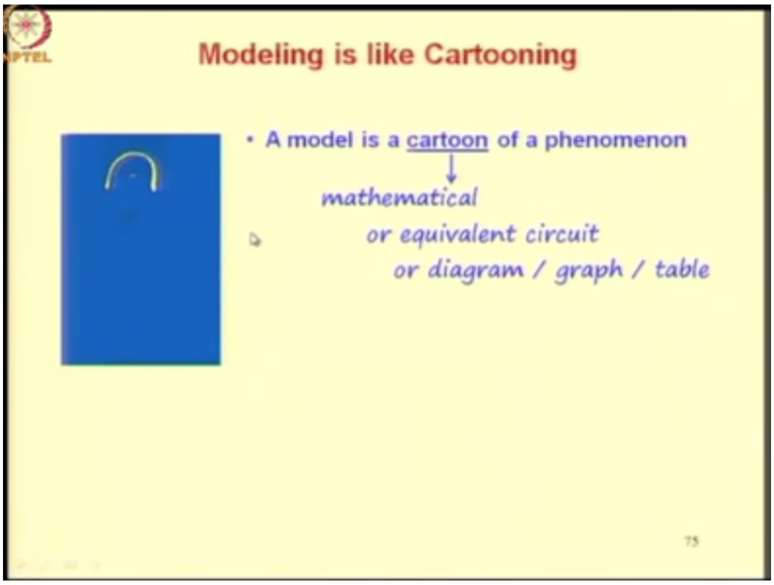

For example, in this case supposing I were to use just 1 curved line, this would not be sufficient to communicate the person.

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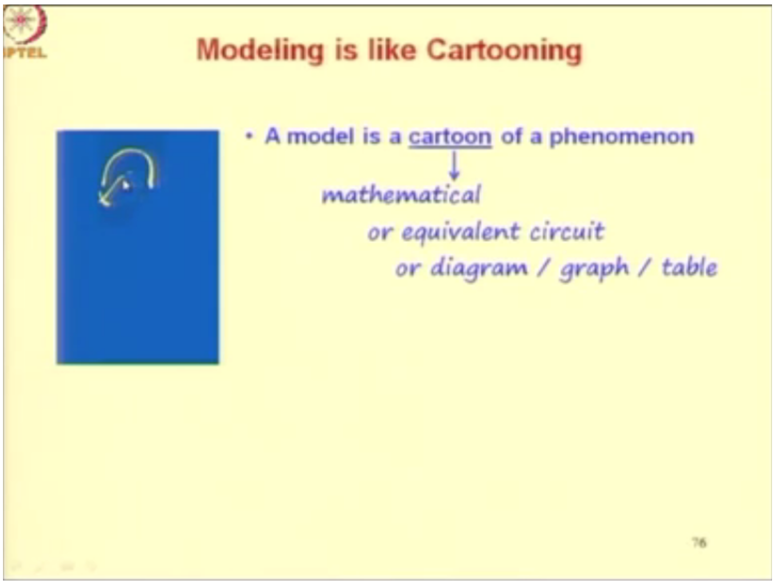

Let me add couple of more lines, now this figure is closer to communicating the person, but still some ambiguity remains.

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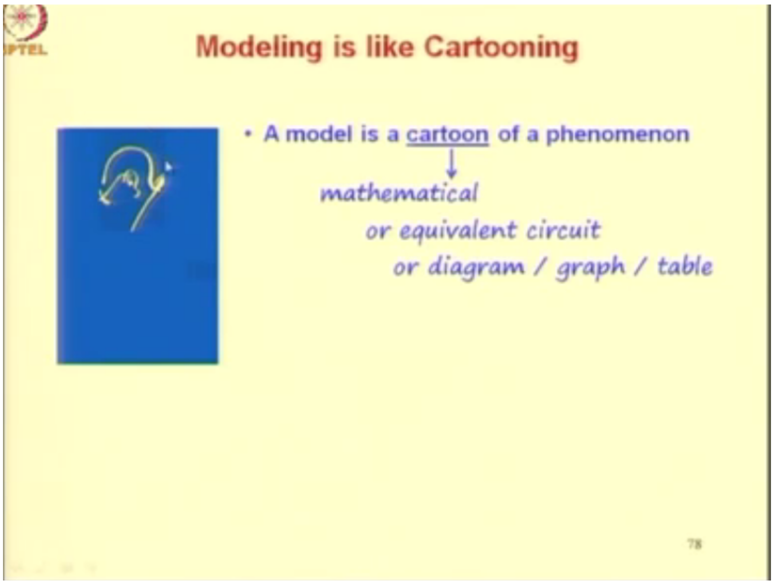

If I add a couple of more lines, these are almost sufficient to depict the person and you can really identify whose cartoon is this. Similarly, in device modeling you are looking for those few equations and those few phenomena, which need to be incorporated in the model.

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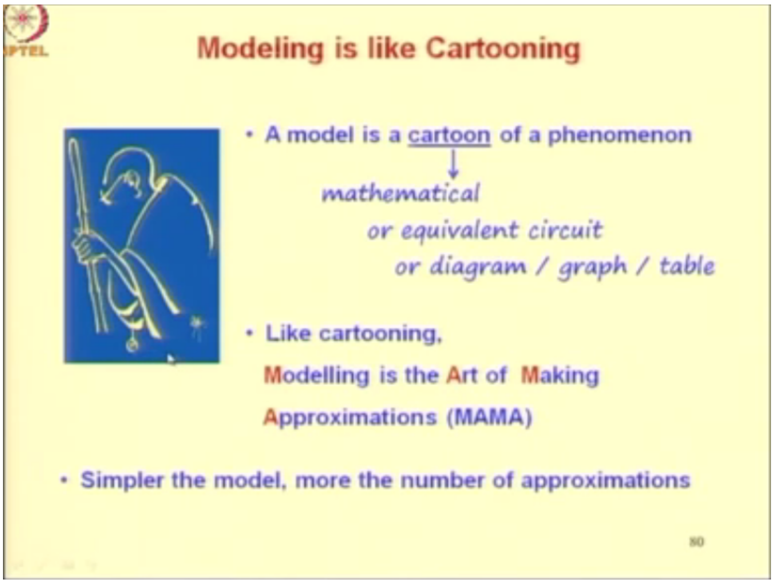

Therefore, we can say like cartooning modeling is the art of making approximations abbreviated as MAMA. So if you remember the word MAMA that will convey a quite vividly what exactly is involved in modeling. It is the ability to come up with approximations, which will be appropriate to provide an equivalent circuit, an equation or a diagrammatic or tabular representation of the situation.

Finally, simpler the model more the approximations. So you can see here that if you add more and more lines definitely the model becomes more and more realistic. The figure becomes more and more realistic and the approximations are less, but then the model is complex. So you are using more lines to represent the person because you want to get the representation closer to reality.

The same thing happens in a model. So if you want to use a simple model then there will a large number of approximations.

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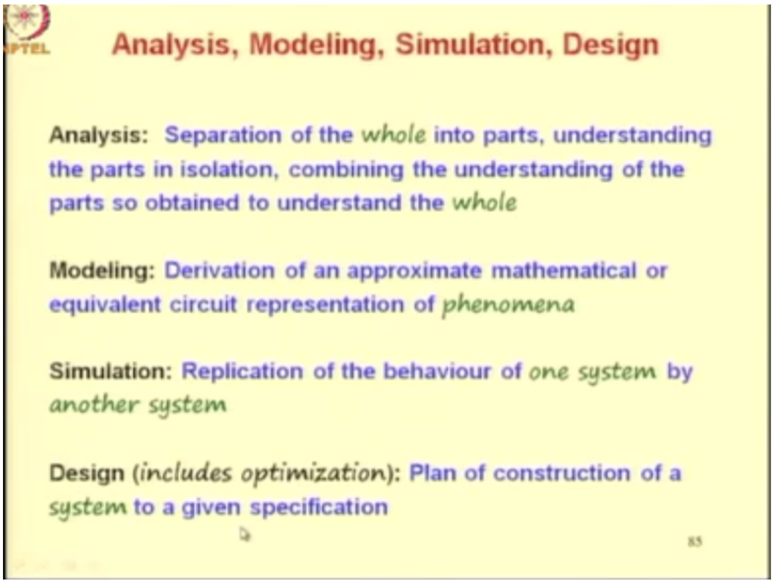

Now we often use terms, analysis, modeling, simulation and design; however, many students are little bit confused about the distinctions between these terms and therefore at times they end up using 1 term for the other. To avoid this kind of a difficulty let us define these 4 terms, analysis, modeling, simulation and design and understand the differences between them.

Analysis means separation of the whole into parts, understanding the parts in isolation and combining the understanding of the parts so obtained to understand the whole. On the other hand, modeling is derivation of an approximate mathematical or equivalent circuit representation of phenomena. Here you can also include diagrams and tables. Simulation is replication of the behavior of one system by another system.

And finally design which includes optimization is nothing, but plan of construction of a system to a given specification. So you must commit these definitions of the 4 terms to help you remember the distinctions between the terms and the correct definitions of these terms. Let us consider some examples.

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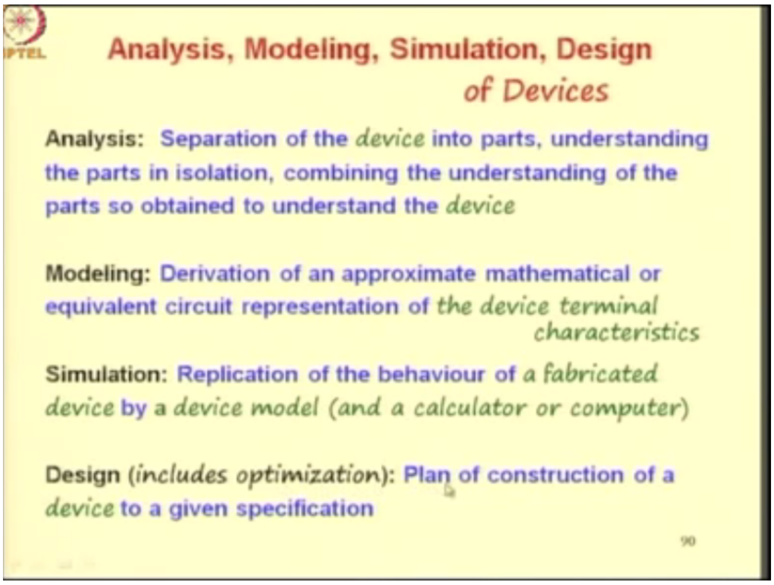

Suppose I am talking of analysis, modeling, simulation and design of devices, then analysis the whole would mean the device so if you replace the word whole by device, which is what has been done here then this definition would correspond to analysis of devices that is separation of the device into parts, understanding of the parts in isolation, combining the understanding of the parts so obtained to understand the device.

Modeling of a device what does it mean? So you replace term phenomena by the device terminal characteristics. So device model is derivation or device modeling activity is derivation of an approximate mathematical or equivalent circuit representation of the device terminal characteristics. Device simulation, you replace one system and another system by the terms of fabricated device and a device model.

So simulation means replication of the behavior of a fabricated device, which is one system by a device model and calculator or computer, which constitutes the other system. Finally, the definition of design the system refers to the device in device design. So device design means plan of construction of a device to a given specification. Let us illustrate these ideas using the example of a PN junction.

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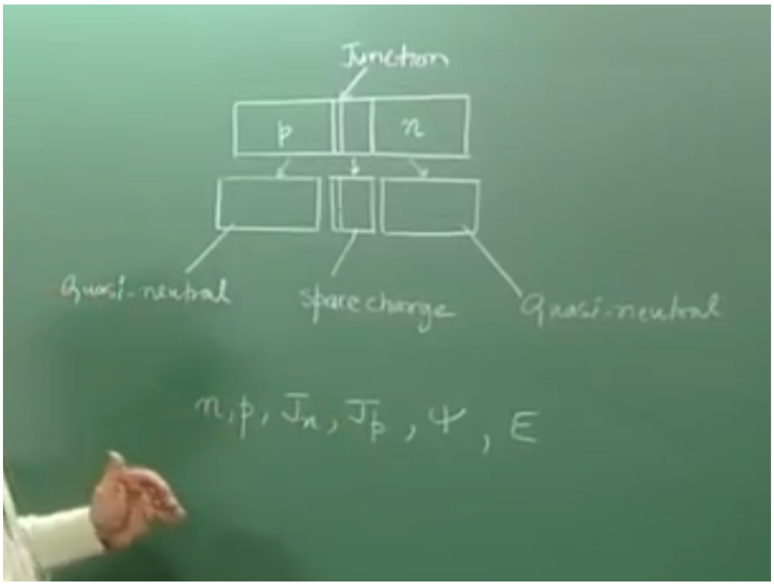

Now what does steady state analysis of a PN junction mean? It means deriving the distributions of n, p, Jn, Jp, psi and E as a function of X in the device. You do this in 3 steps. The first step you separate this PN junction into quasi-neutral and space-charge regions. In the second step, you solve for these distributions in the 3 regions using different approximations of the fundamental equations in the 3 regions.

In the third step, you combine the solutions of these distributions in the 3 regions assuming that these variables are continuous across the boundaries separating the 3 regions so across these boundaries. Now analysis is complete once you get the distributions of n, p, Jn, Jp, E and psi as a function of X. Modeling involves doing this analysis and doing much more.

So there are 3 more steps to do when you talk about modeling of the PN junction. Now these are first converting the information about these distributions into an equation for DC current as a function of voltage. This may involve modifying the equation to improve accuracy and continuity properties. You may add empirical factors. You may add some constants and so on.

For example, I = I0 exponential V/VT-1 is an ideal diode equation, you may add a parameter like eta in the exponential and you may make the equation I = I0 exponential V/eta VT-1. This is to improve the accuracy of the equation. Apart from deriving the current voltage equation, another step in modeling is fixing the values of the parameters of this equation so that the equation matches with experimental data, this is called parameter extraction.

And finally the third step in modeling, which is not a part of analysis is coding this equation into a device or circuit simulator. So this is the difference between modeling and analysis. Now what about design? An example of design activity for PN junction would be something like this, design the geometry and doping profile in a PN junction so that it withstands more than 200 volts in the reverse bias and it drops no more than 1 volt in forward bias while passing a current of 10 amperes.

And when switching from on to off state, it takes no more than say 100 nanoseconds. So these are examples of design modeling and analysis activities related to a PN junction.

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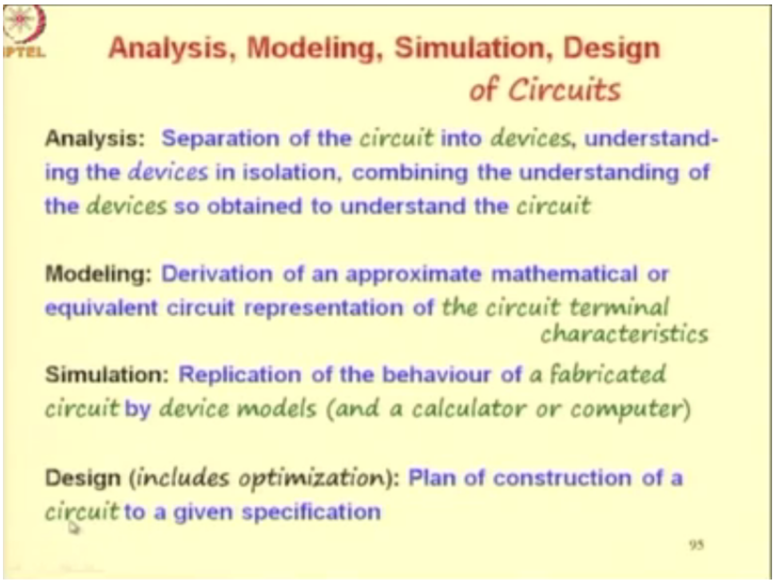

Similarly, if you were to use the term analysis, modeling simulation, design in the context of circuits then what would these definitions mean? So the parts in the definition of analysis become the devices and the whole is the circuit so circuit analysis is separation of the circuit into devices understanding the devices in isolation combining the understanding of the devices so obtained to understand the circuit.

In modeling, you replace the word device by circuit, so circuit modeling is derivation of an approximate mathematical or equivalent circuit representation of the circuit terminal characteristics. Circuit simulation, again replace device by circuit; however, the other system you retain the device models, so circuit simulation is replication of the behavior of a fabricated circuit by device models and a calculator or computer.

So you see the device models are used both in circuit simulation and device simulation; however, the type of models used in the 2 cases would be different something that would become evident in later lectures of the course. Finally, circuit design would be plan of construction of a circuit to a given specification. Let us use these terms analysis, modeling, simulation and design in some sentences.

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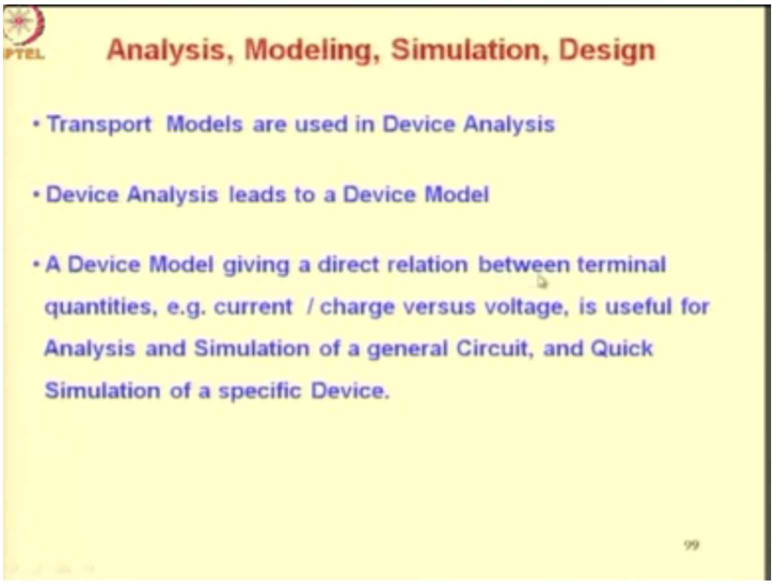

Transport models are used in device analysis, device analysis leads to a device model, a device model giving a direct relation between terminal quantities, example current or charge versus voltage is useful for analysis and simulation of a general circuit and quick simulation of a specific device.

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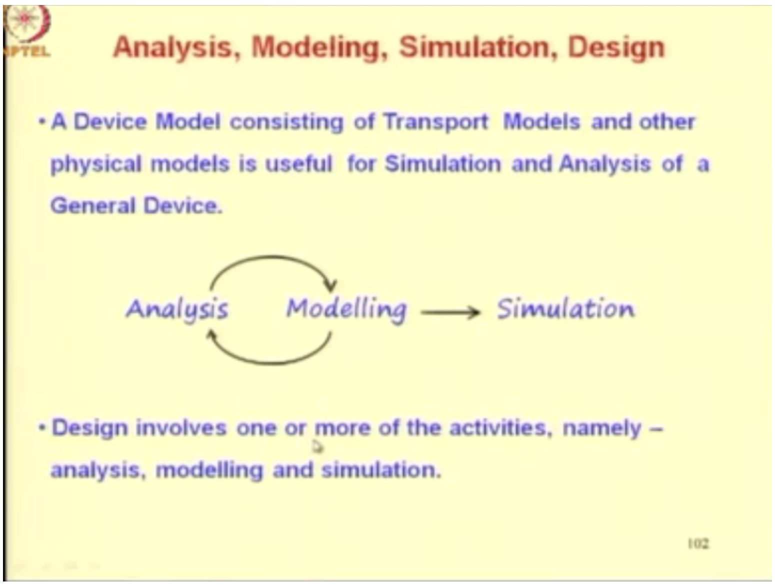

A device model consisting of transport models and other physical models is useful for simulation and analysis of a general device. So from all these sentences you can see that relation between analysis and modeling is like chicken and egg, difficult to say which came first but both are not the same, one leads to the other. So analysis is used in modeling and models are used in analysis.

And modeling activity is necessary for simulation, so device models are used in simulation. Finally, design involves one or more of the activities namely analysis, modeling and simulation. So this discussion on these 4 words analysis, modeling, simulation and design should clarify the distinction among these words. So it will help you to use the right word in the right situation.

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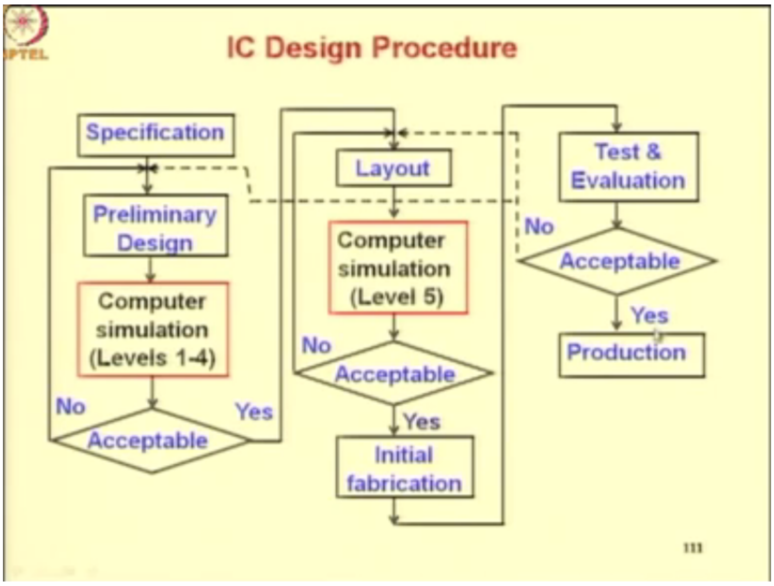

Let us look at the IC design procedure and look at the stages of this procedure where device models are employed. So the IC design starts with a given specification and the end of the procedure is the production of the integrated circuit. So let us put down the steps in between. You first do a preliminary design and then the circuit that comes out of this design is subjected to computer simulation of 4 levels.

What are these 4 levels? We shall look at shortly. If at the end of the simulation you find that the design is acceptable then you move further otherwise, you go back and redo your design. If the design is acceptable as confirmed by simulations, then you move on to the next step namely laying out the circuit. After laying out, you extract the various interconnections of the devices and the devices themselves.

And then subject the extracted interconnection and devices to a computer simulation to check whether the layout has been proper and you are getting the specification that you are aiming at this level 5 simulation. At the end of this step, if things are acceptable you move on otherwise you go back and redo your layout. Assuming that the layout is acceptable, then you do an initial fabrication.

And then fabricate and then test and evaluate the fabricated chip or test chips. Again you have a decision making here. If the test and evaluation is positive favorable, then you can move on further, if it is not then you may have to redo the initial parts. So you may have to go back to the layout step and redo the layout or you may have to go right back to the beginning and redo your design. Now if the test and evaluation is favorable then you go on to do the production.

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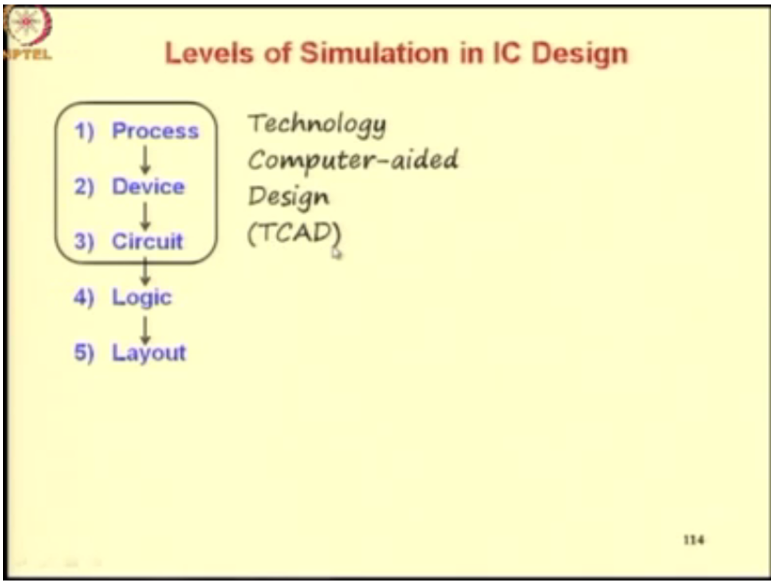

Now let us look at the levels of simulation, the 5 levels of simulation which we just showed on the entire IC design procedure chart. So these 5 levels are process, device, circuit, logic and layout simulations. Let us look at each of these. The combination of process device and circuit simulations is normally referred to as technology computer-aided design or TCAD.

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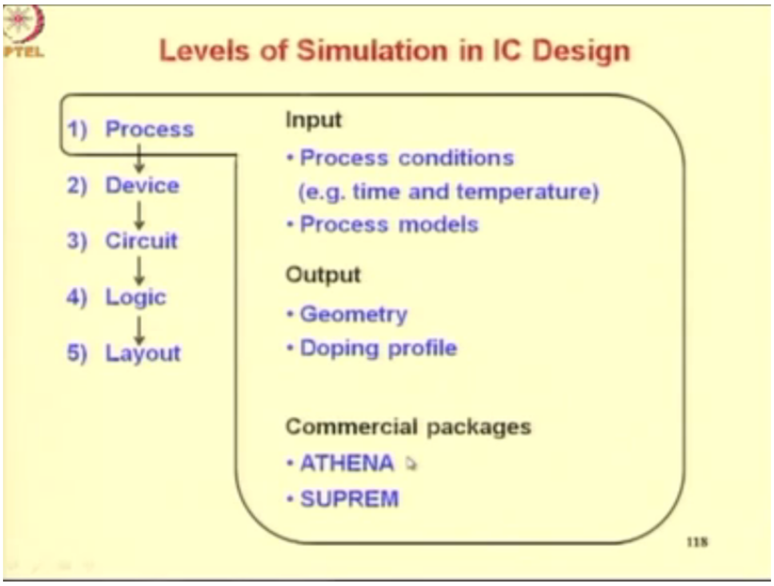

In process simulation, the input is process conditions such as time and temperature and process models. Our course will not discuss these models. So these models can be discussed as a part of some other course such as VLSI technology or process modeling. Now the output of process simulation is device geometry and doping profile. So you get the structure at the end of this process simulation step.

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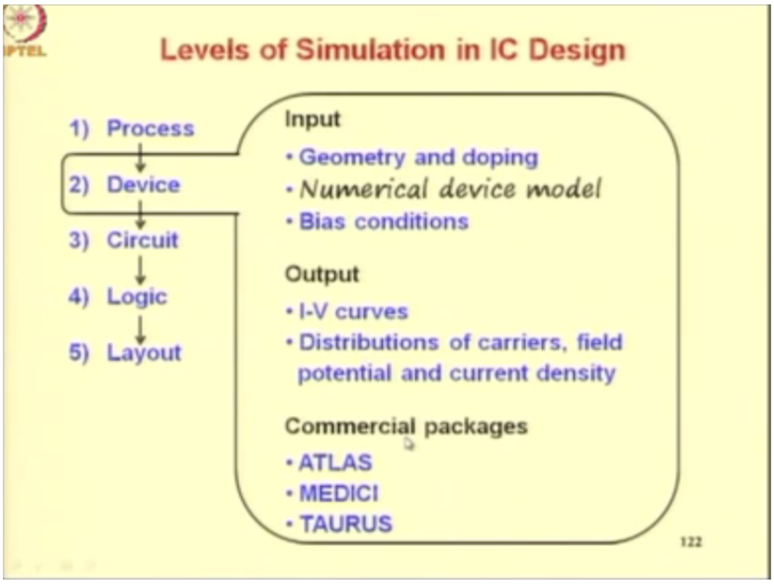

The commercial packages, which are doing this kind of simulation are ATHENA and SUPREM. There are some other examples too. Let us look at device simulation. What are the input and output for in this case? In device simulation, the input is geometry and doping in the device as a function of distance and you use numerical device models. Numerical device models are those equations which have to be solved using numerical procedures.

Newton-Raphson technique and so on and you also have to supply the bias conditions on the device, which impose boundary conditions on the equations of the device model. The output of device simulation is a set of current voltage curves, and distributions of carriers, field, potential and current density throughout the device. Examples of commercial packages, we are doing which are doing this kind of simulation that is device simulation are ATLAS, MEDICI and TAURUS. Some other examples are also there.

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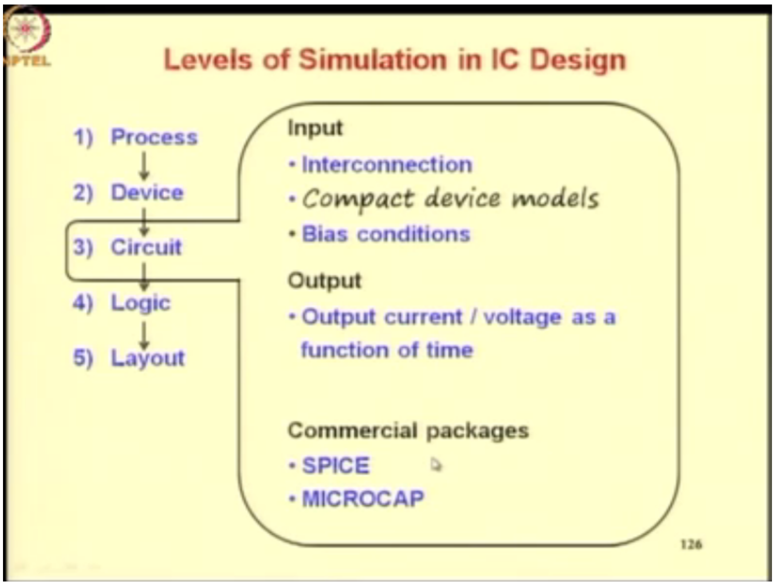

Circuit simulation, in this case the input is the interconnection among the various devices and a set of device models, which are called compact device models. So compact device models are device specific equations having certain properties okay. What are these properties we shall be looking at in this course? So compact device models are different from numerical device models in that these models are specific to the device.

So the compact model of a diode would be different from the compact model of a MOSFET and so on. On the other hand, the numerical device model are generic equations applicable to various or a large variety of devices. The output of circuit simulation is output current or voltage as a function of time. Examples of commercial packages involved in circuit simulation are SPICE and MICROCAP.

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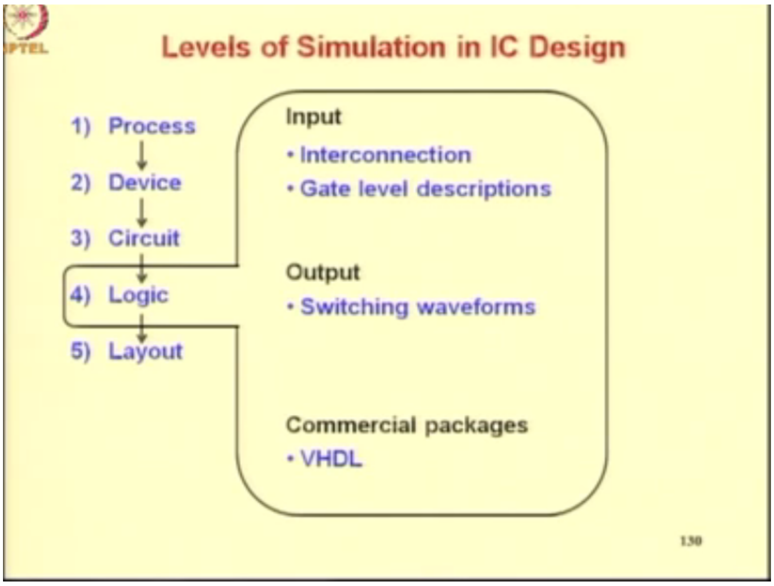

Logic simulation, although this is not a subject of our course, for the sake of completeness we will point out the input/output of logic and layout simulations also. Logic simulation, the input is the interconnection of various parts of the circuit and gate level descriptions of devices are parts of the circuit. The output you get out of logic simulation are switching waveforms and commercial packages the examples are VHDL.

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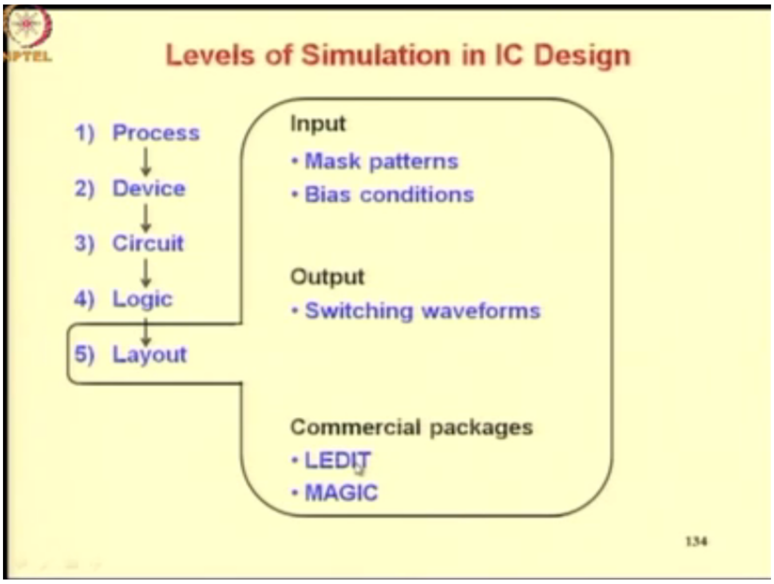

Layout simulation, the input is mask patterns and bias conditions. You get switching waveforms as the output. Examples of commercial packages are LEDIT and MAGIC.

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With that we have come to the end of this particular module, which consists of just 1 lecture namely the introduction module. So let us make a summary of the important points. What we will do is we will revisit the learning outcomes that were specified at the beginning of this module.

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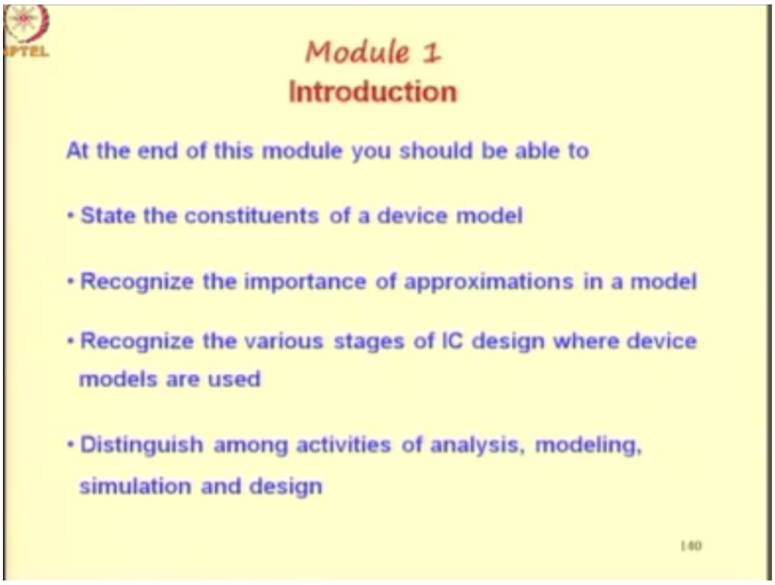

So we hope that at the end of this module, you are able to state the constituents of a device model, recognize the importance of approximations in a model so remember the MAMA quote, modeling is an art of making approximations, recognize the various stages of IC design where device models are used, distinguish among activities of analysis, modeling, simulation and design.

So remember analysis and modeling are like chicken and egg. They are not the same, one leads to the other, but it is difficult to say which comes first and design involves one or more of the activities namely simulation, modeling and analysis.

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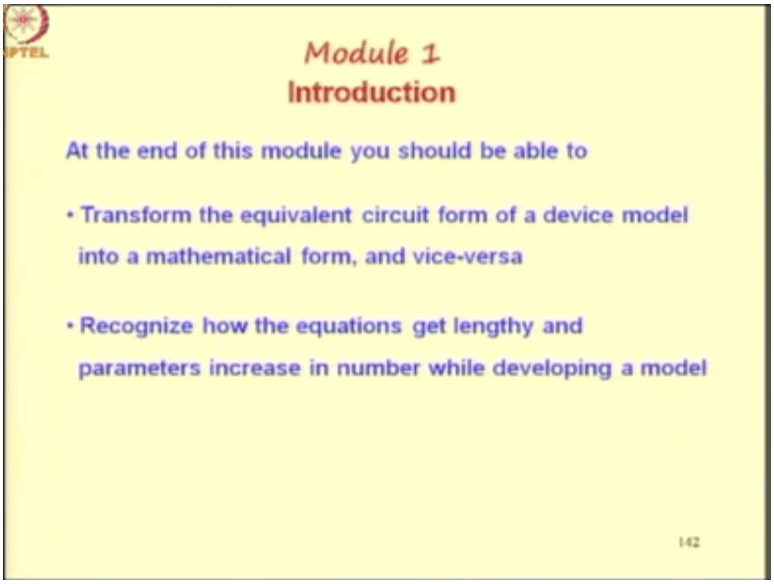

Hopefully at the end of this module, you can transform the equivalent circuit form of a device model into a mathematical form and vice versa and finally recognize how the equation get lengthy and parameters increase in number while developing a model. So as you start going closer and closer to the reality as a model starts incorporating more and more phenomena and dropping approximations, the equations become complex.

And a simple model please remember is always associated with the large number of approximations and you must remember the approximations associated with any model. Now with this introduction, we are ready to plunge head long into the course. So the next lecture onwards we will start the module on semi-classical carrier transport.