Semiconductor Device Modeling
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Lecture - 36
SQEBASTIP: Nine Steps for Deriving a Device Model

In the previous 2 lectures, we have been discussing the 9 steps of deriving a device model namely SQEBASTIP. S and Q stand for structure and characteristics to scale and qualitative model. Then in the previous lecture we discussed 4 steps namely E, B, A, S that is equations and boundary conditions, approximations and solution.

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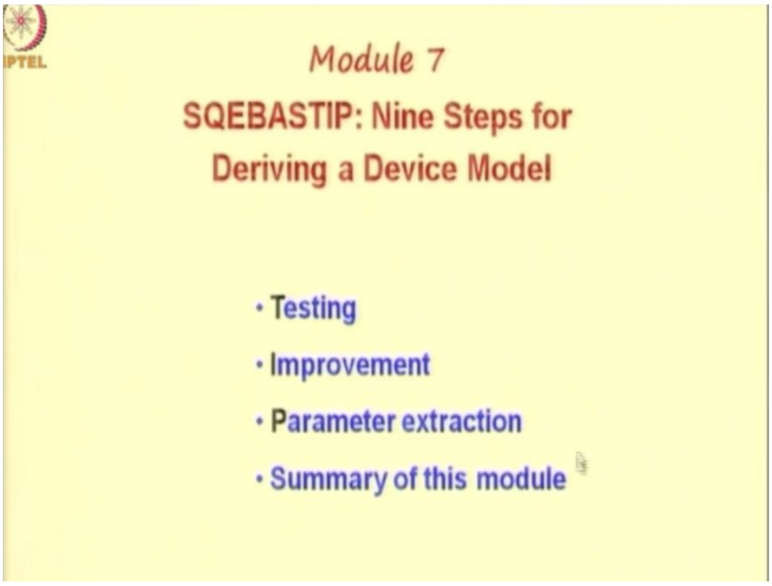

Now, in this lecture, we will discuss the next 3 steps namely testing, improvement and parameter extraction and then we will summarize the proceedings of this entire module on the steps for deriving a device model.

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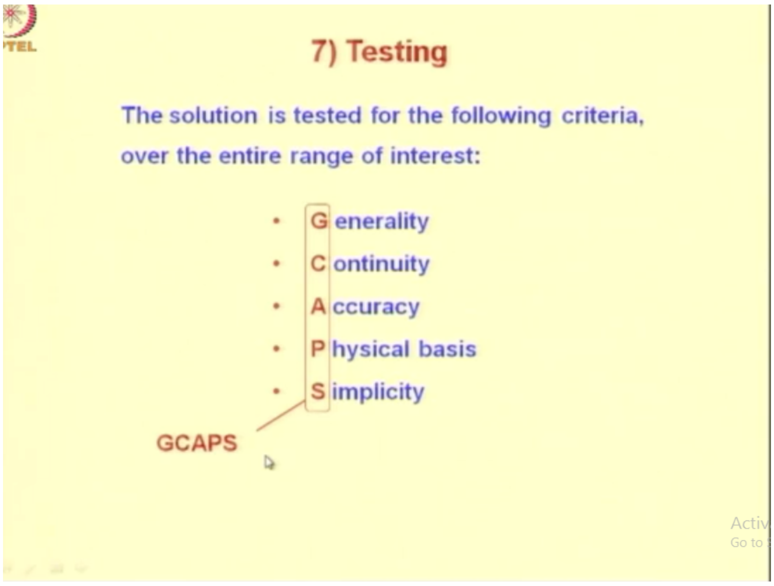

Let us look at testing. The solution is tested for the following criteria over the entire range of interest. The criteria are; generality, continuity, accuracy, physical basis and simplicity. In order that we remember these criteria lets develop a mnemonic. If you collect the first letters of these criteria, then they abbreviate to GCAPS. So like the 9 steps of device model abbreviate to SQEBASTIP.

The 5 criteria for testing a device model abbreviate to GCAPS.

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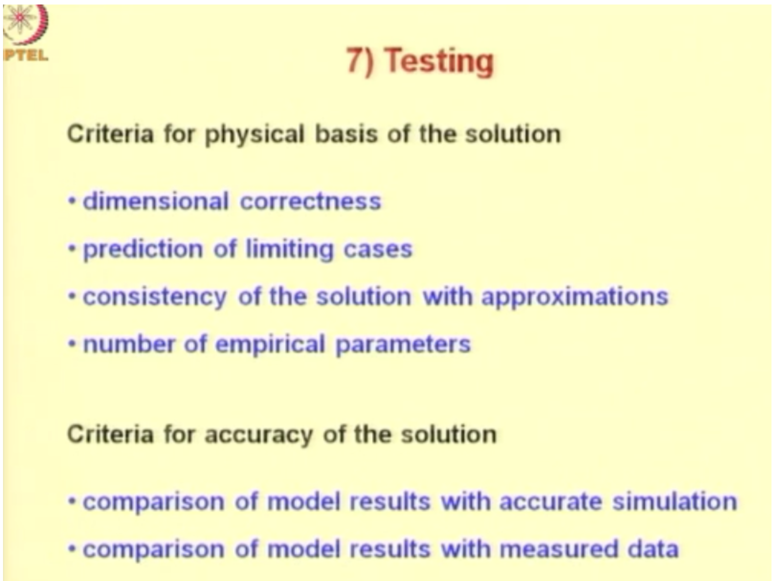

Let us look at the details of the criteria for physical basis of the solution and for solution accuracy. The physical basis of the solution can be tested using the following approaches. We test for dimensional correctness and ability of the model to predict limiting cases. Then we check for consistency of the solution with approximations and we look for the number of empirical parameters in a model.

If the number of empirical parameters is small, then we say the model has a strong physical basis. On the other hand, large number of empirical parameters would imply weak physical basis. For solution accuracy, you compare the model results with accurate computer simulation and finally you compare the model results with measured data. The comparison with measured data is ultimate test of the success of a model.

In the absence of measured data computer simulations may be employed. However, please note that computer simulations depend on the type of models and boundary conditions we provide where we may make approximations without our proper understanding of the actual conditions and therefore comparison with measured data is ultimate test for the correctness of any model.

Now, as far as other criteria are concerned such as generality, continuity and simplicity, these criteria are quite evident from the model equation. For instance, generality means that the model equation should be able to encompass various regimes of device operation or various types of devices of the same class. So a general model for a bipolar transistor would imply that the model is able to capture various bias operations of the device.

As well as various types of bipolar transistors, similarly for general models for MOSFETs and so on. Now as far as continuity is concern, the continuity is a mathematical property that one can always test by looking at the values of the functions over the bias range of interest or the derivatives of the function in the bias range of interest. Now, whether the model is simple or not is also evident from the form of its expression.

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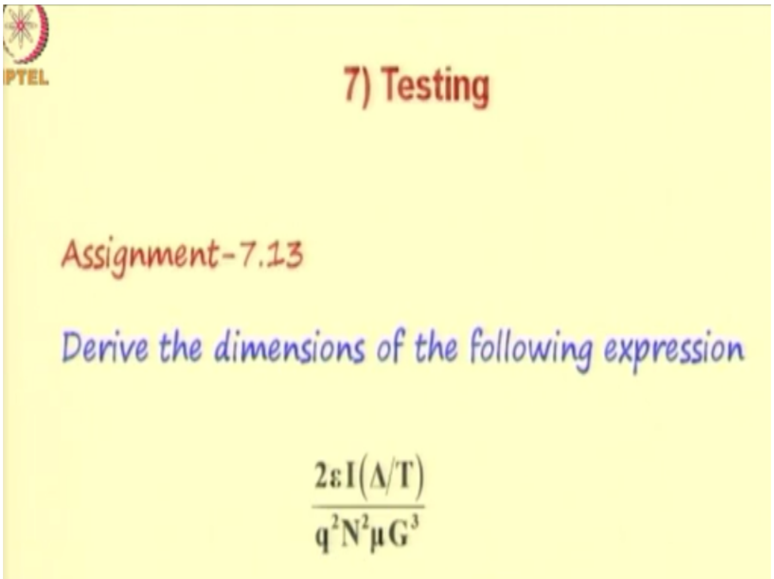

An assignment, derive the dimensions of the following expression. So here I stands for current, epsilon stands for permittivity, delta and T are geometrical dimensions. So, these dimensions correspond to the spreading resistance example that we have chosen to list at various steps of the model. Similarly, G also corresponds to a geometrical dimension of this spreading resistance.

Mu is mobility, N is doping and q is the physical constant namely the electronic charge.

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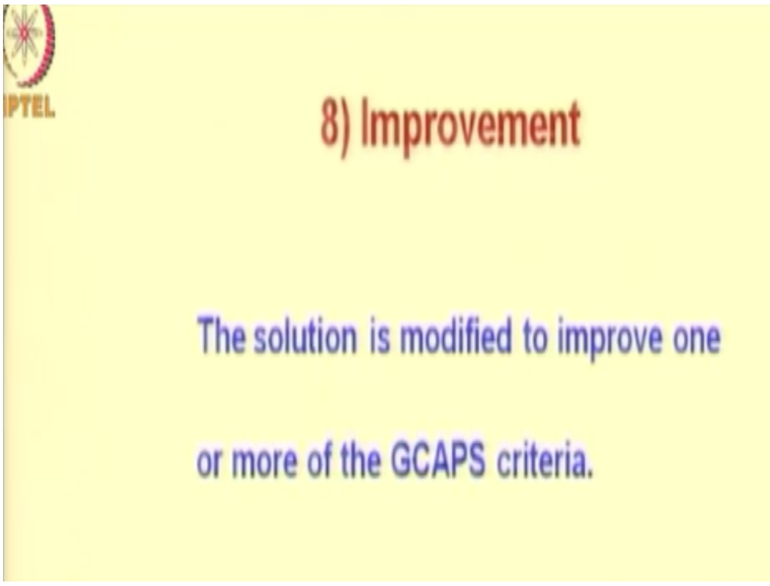

Let us look at improvement, some general comments. The solution is modified to improve one or more of the GCAPS criteria. So in the testing step we will test for the GCAPS criteria and we might find the model is wanting in one or more of these and therefore in the improvement step we would like to correct those lacunae.

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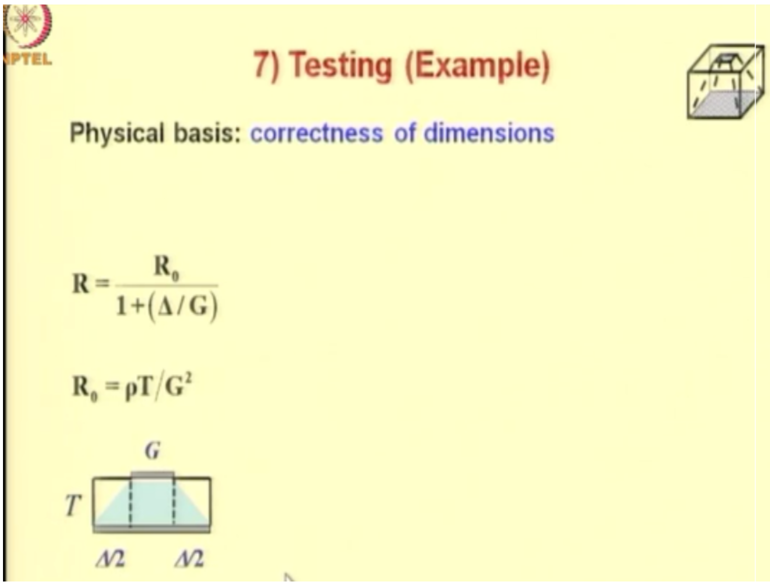

Now, let us illustrate the testing and improvement steps using our spreading resistance example. Let us start with checking the physical basis, correctness of dimensions. Here is your model expression. One can easily check that this dimensionally correct because R0 has a dimensions of a resistance it is rho into our distance divided by an area and delta/G is dimensionless. Therefore, the formula for R has a correct dimensions of ohms.

The parameters G, T and delta are indicated here.

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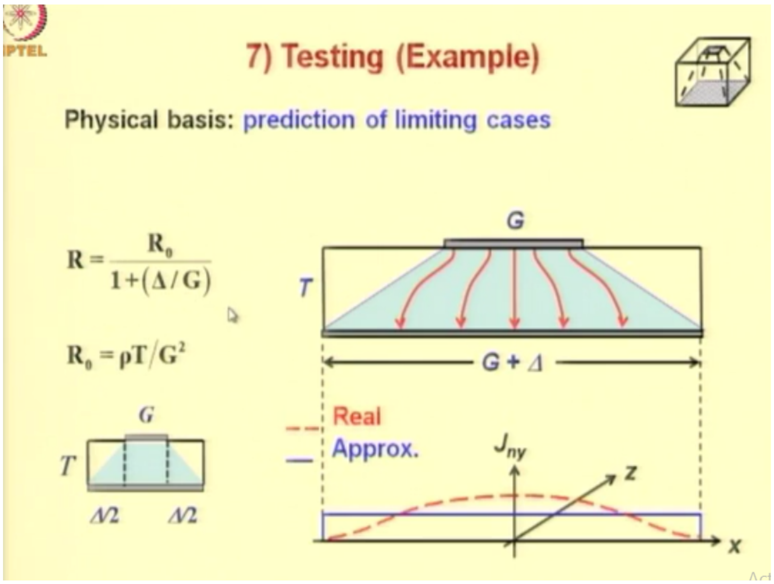

Next test of physical basis is prediction of limiting cases. Does this model predict limiting cases correctly? So one limiting case for example is delta = 0, here R = R0. One can easily check that if I said these extensions to 0 it will become a 1-dimensional resistor and its formula will be given by this. Which is correctly predicted by this model. Let us take the case delta 10 into infinity.

So, in delta 10 to infinity in other words these bottom contact extents further and further away from the top contact. You find the resistance is approaching 0. Now is that really correct? Let us check. Here is the current flow pattern. The actual current flow pattern and our approximate pyramidal current flow that we have assumed. Further while deriving this model we have assumed that over any horizontal area of cross section the current density normal to the area is uniform.

Whereas, the actual current density may have a non-uniform shape, I have shown here for the bottom contact. Now see what happens when delta tends to infinity. In our model since the current density normal to the contact is found to be uniform the total current will approach infinity in our model and that is why the resistance is going to 0. Whereas, in practice or in actuality the current distribution is non-uniform I have shown by this shape.

You can see that the current density is approaching 0 as you move away more and more away from the center of the contact, right. Therefore, if you are more extending the bottom contact to infinity the amount of current will really not change because the area under this curve will get saturated. Therefore, we anticipate that in reality the resistance would approach a non-0 saturation value, whereas, our model predicts the resistance to approach 0.

So, it does not seem to be a predicting the delta attains to infinity case correctly.

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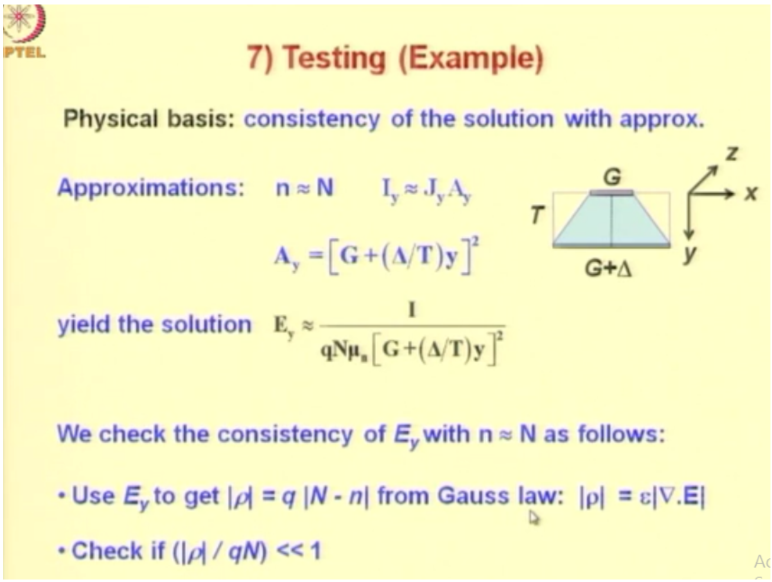

Let us look for the consistency of the solution with approximations. The approximations we have made are space charge neutrality which implies that the electron concentration is approximately equal to the doping concentration. Then the current at any Y, so here is the Y direction when I say current at any Y it means that current over the horizontal area of cross section of this pyramidal current flow.

That is given by Jy into Ay, where Jy is the assume approximately uniform current density over Ay and what is Ay? Ay is given by this formula. So, if you take any distance Y from this top contact and find out the area of cross section of this pyramidal part of the current flow for that why it is given by this formula. This Jy is nothing but the electron current density normal to the Ay. So, these should be J suffix Ny.

Now these approximations have yielded us the solution for Ey in this form. This solution is repeated from our previous slides. Now the consistency of this Ey solution with these approximations can be checked in different ways. One of the ways that we will adopt is the following. So, we check the consistency of Ey with the approximation electron concentration is approximately equal to the doping concentration.

That is the special neutrality approximation in the following manner. So, we use Ey to get the magnitude of the space charge which is given by q times the magnitude of the difference between the doping concentration and the electron concentration from Gauss's law. It says that modulus of rho = epsilon times the modulus of diversions of E and we check whether this value of modulus of rho is indeed much < q times N.

Which is the doping concentration because if that is true then our space charge neutrality assumption is correct.

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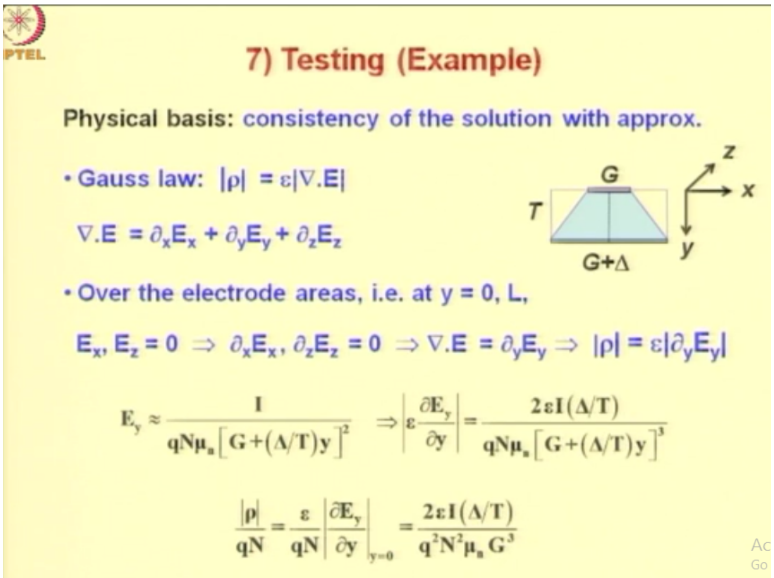

$$E_y \approx \frac{I}{qN\mu_n\left[G+(\Delta/T)y\right]^2} \Rightarrow \left|\varepsilon\frac{\partial E_y}{\partial y}\right| = \frac{2\varepsilon I(\Delta/T)}{qN\mu_n\left[G+(\Delta/T)y\right]^3}$$

$$\frac{|\rho|}{qN} = \frac{\varepsilon}{qN}\left|\frac{\partial E_y}{\partial y}\right|_{y=0} = \frac{2\varepsilon I(\Delta/T)}{q^2N^2\mu_n G^3}$$

Now let us see how we follow this through. So, Gauss law says modulus of rho = epsilon times modulus of diversions of E where diversions of E is given by dou/dou x of Ex+dou/dou y of Ey+dou/dou z of Ez. Here is our cross section of the spreading resistance and here are the x, y, z dimensions. Now over the electrode areas that is over this area and this area which correspond to the XZ plains at y = 0, L. Ex and Ez are 0.

So, by the very definition of an electrode it is equipotential and therefore it cannot have a field in the plain of the electrode. So, Ex and Ez are components of the electric field along the plains of this electrodes. So, since these are 0 over the entire electrode area therefore their derivatives dou Ex/dou x and dou Ez/dou z are also 0 and therefore over the electrode areas diversions of E simplifies to simply the formula dou Ey/dou y.

Because this other 2 terms have gone to 0. And therefore modulus of rho = epsilon times modulus of dou Ey/dou y. Now let us take our Ey expression and differentiate it with respect to y to obtain epsilon times dou Ey/dou y. You can do the differentiation yourself and the result would be as shown here. It is 2 times epsilon into I into delta/T divided by q times N into mu n into G+delta/T into y whole power 3.

So, I leave it you as an assignment to perform this differentiation. Now if you take the ratio modulus of rho/q times doping concentration that will turn out to be at y=0 this expression. So, you take this formula and then divide by q times N and set y = 0. So, when you said y = 0 the delta/T term vanishes in the denominator. So, that is why you have only G cube here from this expression.

Now let us evaluate this expression for some typical values of variables and parameters.

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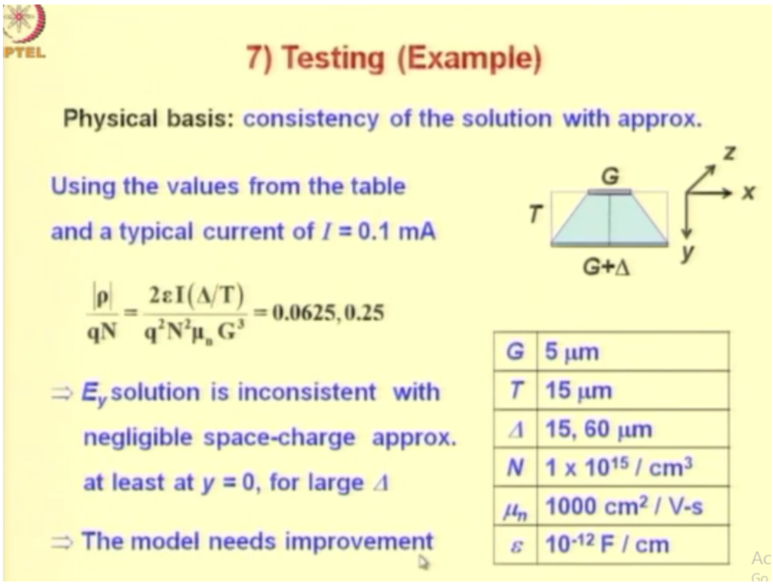

So, using the values from the table this is our table for the various parameters of this spreading resistance and typical current of 0.1 mA. So, the voltage that will result for this current would be of the order of a volt or less. We will take 2 values of bottom contact extension delta 1 is 15 microns and other is 16 microns. That is a large extension and a smaller extension.

Now, substituting the values, we find that the ratio modulus of rho divide by q times N has the values of 0.0625 for 15 microns of delta and 0.25 for 16 microns of delta. Evidently, while 0.0625 is much < 1, 0.25 cannot be regarded as much < 1. So, what does it mean? It means that our model is inaccurate for large values of delta. So, Ey solution is inconsistent with the negligible space charge approximation.

At least at y = 0 for large delta these what we gather, okay, from our consistency check and therefore the model needs improvement. Definitely the model is predicting in correct result for large values of delta. Now, this particular corollary offer consistency check matches with our earlier discussion of the limiting cases of our model expression wherein we found that for delta turn into infinity our model is predicting 0 resistance.

Whereas in practice the resistance should saturate to a non-0 value for large values of delta.

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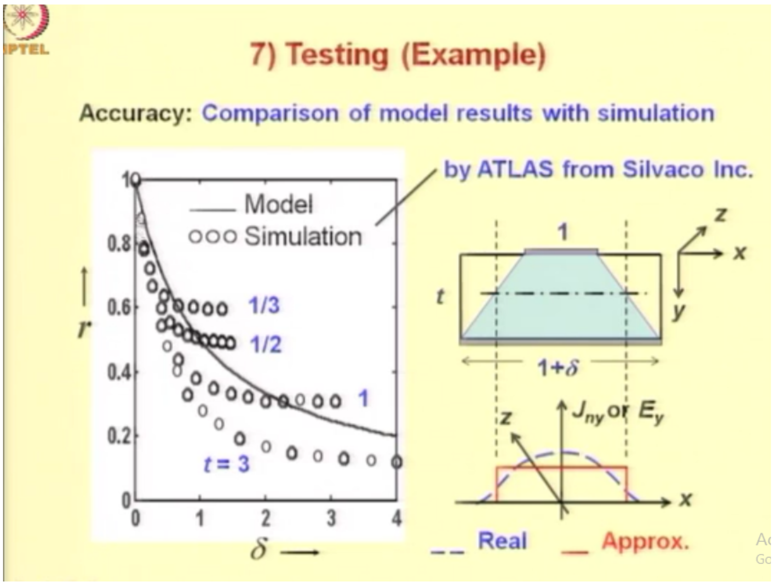

Now let us compare the model result with stimulation to check its accuracy. Now, here is our cross section of the device structure with normalized values of the various dimensions. This is the actual current density distribution normal to the horizontal area of cross section and this is the approximate distribution constant distribution assumed in our model. Now, here are results of stimulation and the model calculations.

Stimulations have been performed by the ATLAS stimulator from Silvaco. Stimulations are indicated by the points and the model is indicated by the solid line. So, the 2 differences between the model and the stimulations are that the stimulations saturate to a non-0 resistance value, whereas our model goes to 0 for large values of delta and secondly our model predicts no dispersion as a function of the distance between the electrodes or small t.

Whereas the stimulation results clearly show that the saturation value of the resistance is different for different values of small t which are indicated here. You also find that the model is somewhat inaccurate even for small values of delta, although it matches for delta = 0 with the stimulation. So we have understood the weaknesses of our model in the testing process. Let us see how we can improve our model to remove all these lacunae.

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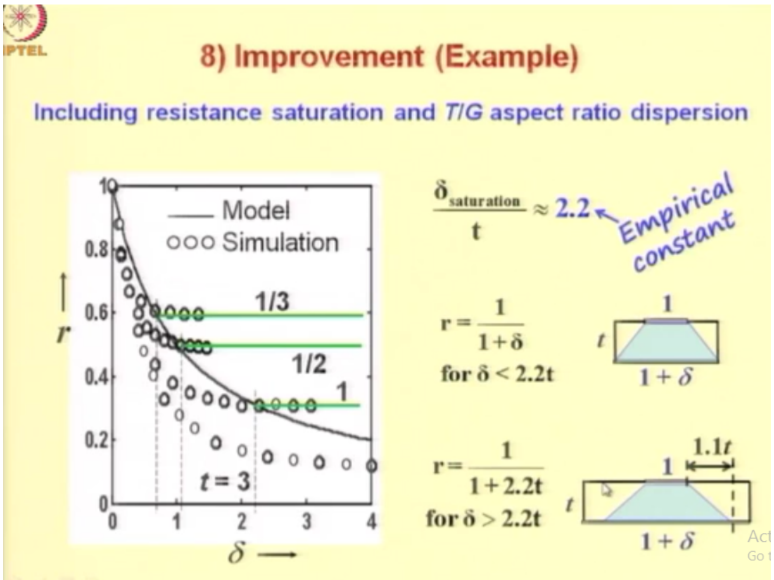

First, let us try to include resistance saturation and T/G aspect ratio dispersion in the model. How do we do that? Let us take resistance saturation. So the green lines here show the saturation values of the resistance. For t = 3 the saturation occurs somewhat later than the values of delta shown here. You can come up with an empirical condition for the saturation. The value of delta beyond which the resistance saturates normalize to the value of t is approximately = 2.2.

This is an empirical observation. Let us check here, how do we get this. So, for t = 1 you find that the resistance saturates beyond delta = about 2.2, okay. So, we take the saturation point as the point of intersection of the model with the stimulation. When you take t = half this is the point of intersection of the model with the stimulation and you find the value here.

Then you take the ratio of this value to half and you once again find it is close to 2.2. Similarly, you do for t = 1/3. The point of intersection occurs here and this is the value of delta beyond which the resistance saturates. So, this value divided by 1/3 and you will again get the value of about 2.2. Note that this value of 2.2 has been determined empirically. We have not done a derivation from the fundamentals.

Therefore, now using this information we can modify our model as follows. We say that our model is given by the formula r = 1/1+delta which is the normalized form for delta < 2.2 t. So, in other words we use this solid line up to delta = 2.2 t for the model. Whereas beyond 2.2 t we use the value corresponding to the point of intersection of the model with stimulation result which is nothing but r = 1/1+2.2 t.

So, delta = 2.2 t is the point of saturation. For delta > 2.2 t we assume that the model saturates, okay. So this is what is the pictorial depiction of the model once the resistances are saturated. So, we assume that the current flow is limited to only a part of the bottom contact where the extension of this current flow from the top contact is limited to 1.1 times this dimension, normalized dimension that is small t.

So, the 2.2 t is obtained by taking 1.1 t on either side of the top contact.

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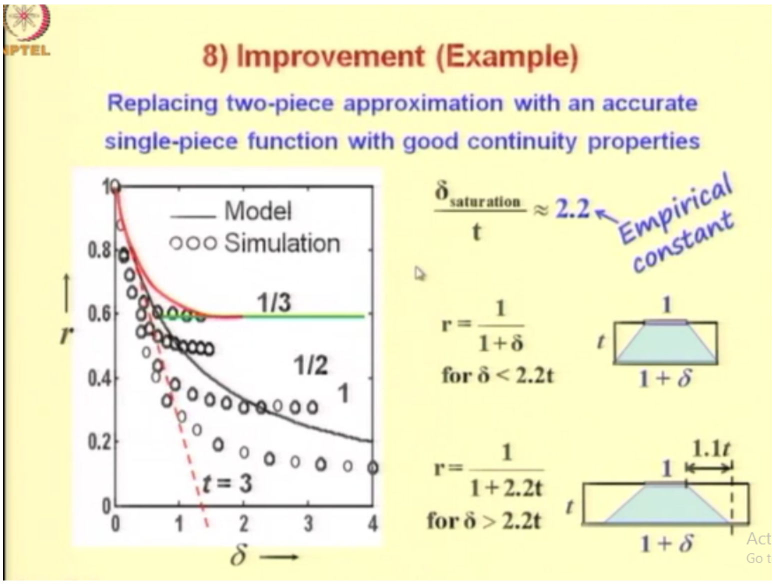

Now, let us consider replacing the 2-piece approximation with an accurate single-piece function with good continuity properties. Note that in the process of incorporating the saturation resistance we have also incorporated the t/G dispersion because the value of the saturation resistance depends on t. So, as t changes the saturation resistance also will change. So, in 1 shot we have incorporated resistance saturation.

As well as the so called t/G or small t dispersion. Now we want to improve the model further to get a single-piece function instead of using 2 segments one for below saturation and another for beyond saturation, we want a single segment which will cover both regions. How do we do that? So, this is the kind of segment we are looking for, a red curve.

Which follows the segment for delta < 2.2 t as well as the constant segment for delta > 2.2 t. The dotted line here indicates the initial slope of this red curve.

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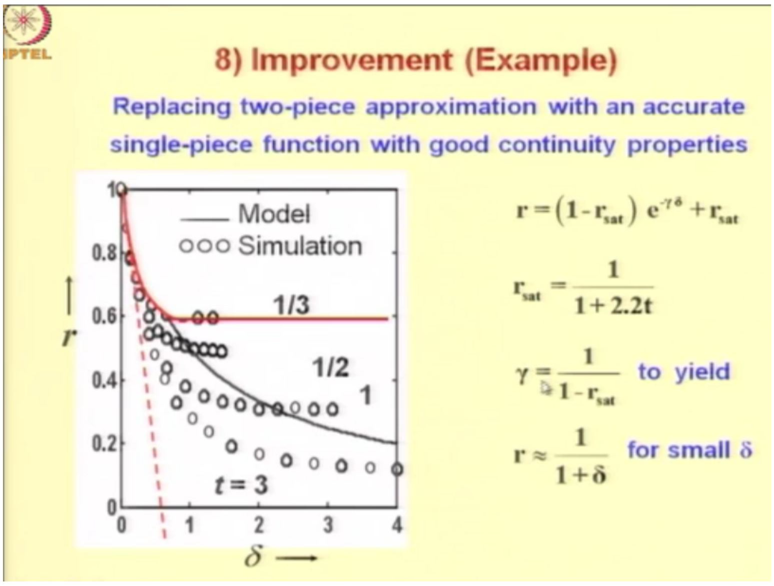

Now if expression which is again empirically determined which has the shape is given by this formula r = 1 - saturation value of r into exponential of - gamma into delta+r sat. Note that as delta turns to infinity this quantity goes to 0 and r becomes r sat. So, that is how you get this constant segment. On the other hand, for delta = 0 this quantity becomes unity the r sat cancels and you get r = 1 that is how you get this value.

The r sat values given by 1/1+2.2 t, so that you can capture the saturation resistance values for different values of t. Now what is gamma? You can show that if you assume gamma = 1/1 – r sat then that will yield the value of r to be 1/1+delta for small delta. So, this expression for small delta will reduced to r = 1/1+delta. In other words, it will match with our model expression.

So, this empirical expression which we have conceived will match with the segment of our model for small values of delta if you assume gamma = 1/1 - r sat. This left you as an assignment. Now you see that even after we have got this single-piece function it is not entirely accurate because you find that this single-piece function is over estimating the resistance as compared to the accurate simulation results for small values of delta.

Though for large values of delta it seems to saturate at the simulated value. So, you can improve matters if you slightly increase the slope of the initial portion of this curve so that your curve will become something like this and it will follow the simulated points. Now that amounts to modifying the value of gamma as follows.

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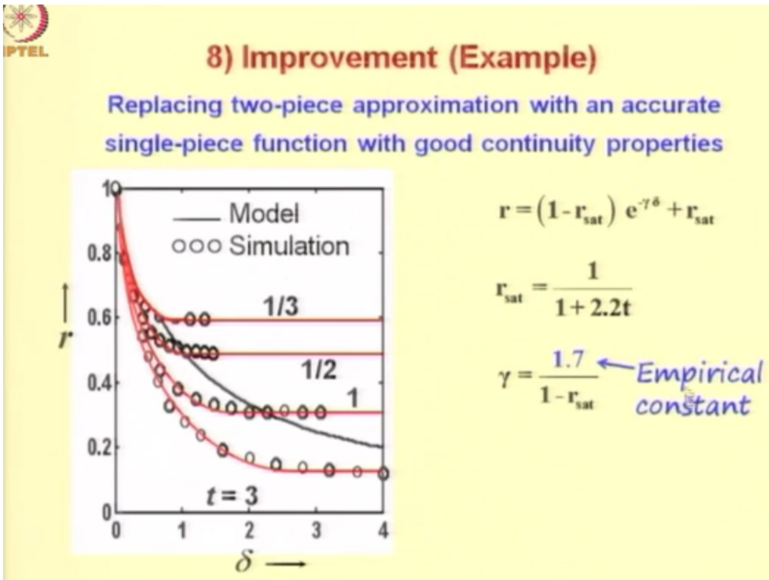

So, if you increase gamma by changing this factor unity to 1.7 it turns out that your curve which is this expression matches the stimulated results quite well. This 1.7 factor is again determined empirically it is by curve fitting. So it is an empirical constant. If you now calculate the model results using this expression and this value of empirical constant it turns out as shown by this red lines. that the model now matches the simulated data extremely well.

Therefore, this is now our final model after improvement.

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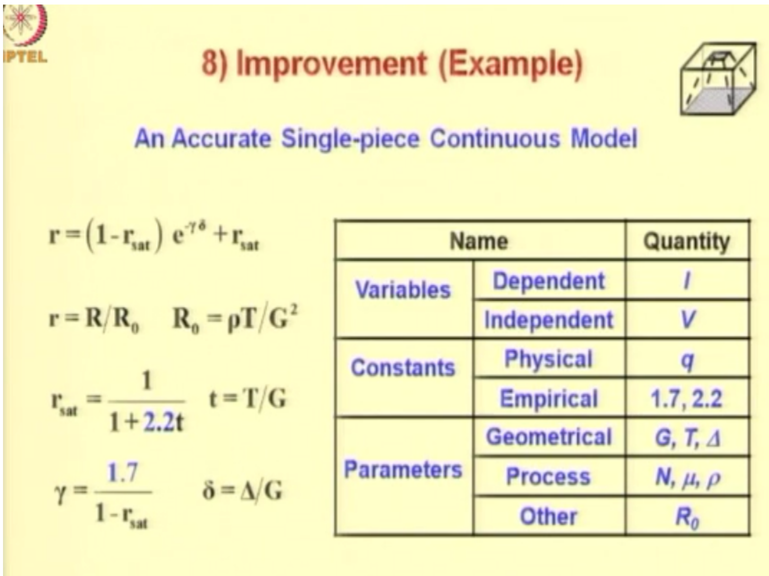

So, let us put our various features of our accurate single-piece continuous model together. Then these are the model expressions and in these model expressions you have the variables constants and parameters indicated in this table. We had put down this table earlier before improvement. The addition you can see after improvement is these empirical constants 1.7 and 2.2.

So, prior to improvement the model had no empirical constants. However, we found that it was inaccurate particularly for large values of bottom contact extensions and to some extent also for small extensions. So, we have improved the model by adding 2 empirical constants and made it accurate. Now this is how you can see that to achieve model accuracy empirical constants are introduced into an analytical model.

In the process the model loses the physical basis somewhat but it gains accuracy.

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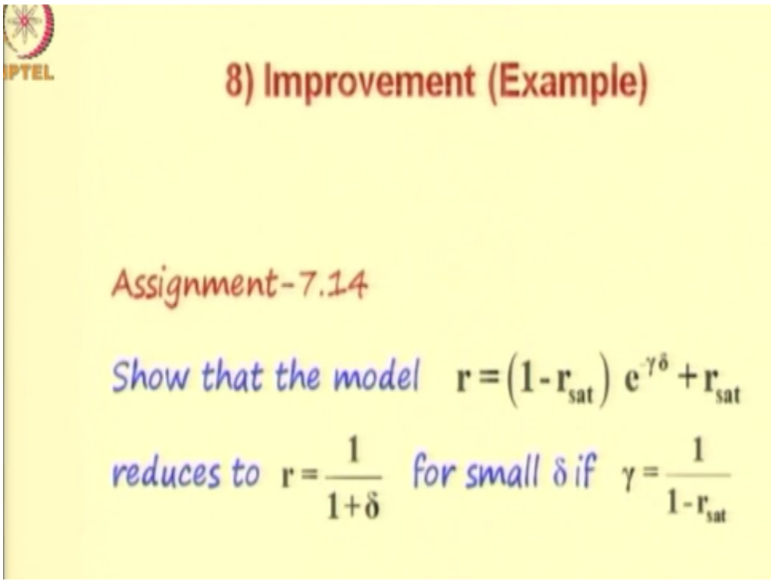

An assignment shows that the model r = 1 – r sat into e power - gamma delta+r sat reduces to r = 1/1+delta for small delta if gamma = to 1/1 – r sat. Let us come to the final step of parameter extraction. First we will make some general comments about parameter extraction and then we will illustrate the procedure of parameter extraction using our spreading resistance example.

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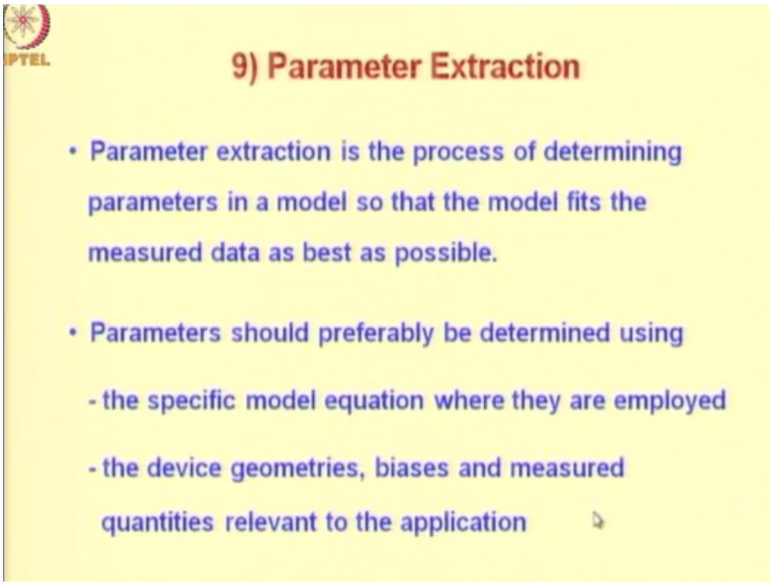

Parameter extraction is the process of determining parameters in a model so that the model fits the measured data as best as possible. Parameters should preferably be determined using the specific model equation where they are employed and using the device geometries, biases and measured quantities relevant to the application. These points are very important. For example, supposing you are deriving the mobility of a MOSFET, to use a particular model.

Now you are aware that different models are available for the same MOSFET phenomena. So, different types of expressions are available and all these different types of expression will contain the mobility. So, what is being said here is that if you derive the value of mobility to fit a particular type of model to the experimental data you should not use the same value of mobility in another model expression.

So, if you do that the other model may not fit exactly to the measured data. Second point is about device geometries, biases and measured quantities. Suppose for example, your MOSFET is a small geometry MOSFET then the mobility that you want to extract for a small geometry MOSFET should not be extracted on a large geometry MOSFET. So, if you extract mobility for a large geometry MOSFET.

And tried to use it in a small geometry device again the model may not match the measured data. Same things, similar comments applied to biases. So, you must use the same biases which are used with the device in practice.

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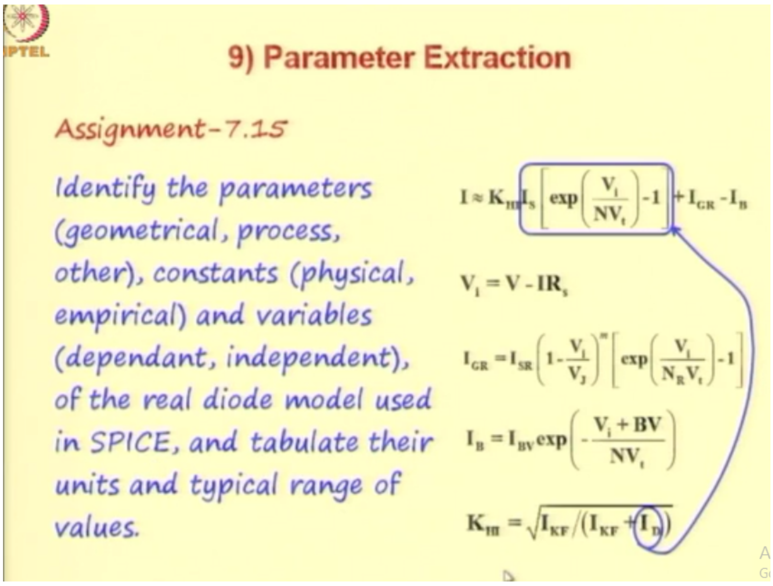

Now before we illustrate the parameter extraction process with our spreading resistance example, here is an assignment. We had talked about the current voltage model, the static current voltage model of a real diode and we have put down this expression in the module on introduction. Identify the parameters namely the geometrically process and other parameters constants physical and empirical and variables dependent and independent of the real diode model used in SPICE.

That is the one that is shown here and tabulate their units and typical range of values. So, you may have do some search to tabulate the typical range of values of the parameters.

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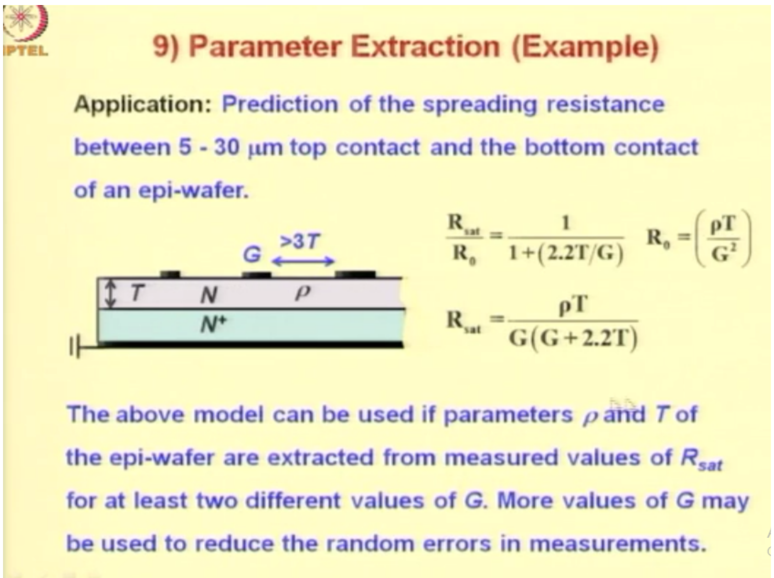

Now let us come to the example of parameter extraction. Let us say you want to use the spreading resistance formula for a situation like this where you have a contact a square contact on an epitaxial wafer. The contact size is small, so that the bottom of the epitaxial wafer which is used as the other contact approaches infinity in a relative term to the contact at the top of the wafer.

Let us assume that is our situation. So, the application is prediction of the spreading resistance between 5 to 30-micron top contact and the bottom contact of an epi-wafer. We assume the bottom contract to be very large. The dimension G varies between 5 to 30 microns in our practical example. So, what we mean is we should extract the parameters using values of G in this practical range.

We should not use let us say value of G = 1000 angstroms or 1000 microns. So, the formula for R sat is given by this expression which is repeated from our previous slides and this can be recast in the form of this equation. You can easily see that. Now based on this expression you can anticipate that the above model can be used that is this expression, if parameters rho and T.

So, the rho here and T of the epi-wafer are extracted from measured values of saturation resistance for at least 2 different values of G. So, this T here is the thickness of the epi-wafer. You have a bulk wafer which is however heavily doped. Evidently, the effect of the resistance of this wafer will be absorbed in an effective value of T in this case because our contact is not here at the distance T from the top contact.

But it includes the heavily doped wafer between the top contact and the bottom contact. Now if you want to solve for 2 values T and rho evidently you need 2 expressions. So, that is why you have to measure R sat for 2 different values of G. In practice more values of G may be used to reduce the random errors in measurements so that is what is shown here. So, you can use different values of g in the range 5 to 30 microns.

So, for each pair of G values you find out the values of rho and T and then you average all these values so that any random errors in the measurements are removed.

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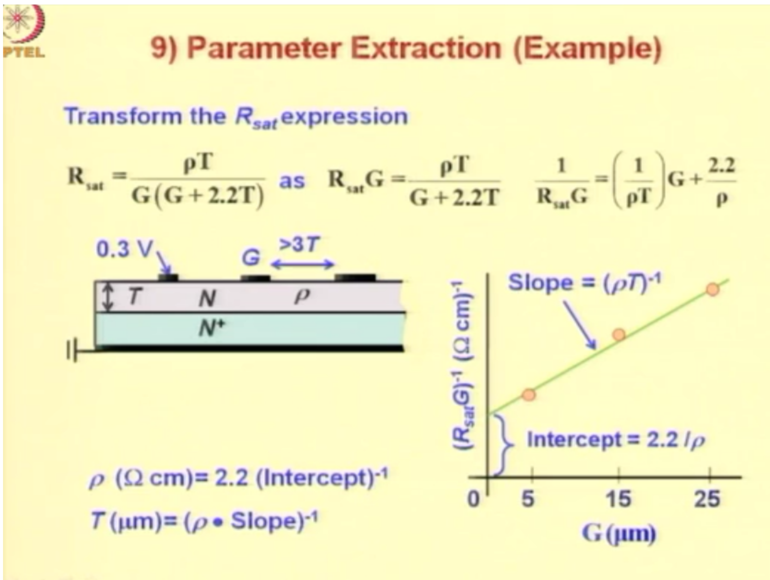

So, transform the R sat expression given here as R sat into G = rho T/G+2.2 T. Now this is an important aspect in parameter extraction. The model expression will have to a transformed so that you can plot the data in a simple graph preferably as a straight line. So that is the intension of transformation. So, we have moved G to the left hand side and taken the product R sat into G. It turns out to be of this form.

You can further transform this as 1/R sat G = to 1/rho T into G+2.2/rho. Once you transform it like this as shown in this graph 1/R sat into G as a function of G is a straight line because rho and T are constants. So, 1/rho T becomes a slope of this straight line and 2.2/rho becomes the intercept. The values of G range between 5 and 30. To measure the resistance you will use a small voltage.

Because if we use the large voltage you may have velocity saturation effects and so on which are not included in the resistance expression. So, our resistance assumes that the mobility is not varying with the applied voltage or field. From the slope and from the intercept one can get the values of rho as follows. So, rho in Ohm centimeter = 2.2 into reciprocal of the intercept and T in micrometers = reciprocal of the product of rho into the slope.

So, please note here that R sat G is expressed in ohm centimeter and G is in microns. Only when you plot it in this form your rho and T will be having the dimensions shown here. Now fitting a straight line to these different points is a graphical method of averaging the results of rho and T, right for a large number of data points.

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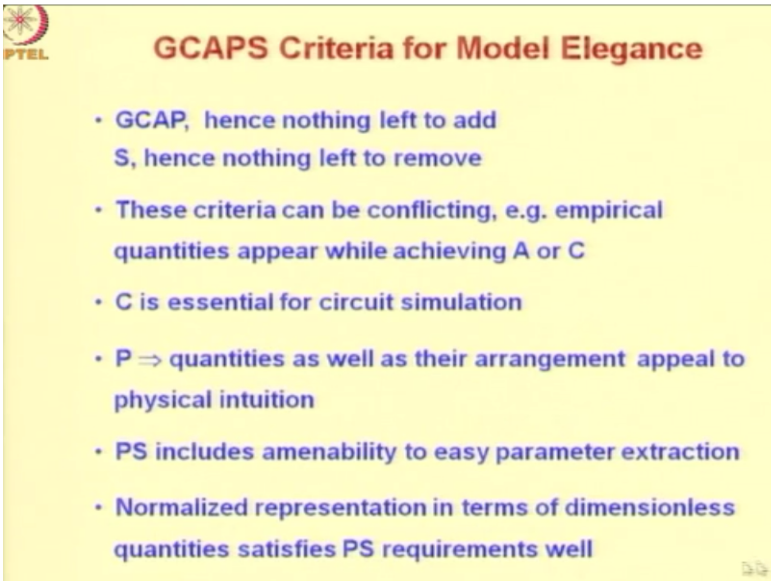

Now we have completed the discussion of various steps of deriving a device model. Let us look at the criteria for elegant model GCAPS criteria for model elegance. So, we had introduced the GCAPS criteria in the testing step where G stands for generality, C for continuity, A for accuracy, P for physical basis and S for simplicity. So, a model is set to be elegant if it satisfies all these criteria.

Now what is the definition of elegance? The thing is said to be elegant if there is nothing more left to add and nothing more left to remove. So, nothing left to add nothing left to remove that thing is said to be elegant. Come into the model, a model which satisfies GCAP, generality, continuity, accuracy and physical basis if at all these and nothing left to add and if it has simplicity then nothing is left to remove and therefore the model is elegant.

Note that these criteria can be conflicting as we have seen empirical quantities appear while achieving accuracy or continuity. We have seen this in our example of the spreading resistance. Now the continuity criterion is very essential for circuit simulation. This something that we have not discussed very much, however device models used for circuit simulation have to satisfy the criteria of continuity.

In other words, the model function should be such that all its derivative of any order, right should be continuous over the range of variables of interest. Now what is physical basis mean? It means quantities as well as their arrangement appeal to physical intuition. So, if you take the example of the spreading resistance all the quantities in the model expression should have physical basis but that is not sufficient.

We should arrange the model so that it appeals to physical intuition. For example, when you write the model expression as r = to r0/1+delta/G then it appeals to physical intuition and also it is very easy to remember. Why does it appeal to physical intuition because you see that the effect of the bottom contact extension is to reduce the resistance from the 1-dimensional resistance value r0.

P and S together include amenability to easy parameter extraction. So, a model is said to be simple on the physical basis if its parameters can be extracted very easily. Finally normalized representation in terms of dimensionless quantities satisfies the physical basis and simplicity requirements very well. So, you must always try to express the model in a normalized form. It is compact easy to remember, it is simple and appeals to physical intuition.

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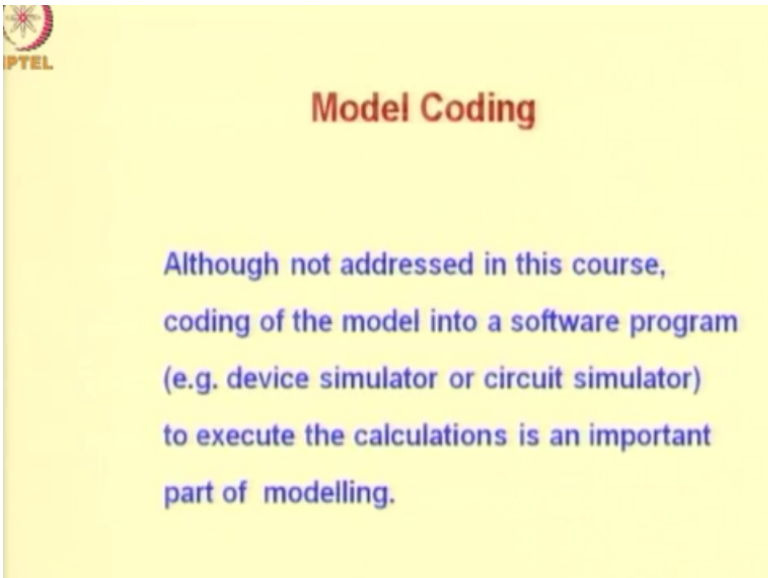

Finally, about model coding, although not addressed in this course coding of the model into a software programme. Example device simulator or circuit simulator to execute the calculations is an important part of modelling. We have not addressed this coding of the model, unless you code the model it does not become a product that can be used by others. In this course however, we are not discussing about model coding.

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Now with that we have come to the end of the module. So, let us summarize the important points that we have understood in this module.

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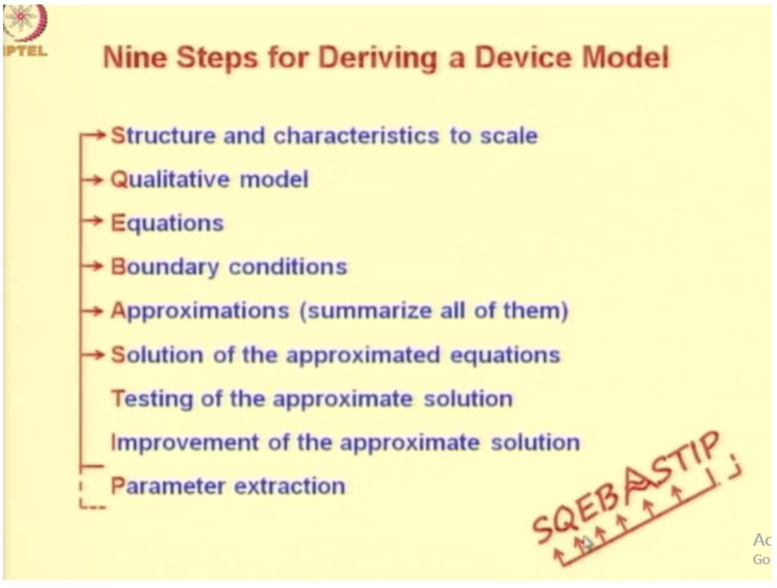

So we began by specifying the 9 steps of deriving a device model which are abbreviated as SQEBASTIP.

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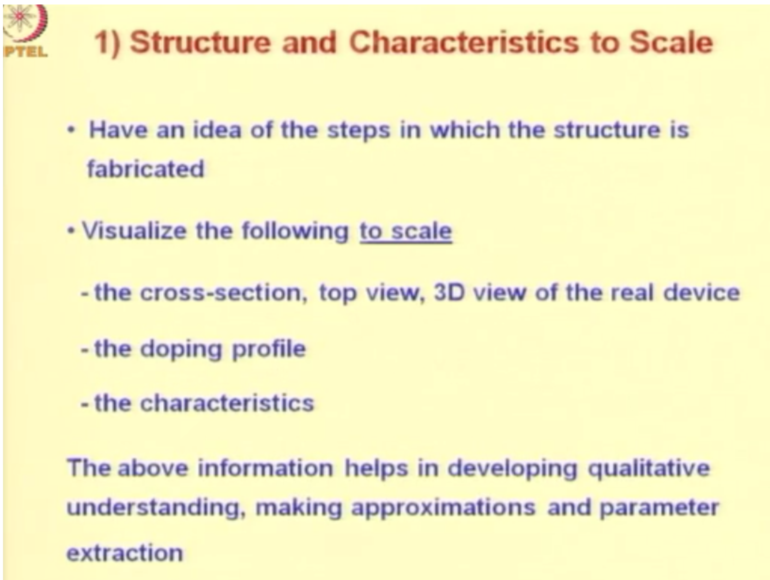

To emphasise that the structure and characteristics should be drawn to scale and in this step we must have an idea of the steps in which the structure is fabricated and we must visualize to scale the cross section top view and 3D view of the real device as well as the doping profile and the characteristics. The above information helps in developing qualitative understanding making approximations and parameter extraction.

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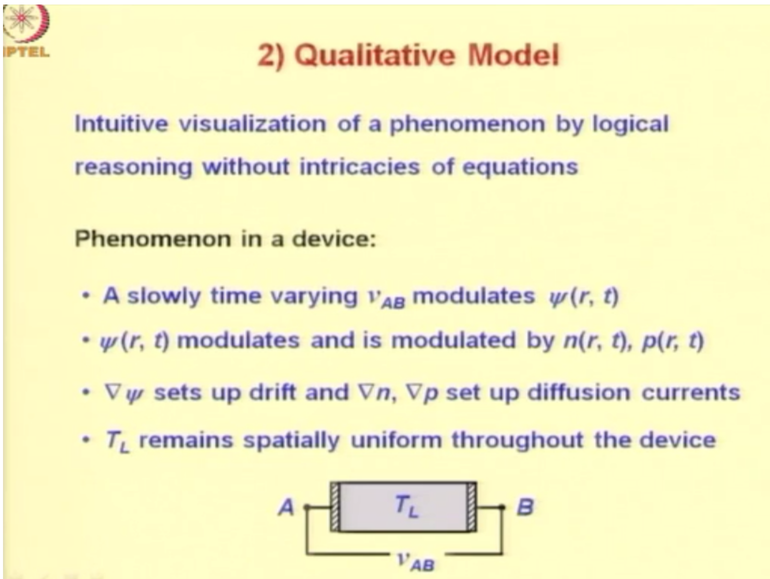

The step of qualitative modelling which is intuitive visualization of phenomenon by logical reasoning without intricacies of equations. The phenomenon that we decide to model in our course can be explained in terms of the following steps. A slowly time varying VAB modulates the potential psi in a device as a function of space and time. Psi modulates and is modulated by the electron and hole distributions as a function of space and time.

Gradient of psi sets up drift and gradient of n and p set up diffusion currents. And finally we assume that the lattice temperature remains spatially uniform throughout the device.

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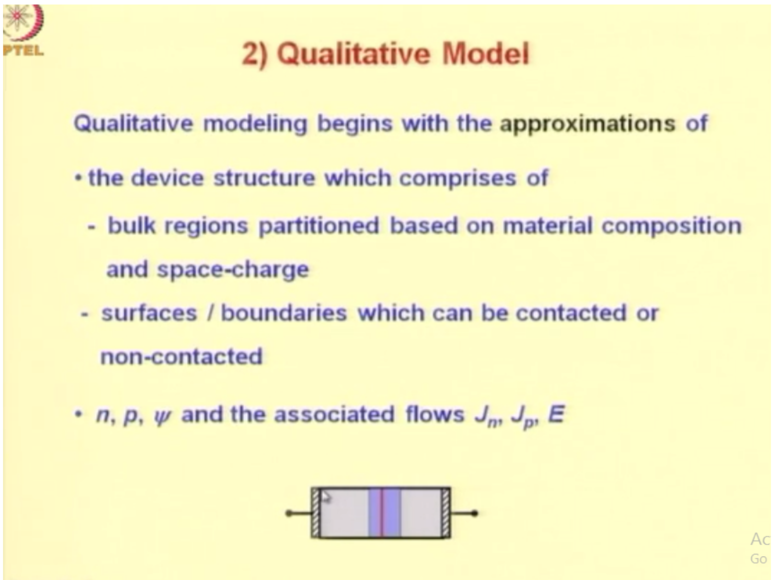

Qualitative modelling begins with the approximations of the device structure which comprises of the bulk regions and surface or boundaries and approximations of n, p, psi and the associated flows of Jn and Jp and E. The bulk regions can be partitioned based on material composition and space charge as shown here in this figure. And the surfaces or boundaries can be contacted or non-contacted.

Here you have this contacted boundaries and these boundaries are non-contacted.

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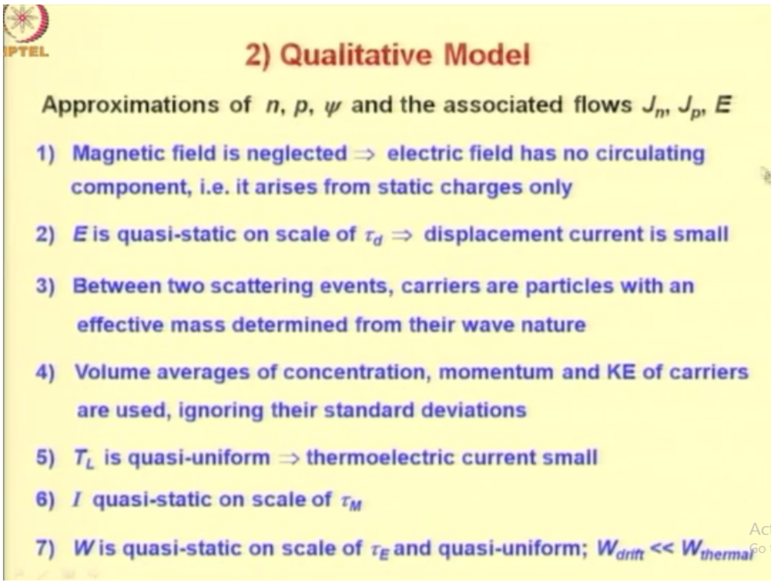

Approximations of n, p and psi and the associated flows Jn, Jp and E. So we discussed 7 approximations associated with this n, p, psi, Jn, Jp and E.

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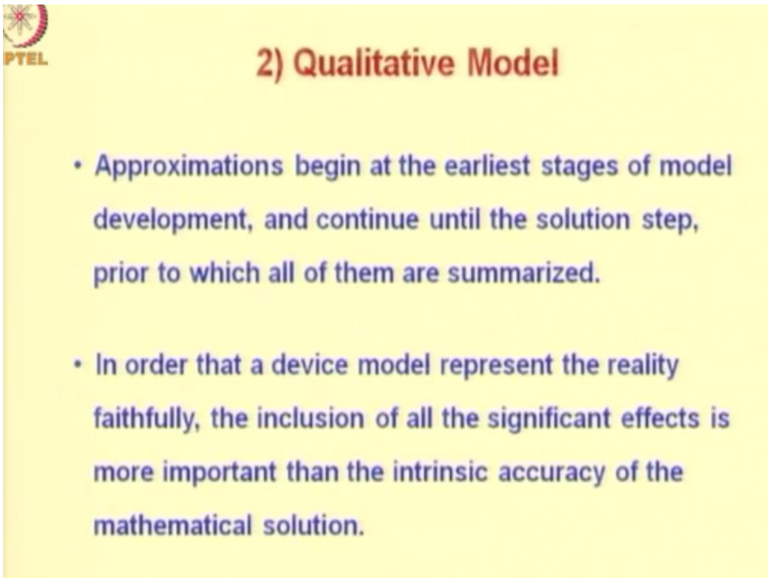

We remarked that approximations begin at the earlier stages of model development and continue until the solution step prior to which all of them are summarized. In order that a device model represent the reality faithfully, the inclusion of all the significant effects is more important than the intrinsic accuracy of the mathematical solution.

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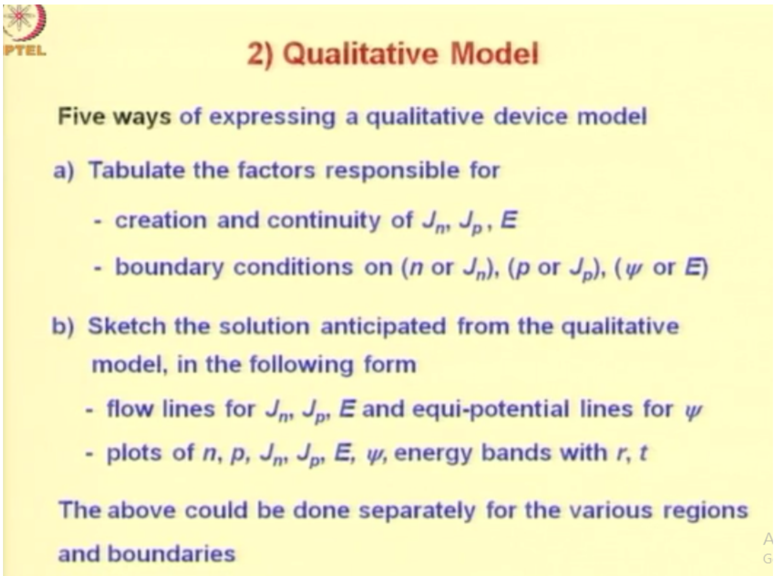

We described 5 ways of expressing a qualitative device model. First, tabulate the factors responsible for creation and continuity of Jn, Jp and E and for boundary condition on n or Jn, p or Jp, psi or E. Then you sketch the solution anticipated from the qualitative model in the following form. Flow lines for jn, Jp, E equi-potential lines of psi and plots of n, p, Jn, Jp, E an psi and energy bands with space and time.

Above could be done separately for the various regions and boundaries.

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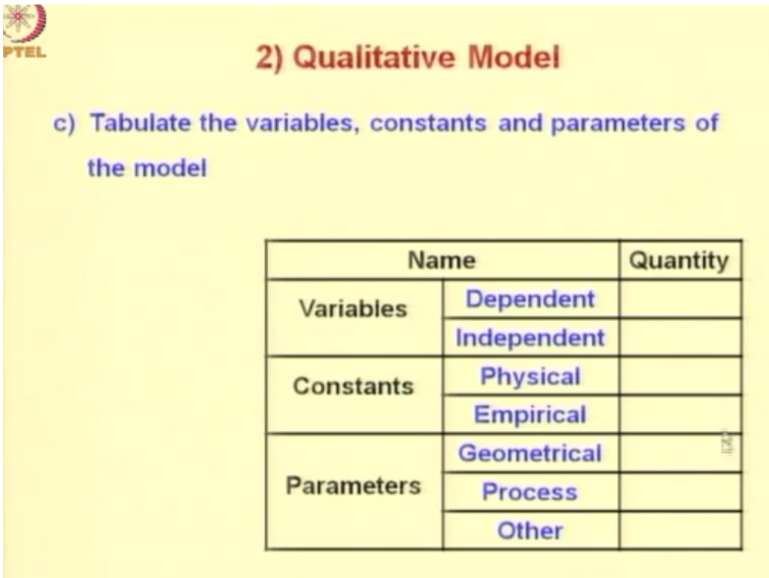

And the fifth way of expressing a qualitative model is to tabulate the variables constants and parameters of the model in the following tabular form.

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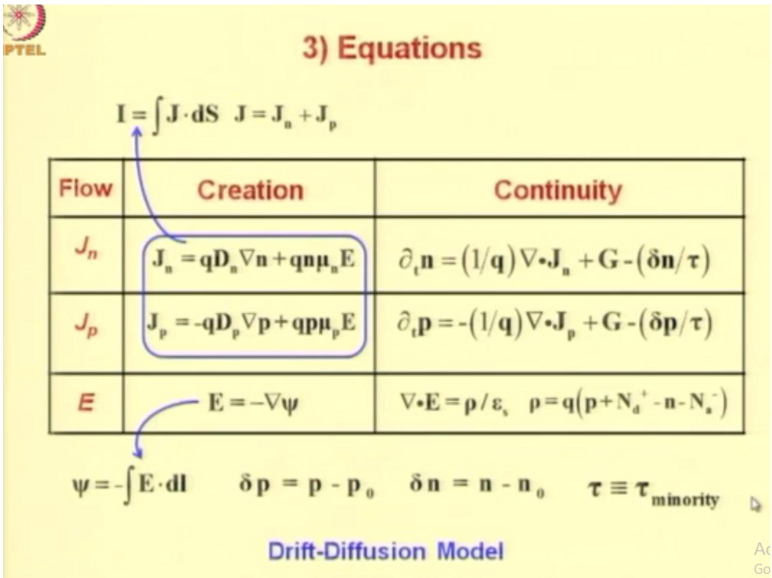

About the equations, we said that we used the equations of the drift diffusion model in this course.

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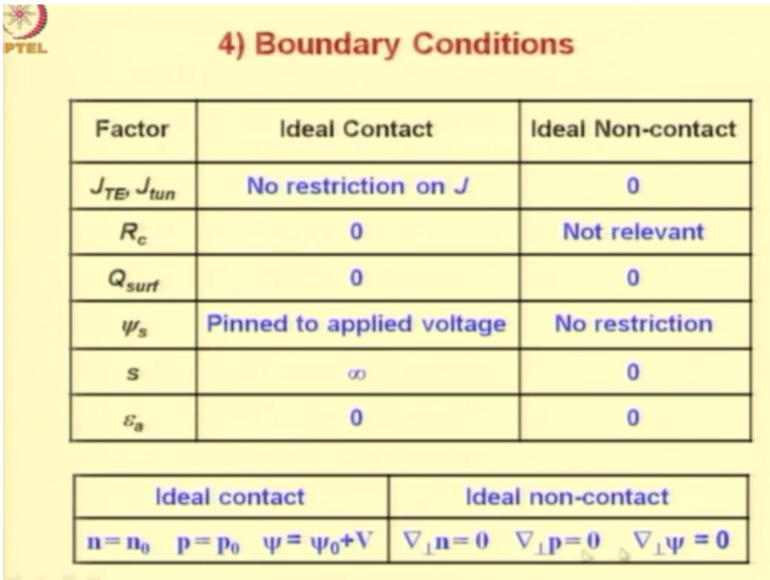

4) Boundary Conditions

Factor	Ideal Contact	Ideal Non-contact
J_{TE}, J_{tun}	No restriction on J	0
R_c	0	Not relevant
Q_{surf}	0	0
ψ_s	Pinned to applied voltage	No restriction
s	∞	0
ε_a	0	0

Ideal contact	Ideal non-contact
$n = n_0 \quad p = p_0 \quad \psi = \psi_0 + V$	$\nabla_{\perp} n = 0 \quad \nabla_{\perp} p = 0 \quad \nabla_{\perp} \psi = 0$

Boundary conditions, these are the factors which affect the boundary conditions. The boundary conditions dependent on this factors were discussed in the module on drift diffusion transport. We said that we shall use in our modelling the boundary conditions corresponding to ideal contact which are described by these conditions of the factors and for ideal non-contacts they are described by these conditions.

The ideal contact the electron and hole concentrations are equal to equilibrium value and the potential is equal to built-in potential plus the applied voltage. While at ideal non-contact normal gradients of electron and hole concentrations and potential are 0.

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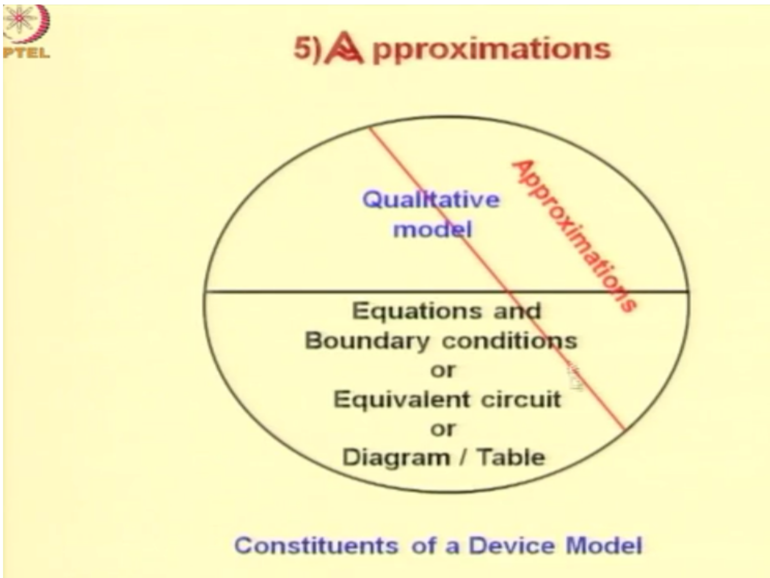

Coming to the approximations, we said you have approximations associated with the qualitative model as well as with the quantitative part.

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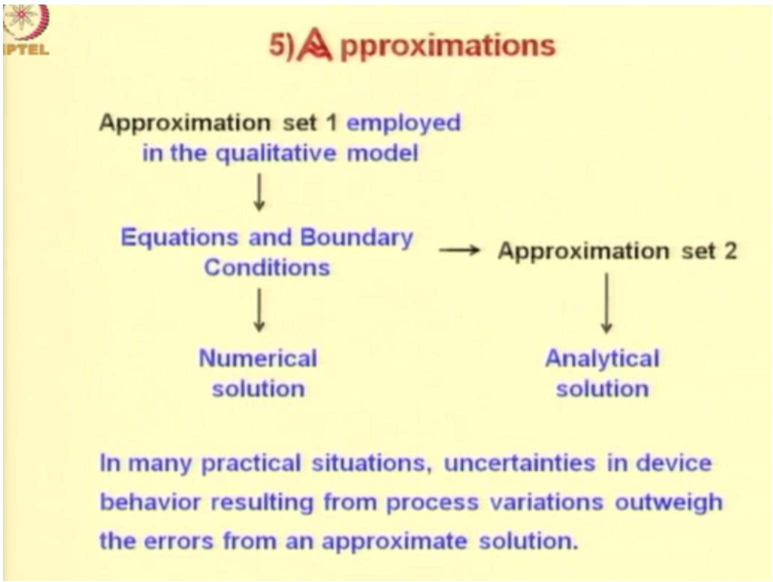

So, the approximations set 1 employed in the qualitative model lead to the equations and boundary conditions. While additional approximations are required of these equations and boundary conditions if you want to derive an analytical model. On the other hand, the approximation made in qualitative model suffice, if you are interested in a numerical solution.

In many practical situations uncertainties in device behaviour resulting from process variations outweigh the errors from an approximate solution and that is why one goes in for an analytical solution with many approximations.

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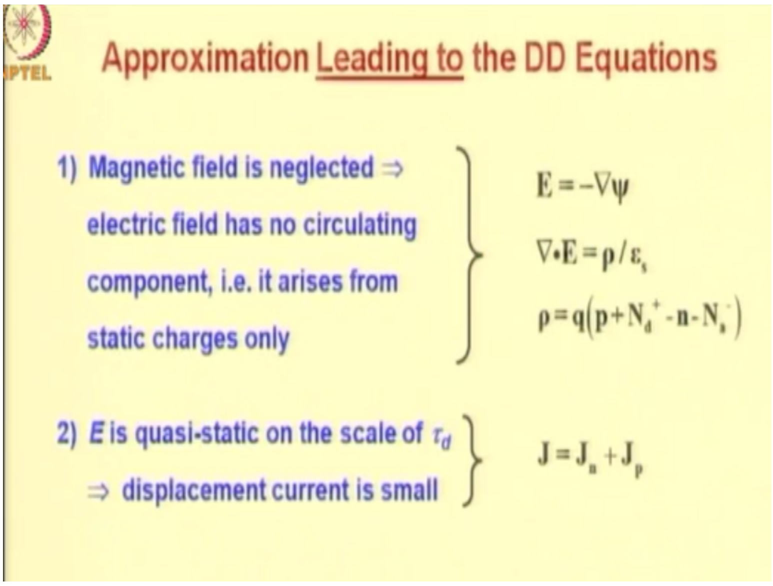

Now approximation leading to the drift diffusion equations, we listed them for the electro static equations for the formula J = Jn+Jp wherein we neglect the displacement current.

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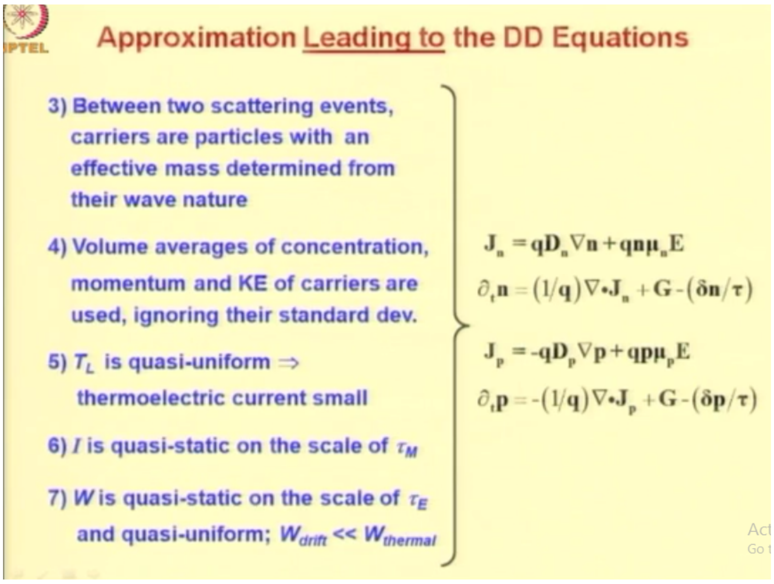

And a number of approximations associated with the current density and continuity equations.

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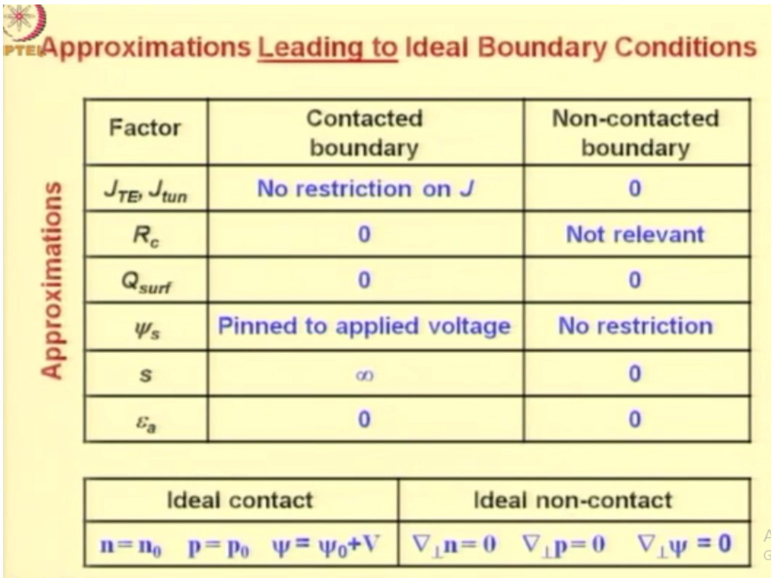

Approximation leading to the boundary conditions, so these were the approximations and these were the boundary conditions for ideal contacts and non-contacts.

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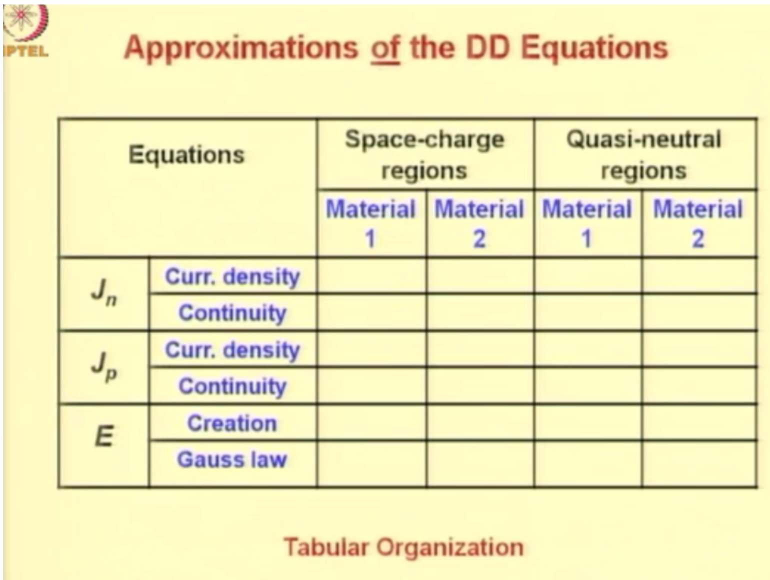

Approximations of the drift diffusions equations we said can be organized in a tabular form where the rows are the equations of the drift diffusion model and the columns are space-charge and quasi-neutral regions in various materials.

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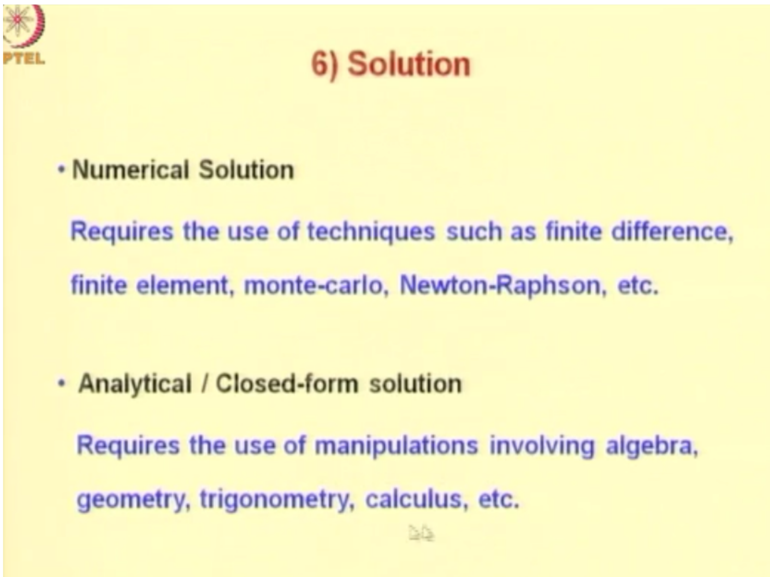

Coming to the solution we said there are 2 types of solutions numerical and analytical or closed-form. Numerical solutions require the use of finite difference, finite element, Monte-Carlo, Newton-Raphson techniques. Whereas analytical or closed-form solutions are obtained from manipulations involving algebra, geometry, trigonometry, calculus, etc.

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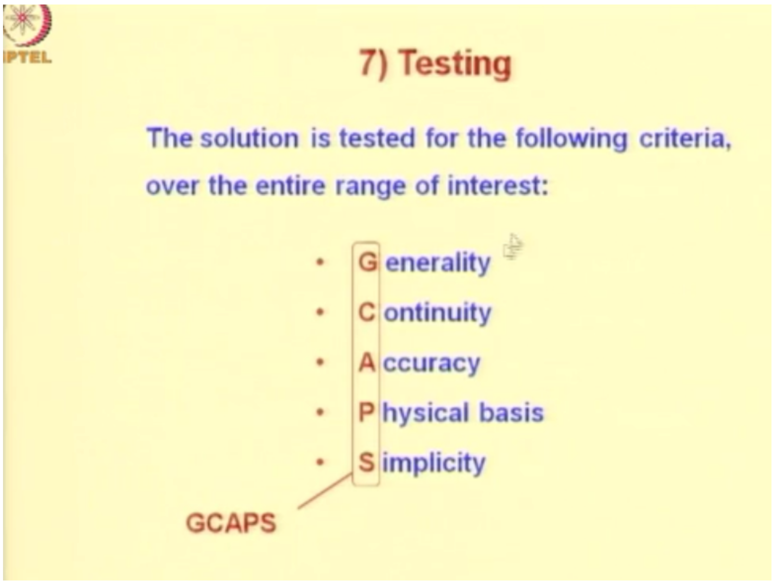

Regarding the testing step we said we test the solutions for the GCAPS criteria.

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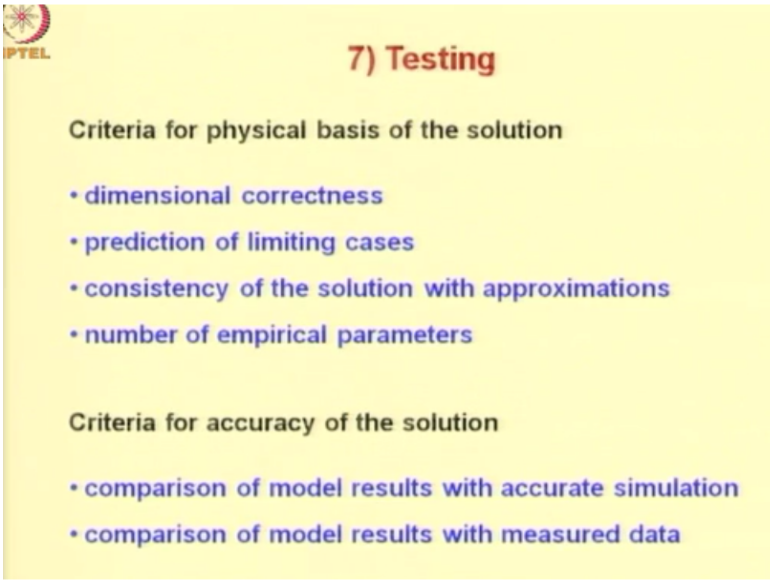

The criteria for physical basis where dimensional correctness, prediction of limiting cases consistency of solution with approximations and number of empirical parameters. While those for accuracy of the solution were comparison of the model with accurate simulation and measured data. Comparison with measured data being the ultimate test of a model.

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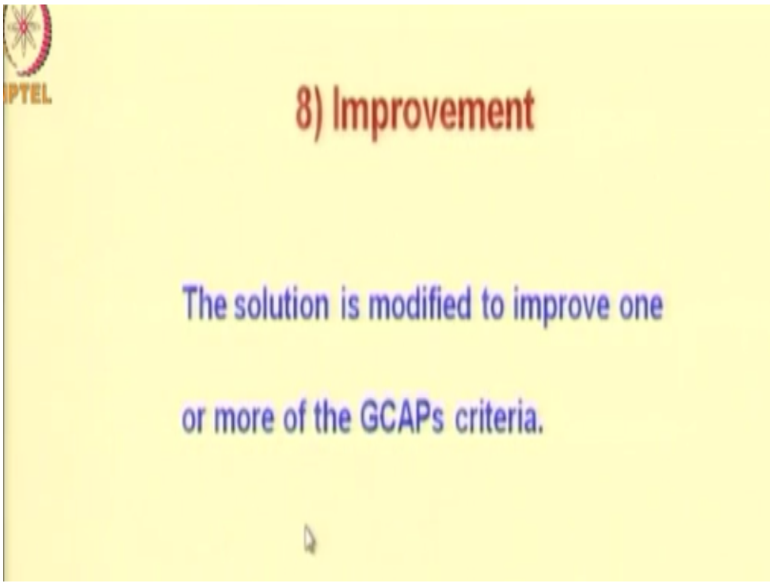

In that testing step if we find that some of the GCAPs criteria are not met satisfactorily then we try to improve them.

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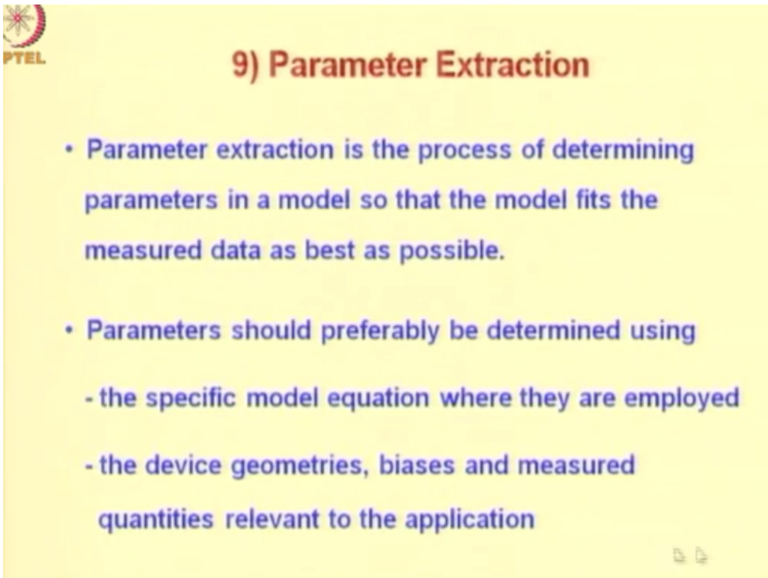

And finally we try to extract the parameters of the model, in order to use the model to fit with measured data. Here the important thing to be borne in mind is that the parameter should be determined using the specific model equation where they are employed and using device geometries biases and measured quantities relevant to the application.

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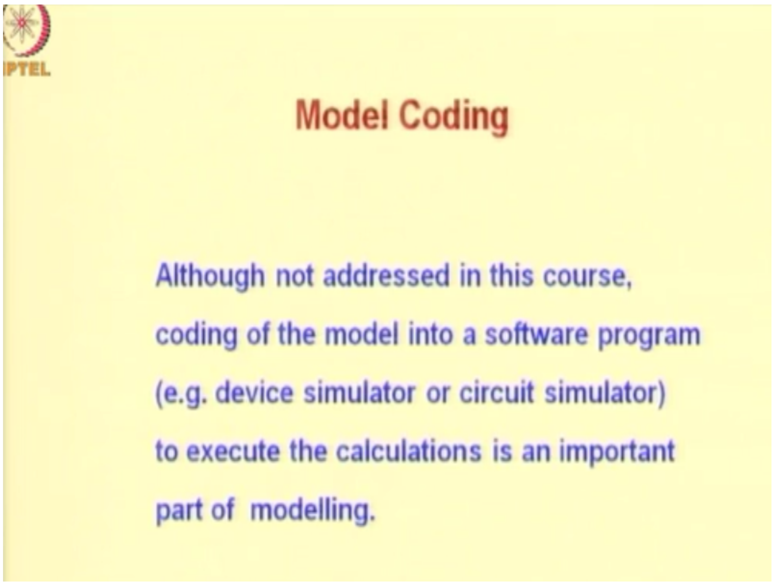

Finally, although not addressed in this course, coding of the model into a software program for just device simulator or circuit simulator to execute the calculations is an important part of modelling.

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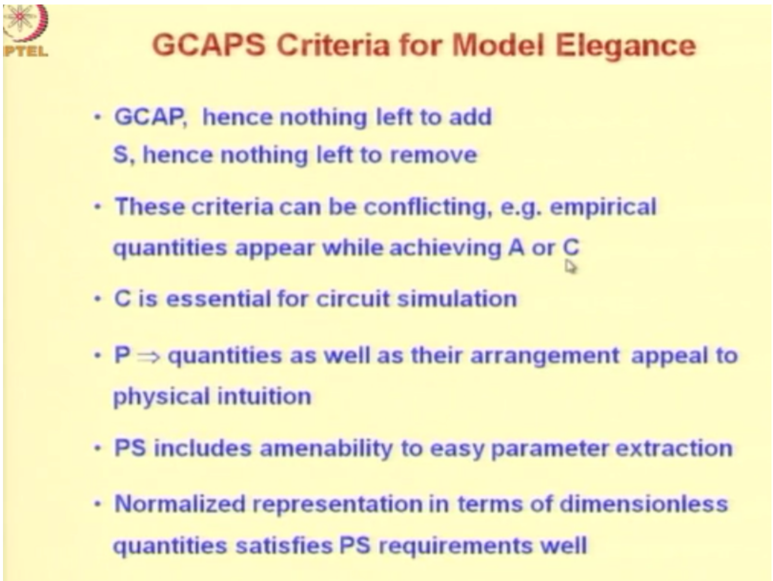

GCAPS criteria for model elegance, we made several comments about it as to why these criteria imply that the model is elegant and we pointed out some of the features associated with the criteria such as the continuity is essential for circuit simulation and the fact that the criteria can be conflicting that is in order to then one criterion you may lose the other to some extent.

Also normalize representation in terms dimensionless quantities is very important because it satisfies the physical basis and simplicity requirements very well.

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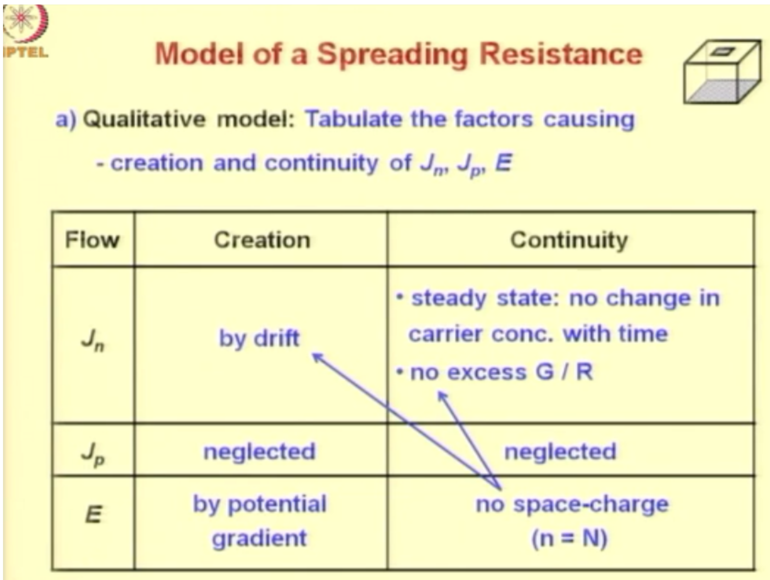

We illustrated the various steps of device modelling procedure using the model of a spreading resistance. First we discussed the qualitative model, which involve tabulating the factors for causing creations and continuity of Jn, Jp and E and this tabulation looks something like this.

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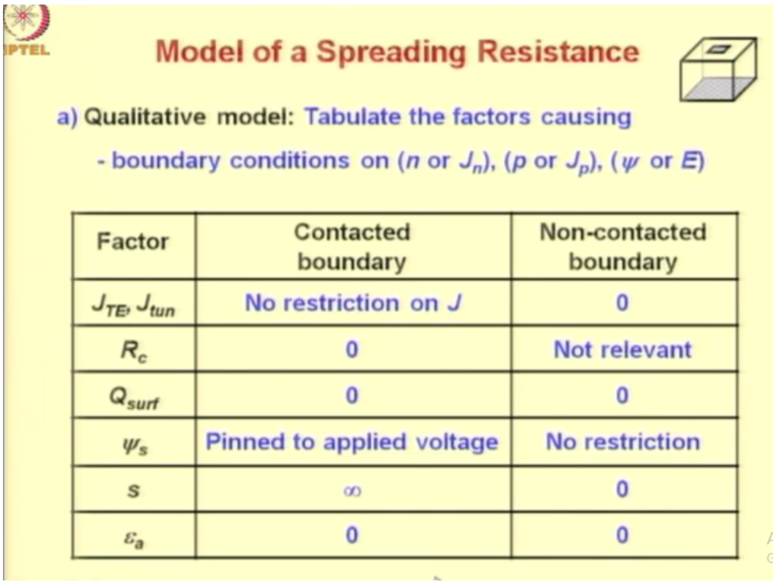

Then we tabulated the factors causing boundary conditions on n or Jn, P or Jp and psi or E. This table had the appearance shown on this slide.

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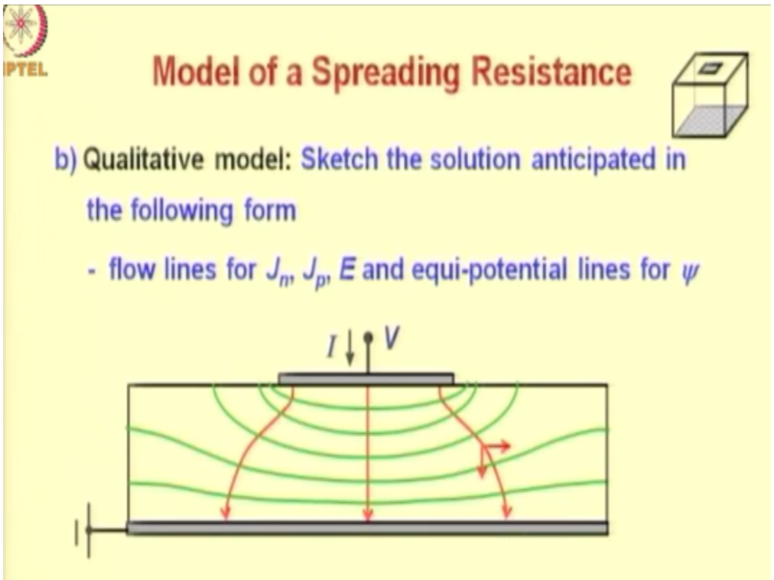

Next as a part of qualitative modelling we sketch the solution anticipated in the form of flow lines of Jn, Jp and E and equi-potential lines for psi. So, these red lines are the flow lines in the spreading resistance and the green lines are the equi-potential lines.

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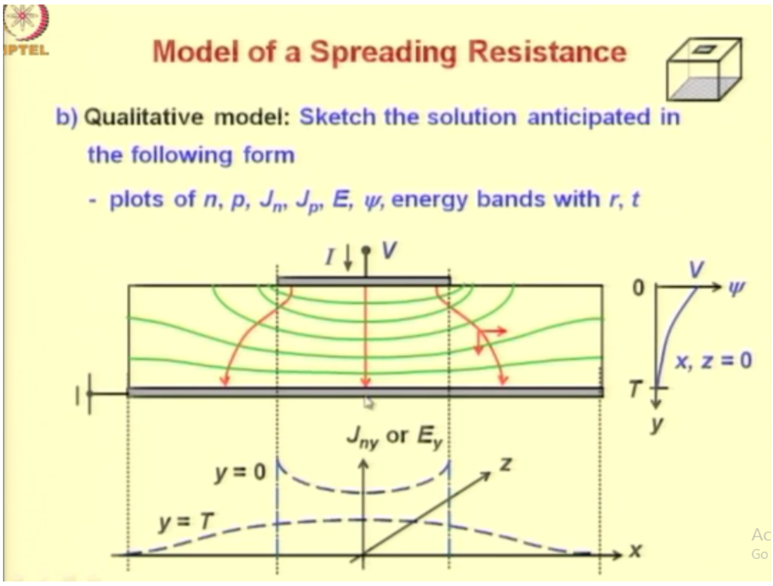

Next we anticipated the solution as plots of n, p Jn, Jp, E, psi or energy bands with space and time. **Now**, we did not bothered about energy bands because energy bands are not required for understanding the operation of a spreading resistance. We did not sketch the n and p concentrations because they were uniform throughout the device. Further, we did not bother about the hole current density.

Because we are neglected the hole concentration and contribution of holes to device phenomena. Therefore, we sketched Jn, the electric field and psi. The y component of the electron current density Jn or the electric field had this appearance over the top and bottom contact as a function of distance. The edges had higher values near the top contact because the field at the sharp corners or edges is higher than in the centre.

In the bottom contact however, the current density or electric field drop to 0 as we moved further **away** from the centre line because the length of the field or flow line went on increasing as we moved away from the centre of the bottom contact. And this was the distribution of psi as a function of y along the centre line.

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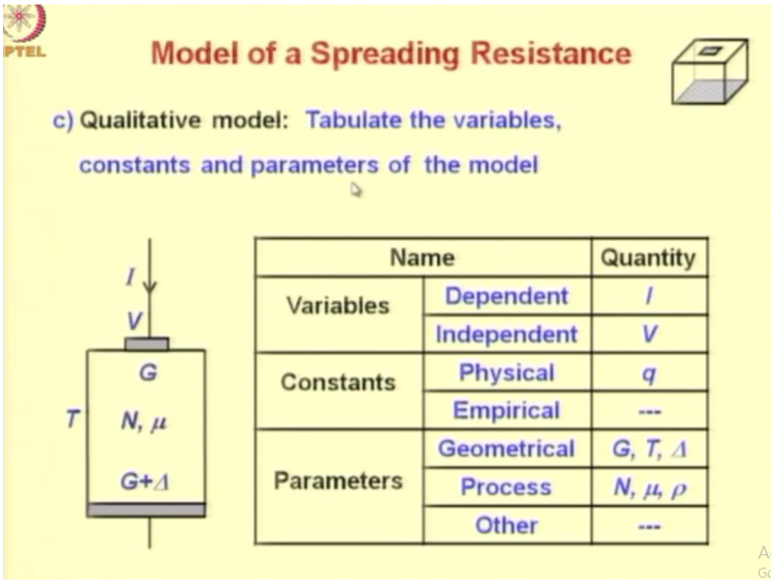

As a part of qualitative model we finally tabulated the variables constants and parameters.

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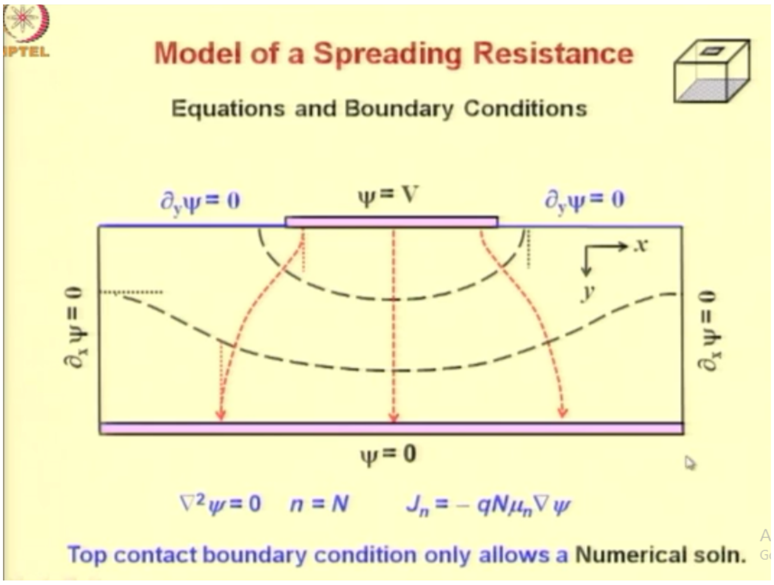

Next, we considered equations and boundary conditions. The equations were Delta square psi = 0. Electron concentration = doping concentration and electron current density = - q, doping concentration into mobility into gradient of psi, because the current was only due to drift. These equations followed from the qualitative model. Similarly, the boundary conditions shown here also followed from the qualitative model.

And these boundary conditions were responsible for the electric field or current flow lines and equi-potential lines shown here. Coming to the solution these equations and boundary conditions particularly the boundary condition on the top contact only allowed a numerical solution of this spreading resistance.

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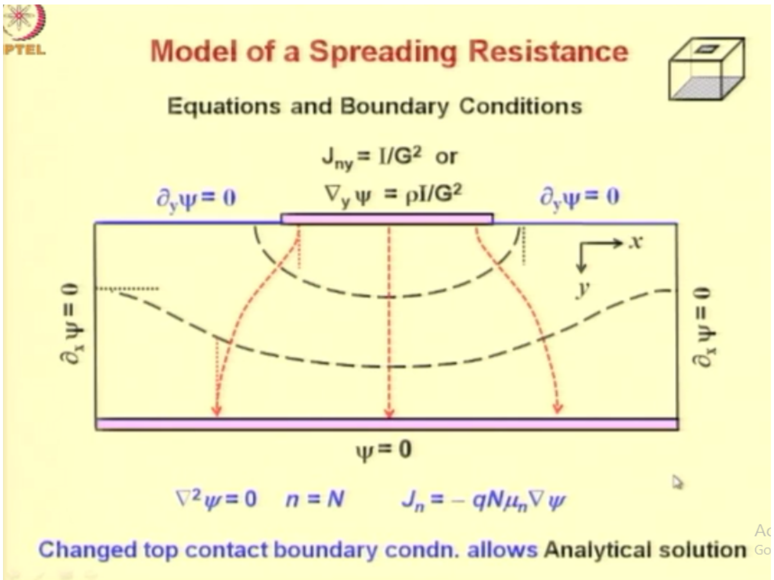

A change in the top contact boundary condition allowed us to obtain an analytical solution. However, the analytical solution was of infinite series form and therefore computationally it was intensive for a model to be used in circuit simulation.

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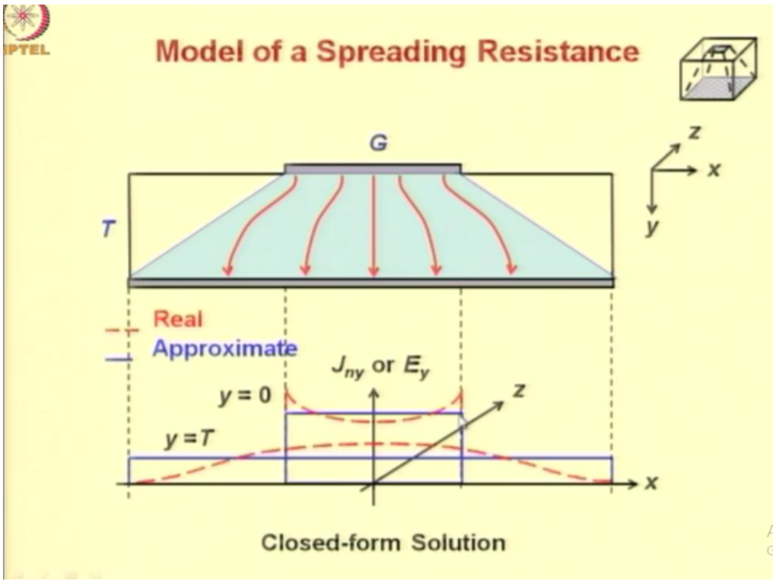

Therefore, we went in for a closed-form solution in which the following assumptions were made. Firstly, that the current spread at a constant angle from the top contact to the bottom contact. And secondly the distribution of electron current density or electric field normal to the horizontal cross sectional area of the device was assume to be uniform over the current flow cross section.

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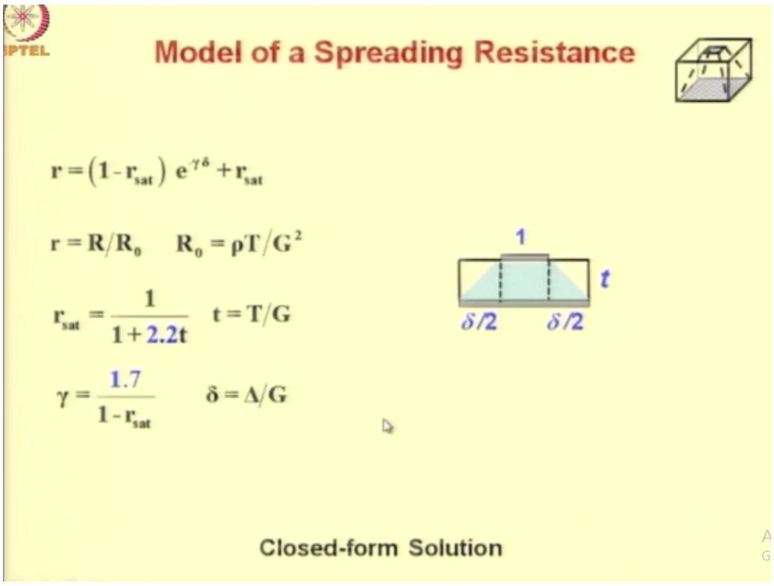

Now based on this, we obtained the model shown here after attempting the improvement of the basic model based on the constant angle current spreading approach.

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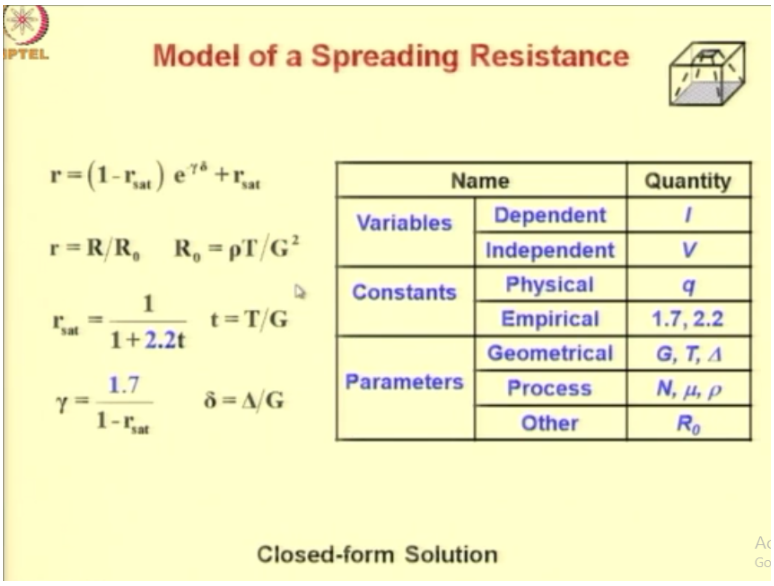

The variables, constants and parameters of the model were as listed in this figure. The empirical constants of 1.7 and 2.2 were necessary to improve the continuity and accuracy properties of the model.

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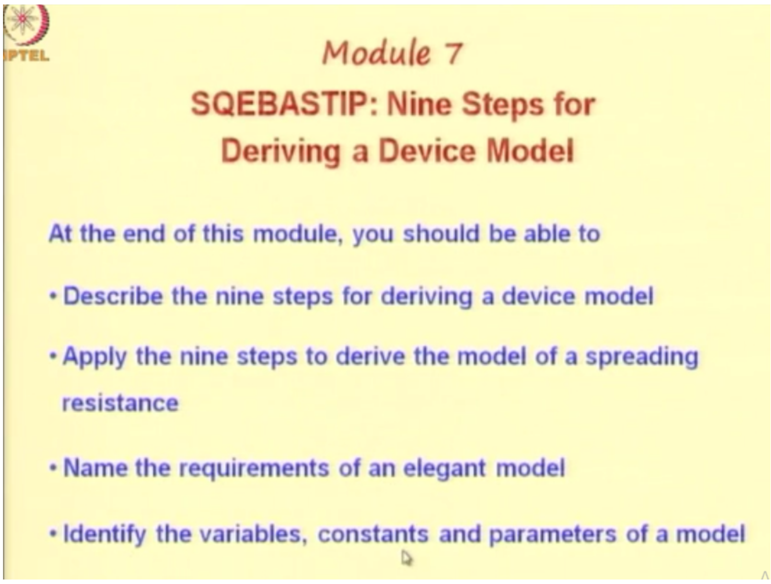

So towards the end of the lecture, let us just review the achievements. At the end of this module, I hope that you should be able describe the 9 steps for deriving a device model. Apply the 9 steps to derive the model of a spreading resistance. Name the requirements of an elegant model and identify the variables constants and parameters of a model.

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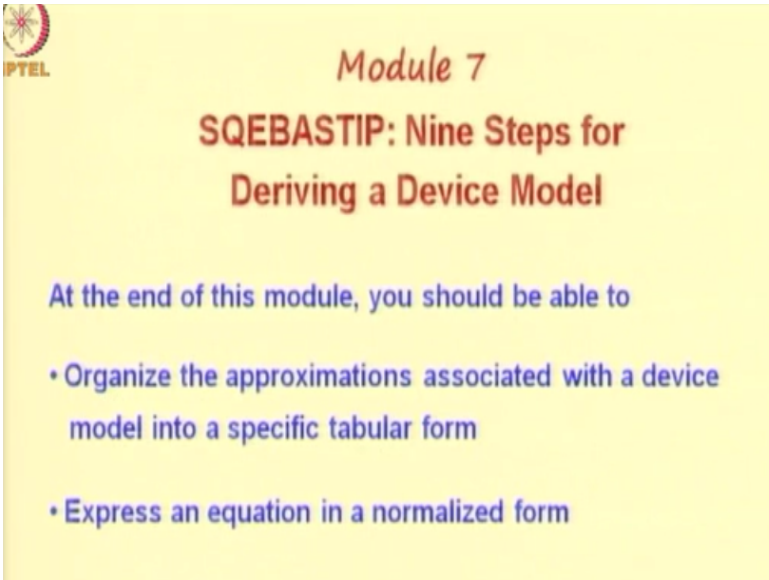

In addition, you should be able to organize the approximations associated with a device model into a specific tabular form and express and equation in a normalized form. So, with that we have come to the end of this module and we will start a fresh module namely the types of models in the next lecture.