Semiconductor Device Modeling

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Lecture - 34
SQEBASTIP: Nine Steps of Deriving a Device Model

So far we have gained a thorough understanding of carrier transport. We discussed qualitative and quantitative model of carrier transport and we said that in this course we shall be using the drift diffusion transport model. Subsequently, we discuss the characteristics times and lengths used in modeling of semiconductor devices and we also discussed the energy band diagram.

We pointed out how the energy band diagram can be used as a tool for solving problems apart from a representation of the conditions in a device. With this background we are now ready to embark on modeling on various devices. In this module, we shall look at the procedure which we employ for modeling any semiconductor device.

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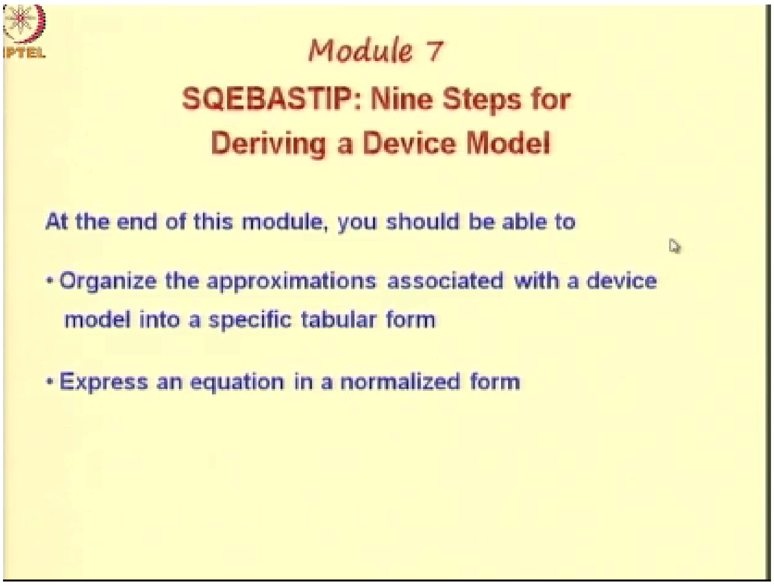

Module 7

SQEBASTIP: Nine Steps for Deriving a Device Model

At the end of this module, you should be able to

- Organize the approximations associated with a device model into a specific tabular form
- Express an equation in a normalized form

We shall abbreviate the procedure as SQEBASTIP. Thus, there will be 9 steps for deriving a device model. Now at the end of this module, you should be able to 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. Identify the variables constants and parameters of a model. Organize the approximations associated with the device model into a specific tabular form.

And finally express an equation in a normalized form.

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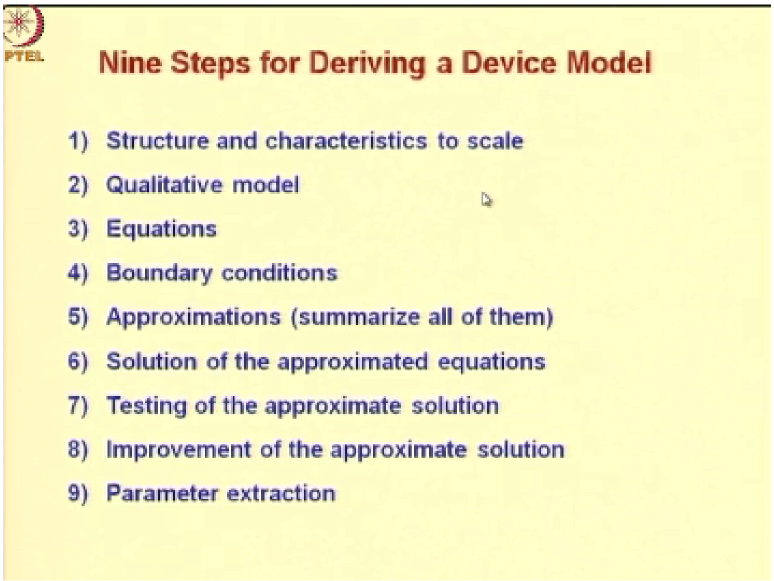

Nine Steps for Deriving a Device Model

1) Structure and characteristics to scale
2) Qualitative model
3) Equations
4) Boundary conditions
5) Approximations (summarize all of them)
6) Solution of the approximated equations
7) Testing of the approximate solution
8) Improvement of the approximate solution
9) Parameter extraction

Now let us look at what are the 9 steps for deriving a device model. The first step is visualizing the structure and characteristics of the device to scale. And next we develop a qualitative model of the device for the particular characteristics of interest. The third step involves writing down the equations. These equations follow from the qualitative model. After writing the equations we write the boundary conditions which also follow from the qualitative model.

In the fifth step we summarize all the approximations we have made starting from the qualitative model and then regarding the equations and boundary conditions. After all the approximations are summarized we solve the approximated equations and then we test the approximate solution for accuracy and physical correctness. After testing we might find that the model may need improvement.

And therefore the 8 step involves improving the approximate solutions and finally we need to decide the values of the parameters that are used in a model and therefore the final step is parameter extraction.

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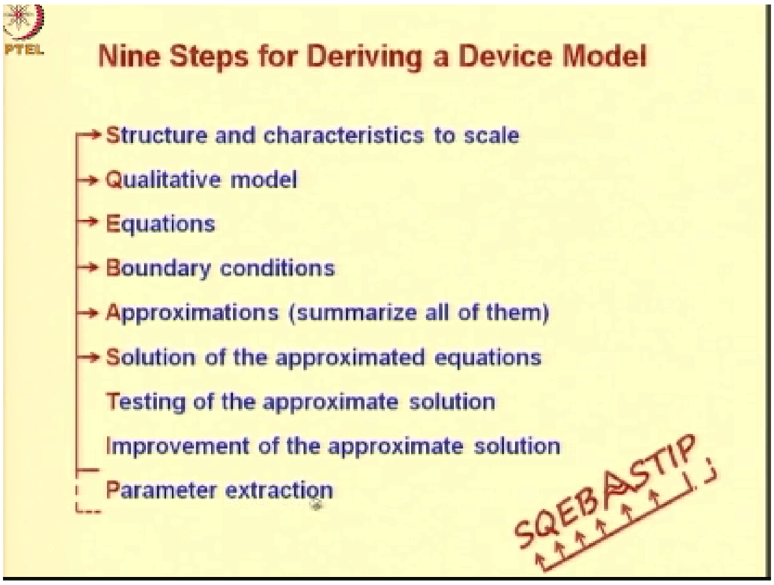

Nine Steps for Deriving a Device Model

- Structure and characteristics to scale
- Qualitative model
- Equations
- Boundary conditions
- Approximations (summarize all of them)
- Solution of the approximated equations
- Testing of the approximate solution
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SQEBASTIP

Now if you collect the first letters of the various steps then these first letters abbreviate to the word SQEBASTIP. This word is very easy to remember and therefore it acts like a mnemonic for the device modeling procedure. Once we remember this word then we remember all the 9 steps of the activity of device modeling.

Now it is important to recognize that the device modeling procedure is in general iterative that is after you attempt improvement of the approximate solution you might find that the model accuracy is still not very good or the model is for some reason not capturing the dominant physical phenomenon. In that case, you may have to go back to the previous steps and start all over again.

So you may go back to the solution step or you may go back to the approximation step to check whether your approximations are right, you may go back to boundary conditions and equations to see whether you have used the right equations and boundary condition. In fact you may go back right up to the structure and characteristics to see whether your assumption of the device structure has been correct.

Similarly, one may also have to redo that modeling exercise after parameter extraction if one finds that the model that we have developed is not amenable for easy parameter extraction. So we have a model which seems to be fairly accurate as shown by let us say comparison with experiments, but the point is when we apply the model to various device structures we must be able to fix the values of the parameters in the model in an easy manner for different devices.

Now if we find that this parameter extraction process is becoming difficult then one may have to go back and re-derive the model in a different form.

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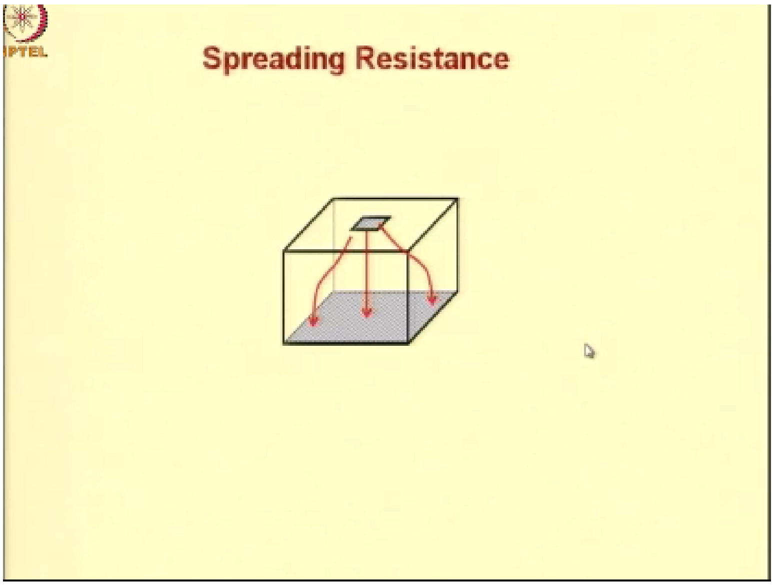

Spreading Resistance

We shall look at the various steps of modeling in detail and we will illustrate each of the steps using the modeling of what is called a spreading resistance. This simple device structure is shown in the diagram here. It consists of 2 electrodes which are parallel to each other. One of the electrodes is smaller than the other. The specific type of arrangement that we are going to discuss will involve 2 square contacts.

The smaller square contacts is placed over the center of the larger square contact at the bottom. In this case the current flow from the smaller contact to the larger contact is 3 dimensional as shown by this flow lines and therefore deriving a model of such simple characteristics as a resistance for this particular configuration is reasonably challenging exercise.

That is why we have chosen this spreading resistance device for illustrating the various modeling steps.

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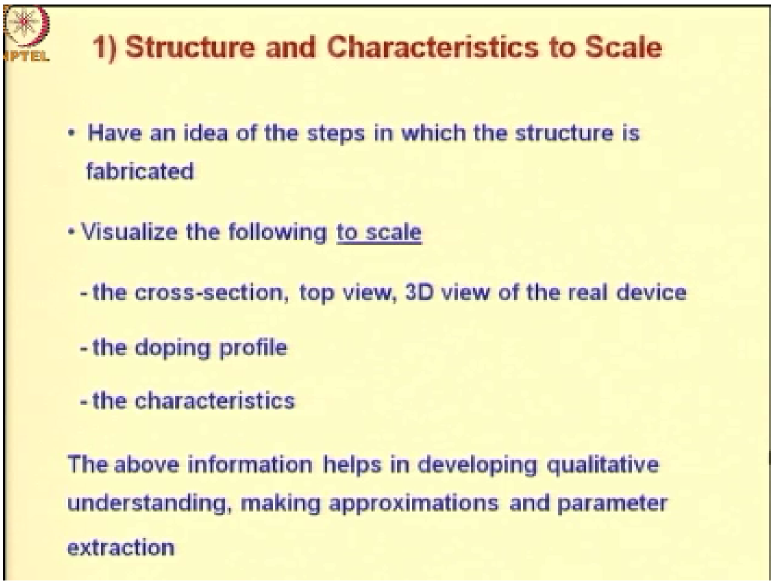

1) Structure and Characteristics to Scale

- Have an idea of the steps in which the structure is fabricated
- Visualize the following to scale
  - the cross-section, top view, 3D view of the real device
  - the doping profile
  - the characteristics

The above information helps in developing qualitative understanding, making approximations and parameter extraction

Let us begin with the first step namely visualization of structure and characteristics to scale. First, we should have an idea of the steps in which the device structure is fabricated. After which we should visualize the following to scale. First the cross section, top view and 3D view of the real device. Then the doping profile and finally the characteristics. The above information helps in developing qualitative understanding, making approximations and parameter extraction.

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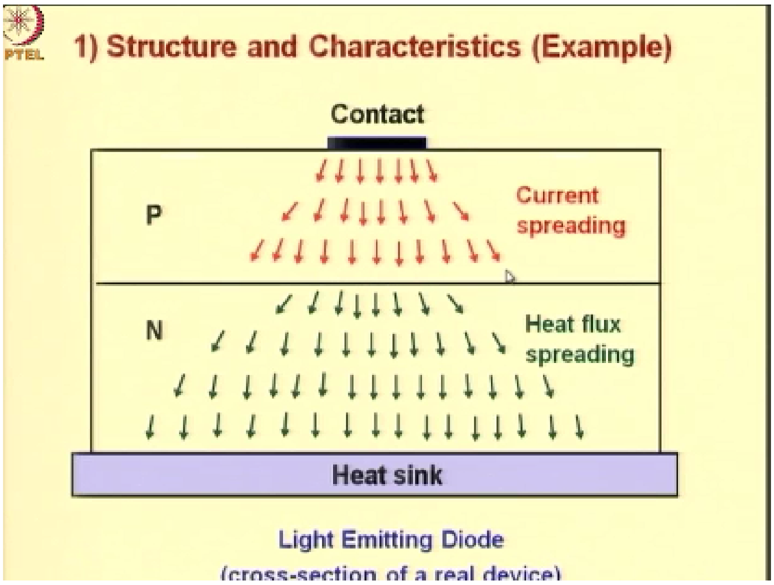

1) Structure and Characteristics (Example)

Contact

P

Current spreading

N

Heat flux spreading

Heat sink

Light Emitting Diode

(cross-section of a real device)

Let us illustrate these ideas using the example of a spreading resistance. First, we give some practical instances where spreading resistance arises. We shall however not discuss the fabrication steps because we would like to retain the focus on the device modeling procedure. Later when we take up devices like MOSFET and so on we shall discuss the fabrication steps in detail.

The first example that we give for a spreading resistance is that of high frequency BJT. We have shown a cross section of this device here. So you have the emitter fingers and between them you have these base terminals. This is NPNBJT. In the active region the electrons flow from emitter to collector and the flow of electrons in the N-type region is not 1-dimensional, but the flow spreads as the electrons move from the emitter end to the collector end.

Please note that the arrows indicate the direction of the electron flow and not the direction of the current. The current would be in the opposite direction to that of the arrows. So here is one example of a device where spreading resistance occurs and a model for the spreading resistance could be useful in modeling of the device. Another example is light emitting diode. So here the top contact is small from which the current spreads to the junction and then from the junction to the heat sink.

Now not only the current even the heat which is also some kind of a current spreads from the junction area to the heat sink area. So you can have not only electric current spreading, but you can also have spreading of the heat. Both these types of spreading are analogous and therefore the formula derived for an electrical spreading resistance can also be used for thermal spreading resistance in which the heat flux is non parallel and has a spreading type of situation.

Now let us assume some spreading resistance like this and assume that the top contact is s square one. And this junction area let us regard it as another contact and let us assume that it is also a square.

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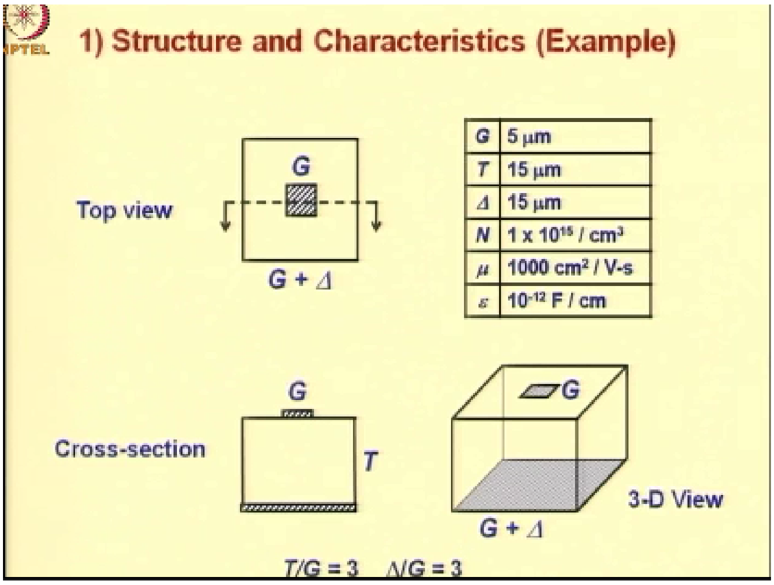

1) Structure and Characteristics (Example)

G	5 μm
T	15 μm
Δ	15 μm
N	1×10^{15} / cm^3
μ	1000 cm^2 / V-s
ε	10^{-12} F / cm

$T/G = 3 \quad \Delta/G = 3$

And let us assume the entire arrangement is symmetric in which case we come up with this kind of structure for our spreading resistance. The length of the smaller contact is G. We are assuming a square contact and the distance between the 2 contacts is T. So this is the top view. The dimension of the bottom contact is G+delta and this line shows the cutting plane for which the cross section is shown here. Here is a 3D view of the spreading resistance.

Now we need to have a feel for the various geometrical process and other parameters of this device so that we can then visualize the device structure to scale. Now here is the typical value of G, T and delta. They are of the order of several microns. N is a doping. We will assume that the spreading resistance is N type and the doping is uniform. This is the mobility of electrons.

This kind of mobility, this value of mobility you find for electrons in silicon and this is the dielectric constant of silicon. Now you can see for our device the ratio t/g is 3 and delta/ g also is 3. So drawing the diagram to scale would mean that the relative dimensions of this figure should reflect these ratios. So you can see here that this G is about 1/3 of this T.

Similarly, delta which is the difference between G that is the top contact and the bottom contact. You can see that this + this is about 3 times G. So this is what is a meaning of drawing the diagram to scale.

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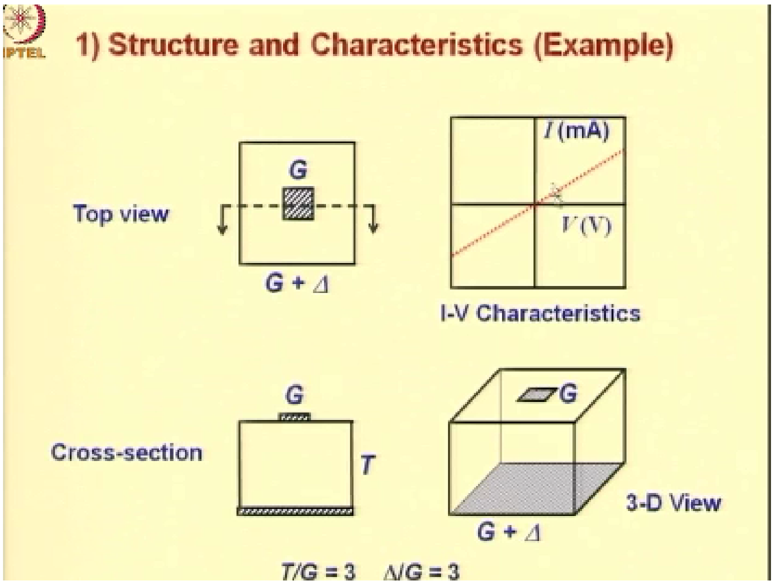

1) Structure and Characteristics (Example)

Top view

G

G + Δ

I (mA)

V (V)

I-V Characteristics

Cross-section

G

T

G

3-D View

G + Δ

T/G = 3 Δ/G = 3

Now here the characteristics because this is a resistor the current voltage characteristics are linear for the voltage S of the order of volts the current is of the order of (()) (13:29). This is something that you need to appreciate. So this is what is meant by visualizing the characteristics to scale, what are the order of magnitudes of the voltages and currents and what is the shape of the current voltage relation. Visualization of characteristics and structure to scale is very, very important.

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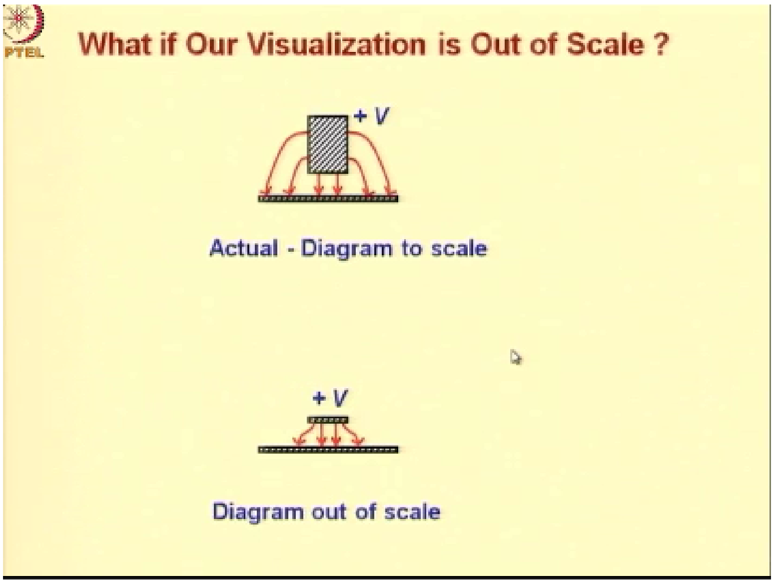

What if Our Visualization is Out of Scale ?

+ V

Actual - Diagram to scale

+ V

Diagram out of scale

Let give us some examples to show what happens if our visualization is out of scale? So we shall show the actual structure and structure that is not drawn to scale that is it is out of scale. Very often when we draw diagrams reflecting the structure we may not be drawing the diagram to scale and there are various reasons for it because when you try to draw a diagram to scale certain dimensions may become too large or too small.

That is why since we want to show the various parts of a device we tend to draw the diagram out of scale. However, after drawing a diagram out of scale one must also draw the diagram to scale because our qualitative understanding of the situation is very much dependent on our visualization of the structure to scale. Let us take a spreading resistance in which the distance between the electrodes T is much < G.

So a diagram to scale would look something like this. However, suppose we draw the diagram as follows and we do not take care to show the T to be much < G. Now what difficulties can arise in modeling? Let show the current flow picture. Now you see that the current flow in our resistor for T much < G is predominantly one dimensional whereas if you draw the structure in this fashion current flow is clearly 2 dimensional because there is lot of scope for the current to spread laterally.

The distance between the 2 contacts has increased and therefore while the current flows from the top to bottom contact there is lot of scope for the current to spread laterally. Now if you start with a structure like this then you might think that to model the current flow or the resistance you may have to take into account 3 dimensional effects. Therefore, you will take a path in which your modeling exercise will become somewhat complicated.

Now you might derive a more complicate expression and in that expression you may put T much < G to get a simple expression which will apply to the device under question. However, this amounts to holding the nose in this way rather than holding the nose straight. Let us take another example. Suppose I want to get the capacitance of an electrode arrangement such as this where 1 electrode is fairly thick as compared to the other electrode.

Now as it usually happens we tend to draw electrodes as thin plates and suppose I draw this electrode arrangement in this fashion then I draw the field lines to get the capacitance and do the analysis the field lines would look something like this whereas in actual practice the field line picture as shown here for the actual diagram where you have a number of field lines emanating from the side of the upper electrodes.

The number of field lines emanating from the side of the electrode in the diagram drawn out of scale is negligible. Thus, the capacitance derive for this arrangement would be less than the capacitance of this arrangement. So in this case you have simplified the picture and causing inaccuracy. In the previous case of spreading resistance with T much < G we had complicated the picture by drawing the diagram out of scale.

So this is the kind of thing that can happen if you visualize the structure out of scale.

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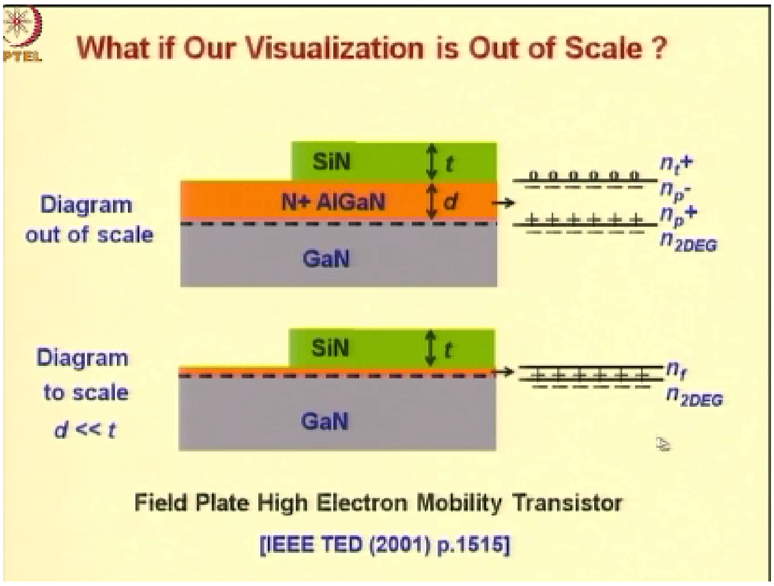

What if Our Visualization is Out of Scale ?

Field Plate High Electron Mobility Transistor

[IEEE TED (2001) p.1515]

Let us take one more example. In the introductory module, the very first module in fact that is module 0 we have shown the diagram of a field plate high electron mobility transistor. This diagram looks something like this. Here this arrangement which is a protrusion of the gate towards the drain side was used to enhance the breakdown voltage of the device. And this arrangement is called the field plate because the field from this plate affects the conditions in the channels and helps in improvement of the breakdown voltage.

Now suppose we want to model this effect of field plate. Let us concentrate on the layers of the silicon nitride, aluminium gallium nitride and gallium nitride and let us see the layer arrangement. This is how the layer arrangement looks like T is the thickness of silicon nitride insulators and D is the thickness of the aluminium gallium nitride semiconductor. Now I want to remark that it is not necessary to understand the operation of the high electron mobility transistor.

And the field plate in detail for grasping the discussion regarding the difficulties arising from visualization out of scale. So we only focus on a small part of this device operation here. Now if I want to put a field plate over here and model the effect of the field plate on the charge on this channel. I have to take into account the charge picture in aluminium gallium nitride as well which looks something like this.

It turns out that in aluminium gallium nitride layer you have a polarization charge which is positive at the interface with gallium nitride and negative at the interface with silicon nitride. Then you have trap on the silicon nitride, aluminum gallium nitride interface. The 2 dimensional electron gas or the electron concentration that is resulting in the channel is the net result of this configuration since np- = np+ clearly the electron concentration here is equal to the concentration of positively charge trap.

However, there is a separation between the electron concentration in the channel or location of electrons in the channel and the location of trap. This is how it appears in the diagram out of scale. This diagram in fact is out of scale if you take the practical values of the thickness of the silicon nitride insulator and the thickness of the aluminium gallium nitride layer then the picture to scale look something like this D is much < T that is the way it happens in practice.

So the aluminium nitride layer would look so thin as compared to the silicon nitride layer. Now in this case you find that the separation between the charges is not really important taking into account the separation between the charges can complicate the modeling exercise whereas when you visualize the diagram to scale the aluminium gallium nitride layer can simply be modeled as a sheet of positive charge equal in magnitude to the positively charge trap concentration at the interface between aluminium gallium nitride and gallium nitride.

And this positive charge sheet contributes to the electrons. So this more involved charge distribution can be approximated by the simple charge distribution if you visualize the diagram to scale because the separation between the charges is not really important when visualized to scale and this simplification of the charge picture in aluminium gallium nitride is responsible for considerable simplification in the modeling and simulation of this device.

So here is a practical example where visualization of device structure to scale simplifies modeling.

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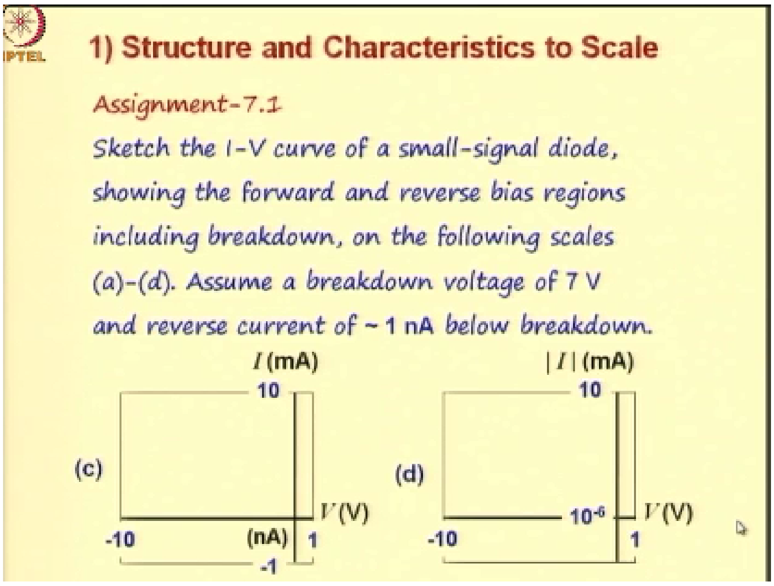

1) Structure and Characteristics to Scale

Assignment-7.1

Sketch the I-V curve of a small-signal diode, showing the forward and reverse bias regions including breakdown, on the following scales (a)-(d). Assume a breakdown voltage of 7 V and reverse current of ~ 1 nA below breakdown.

Let us look at some assignments. Sketch the current voltage curve of a small signal diode showing the forward and reverse bias regions including breakdown on the following scales A to D. Assume a breakdown voltage of 7 volts and reverse current of 1 nanoampere below breakdown. So A and B the scales are as follows. The voltage excess goes from -10 to +10 volts and the current excess is in milliampere and it goes from 10 to -1 milliampere.

In B the voltage excess has been shrunk between the limits -1 to +1 volts and the current excess is in nanoampere rather than milliampere. In C the positive current excess is in milliampere whereas negative current excess is in nanoampere. Similarly, the positive voltage is the order of volts whereas on the negative side the voltage excess goes up to - 10 volts. And finally in part D the current excess is in logarithm of the current.

So this is a semi-log plot.

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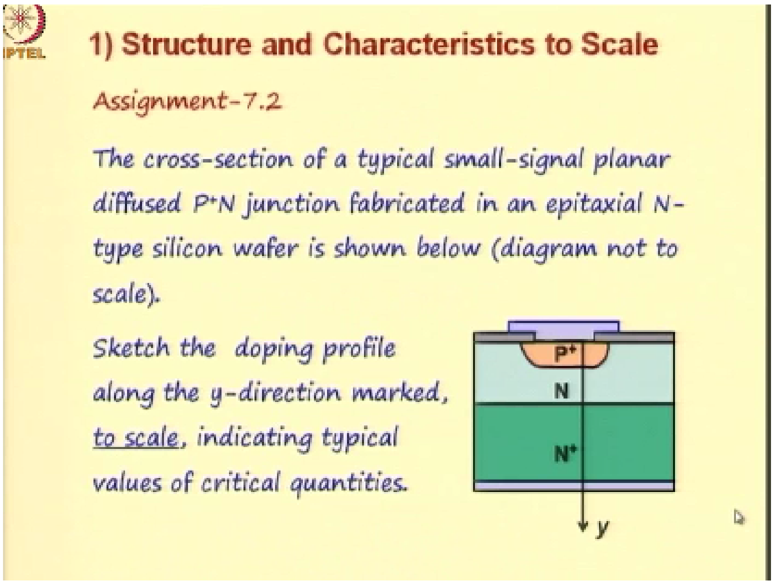

1) Structure and Characteristics to Scale

Assignment-7.2

The cross-section of a typical small-signal planar diffused P^+N junction fabricated in an epitaxial N-type silicon wafer is shown below (diagram not to scale).

Sketch the doping profile along the y-direction marked, to scale, indicating typical values of critical quantities.

In assignment related to doping profile. The cross section of a typical small signal planar diffused P+N junction fabricated in an epitaxial N type silicon wafer is shown below. So diagram is not to scale here. Sketch the doping profile along the Y direction marked to scale indicating typical values of critical quantities. Let us move on to the next step namely deriving a qualitative model.

You will recall from our earlier discussion that we have always said that modeling exercise involves 2 parts qualitative modeling and quantitative modeling. The qualitative model is very important initial stage of modeling. So we are going to look at the qualitative modeling step in detail what are all the things we can do in this step.

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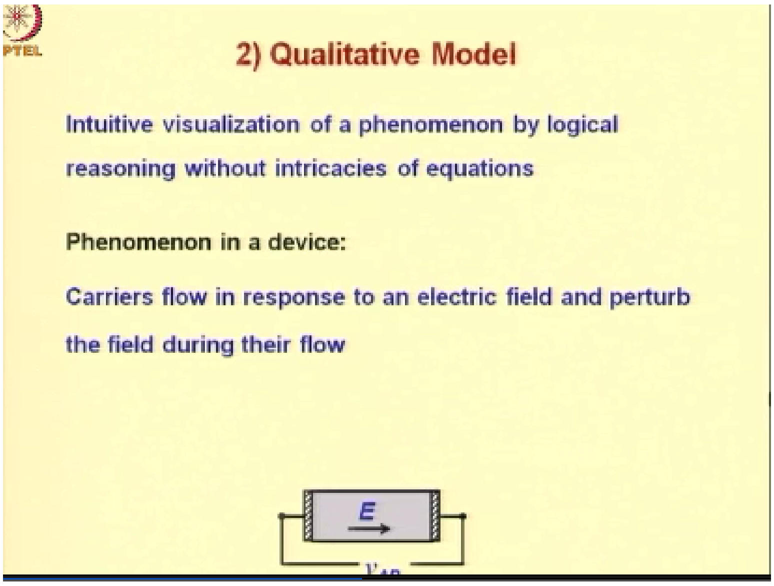

2) Qualitative Model

Intuitive visualization of a phenomenon by logical reasoning without intricacies of equations

Phenomenon in a device:

Carriers flow in response to an electric field and perturb the field during their flow

Qualitative model is intuitive visualization of a phenomenon by logical reasoning without intricacies of equations. What is a phenomenon in a device? In a single statement for any device we could say that carriers flow in response to an electric field and perturb the field during their flow. So you are applying a voltage here 2 terminal devices are shown. However, a device can have multiple terminals.

And this applied voltage is setting up an electric field which is driving a current, but as the carrier moves their concentration may get redistributed in the device thereby affecting the electric field. So this is what is implied in the statement, carrier flow in response to an electric field and perturb the field during their flow.

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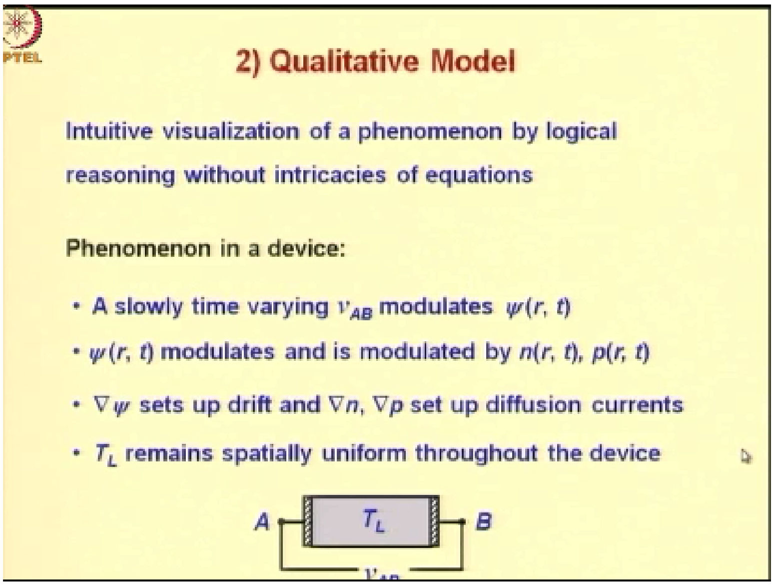

2) Qualitative Model

Intuitive visualization of a phenomenon by logical reasoning without intricacies of equations

Phenomenon in a device:

- A slowly time varying v_{AB} modulates $\psi(r, t)$
- $\psi(r, t)$ modulates and is modulated by $n(r, t)$, $p(r, t)$
- $\nabla \psi$ sets up drift and ∇n, ∇p set up diffusion currents
- T_L remains spatially uniform throughout the device

Now this is somewhat abstract statement. Let us make the description concrete. Now slowly varying Vab modulates the potential distribution psi has a function of distance and time. So R here stands for X, Y, Z. So for a general 3 dimensional case. In 1-dimensional case R would be X. So psi is a potential distribution within the device. You will recall we have said that our models will be based on quasi-static assumption.

So we are not going to consider high frequency effects. Therefore, we are assuming that the voltage between the terminals is varying sufficiently slowly. The next step is that the potential distribution psi modulates and is modulated by the electron and hole distributions as a function of space and time. So you have psi n and p inside the device. They have effects on each other.

The gradient of psi sets up drift and gradient of n and p setup diffusion currents. Finally, the lattice temperature remains spatially uniform throughout the device. This is our assumption. Again, if you recall our discussion of the carrier transport in earlier module. We said that we are going to neglect thermoelectric effects which means temperature gradients will be assumed to be 0 so that there is no current because of temperature gradients.

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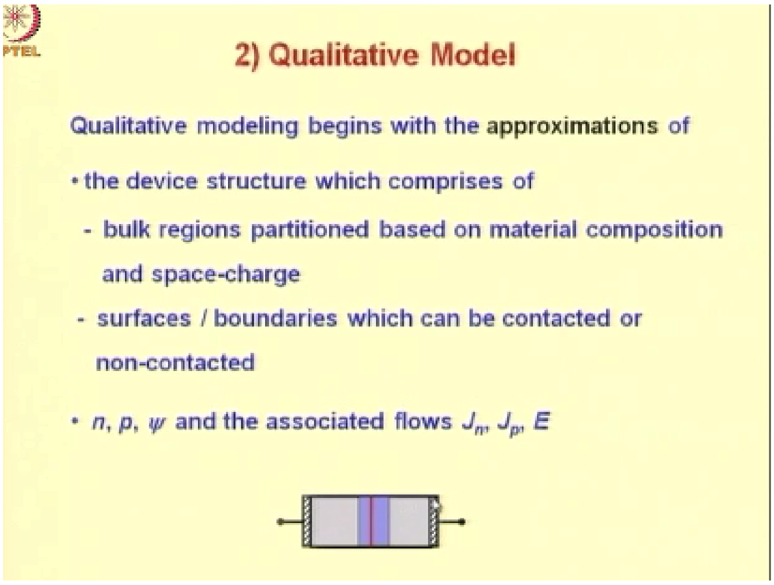

2) Qualitative Model

Qualitative modeling begins with the approximations of

- the device structure which comprises of
  - bulk regions partitioned based on material composition and space-charge
  - surfaces / boundaries which can be contacted or non-contacted
- n, p, ψ and the associated flows J_n, J_p, E

The important point is that qualitative modeling begins with the approximations of the device structure and the electron hole concentrations and potential distributions as also the associated flows Jn, Jp and E. For the device structure there are 2 parts the bulk regions that is this region here and surfaces or boundaries. So the outline constitutes the surfaces of boundaries. Further for the bulk regions you have partition based on material composition.

For instance, here we have illustrated the heterojunction this particular red line partitions the hole device in to 2 parts. The material on the left hand side is different from the material on the right hand side. Now another basis of partition is the space charge. For example, we know that near a junction there will be a space charge region. So in this case this shaded region is a space charge region.

And the 2 regions outside the shaded region that is this side and this side these are the neutral regions. So as regard surfaces and boundaries these can be partitioned into contacted or non contacted areas. So in this device, for instance the left end and right end are contacted boundaries and these 2 horizontal surfaces are non contacted.

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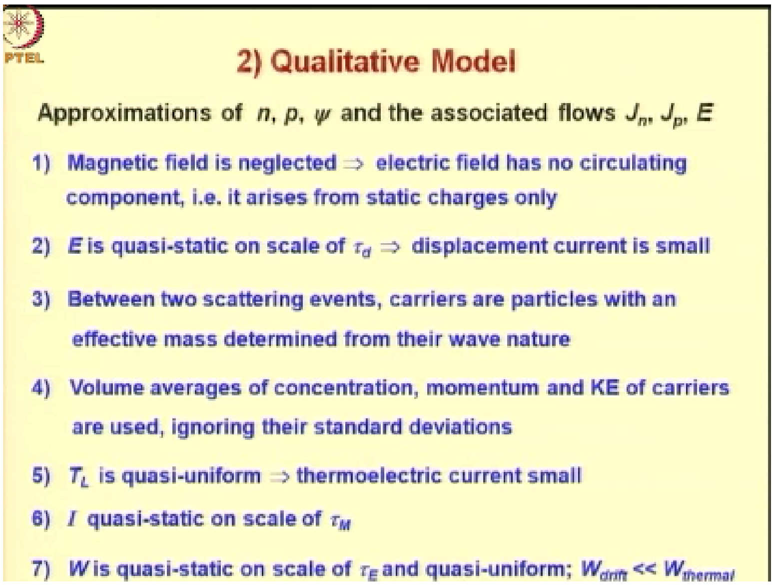

2) Qualitative Model

Approximations of n, p, ψ and the associated flows J_n, J_p, E

1) Magnetic field is neglected $\Rightarrow$ electric field has no circulating component, i.e. it arises from static charges only
2) E is quasi-static on scale of τ_d $\Rightarrow$ displacement current is small
3) Between two scattering events, carriers are particles with an effective mass determined from their wave nature
4) Volume averages of concentration, momentum and KE of carriers are used, ignoring their standard deviations
5) T_L is quasi-uniform $\Rightarrow$ thermoelectric current small
6) I quasi-static on scale of τ_M
7) W is quasi-static on scale of τ_E and quasi-uniform; $W_{drift} << W_{thermal}$

Now let us look at approximations of n, p, psi and the associated flow Jn, Jp and E. These approximations are repeated from an earlier discussion of the carrier transport in module number 3. So the first approximation is that the magnetic field is neglected implying that electric field has no circulating component and it arises from static charges only. Next, the electric field is a quasi-static on the scale of the dielectric relaxation time implying that the displacement current is small.

Third between 2 scattering events carriers are particles with an effective mass determine from their wave nature. 4th, volume averages of concentration, momentum and kinetic energy of carriers are used ignoring their standard deviation. The dopant are randomly distributed and therefore the electrons and holes are also randomly distributed. Therefore, if you take a volume let us say 1-micron cube in a device of 1 centimeter cube volume and we look at different 1-micron cube volumes in the device.

These different 1-micron cube volumes will have different concentrations of electrons and holes and dopant even if we assume that the doping is uniform. So more on this please review the discussion in module number 2. The fifth approximation is that the lattice temperature is quasi uniform implying that thermoelectric current is small and 6th the current is quasi static on the scale of momentum relaxation time.

Finally, the kinetic energy density is quasi-static on scale of energy relaxation time and quasi uniform as a function of space and further the drift component of kinetic energy density is much < the thermal or random component.

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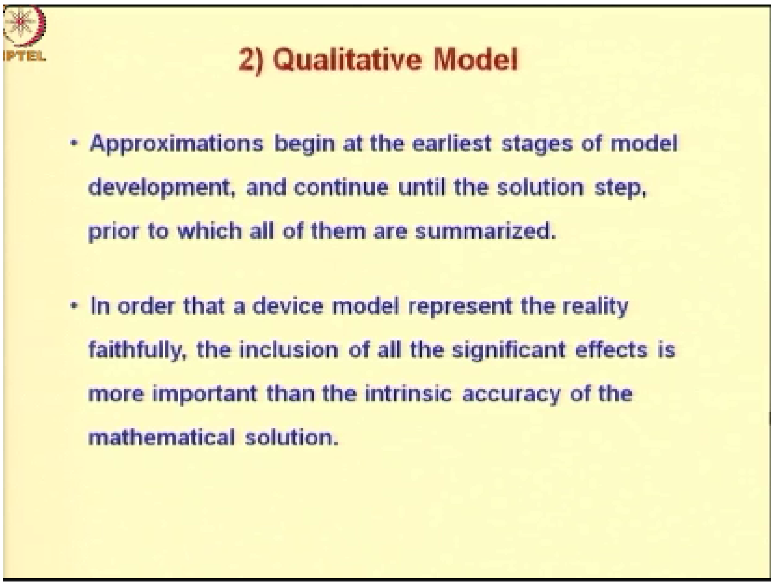

2) Qualitative Model

- Approximations begin at the earliest 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.

Let us make a couple of observations. Approximations begin at the earliest stages of model development and as we will see they continue until the solution step prior to which all of them are summarized. Further, in order that the device model represent the reality faithfully, the inclusion of all the significant effects is more important than the intrinsic accuracy of the mathematical solution.

Therefore, at the qualitative modeling stage we must take into account all those effects which we think will be important.

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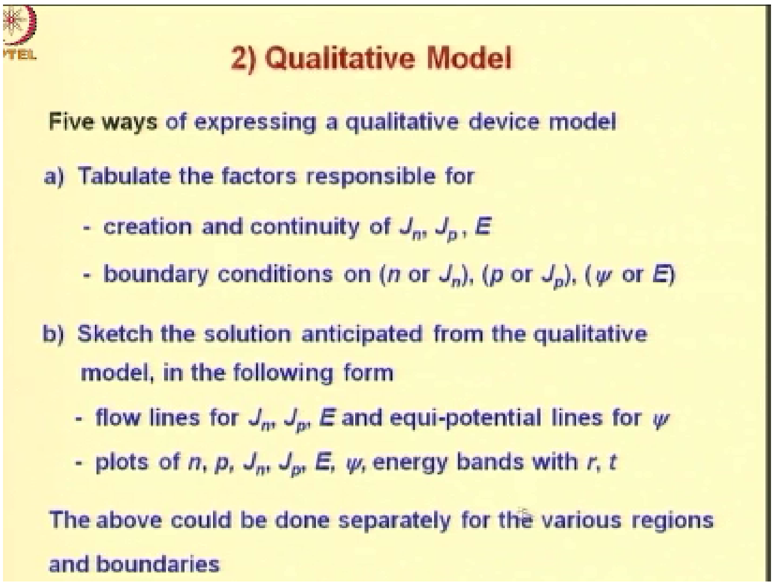

2) Qualitative Model

Five ways of expressing a qualitative device model

a) Tabulate the factors responsible for
  - creation and continuity of J_n, J_p, E
  - boundary conditions on (n or J_n), (p or J_p), (ψ or E)

b) Sketch the solution anticipated from the qualitative model, in the following form
  - flow lines for J_n, J_p, E and equi-potential lines for ψ
  - plots of n, p, J_n, J_p, E, ψ, energy bands with r, t

The above could be done separately for the various regions and boundaries

Now what are the ways in which we can express our qualitative understanding? There are 5 ways of expressing a qualitative device model. Tabulate the factors responsible for creation and continuity of Jn, Jp and E and factors responsible for boundary conditions on n or Jn p or Jp psi or E. So these are the first 2 ways in which you can express the qualitative understanding.

The next 2 ways are sketching the solutions anticipated from the qualitative model in the following form. You can sketch the solution either in the form of flow lines for Jn, Jp and E and equi-potential lines for psi and or you can plot Np, Jn, Jp, E and psi as well as the energy bands as a function of space and time. The above could be done separately for the various regions and boundaries. So we have discussed a couple of minutes ago that you can have space charge regions, neutral regions.

Your regions may differ in material and boundaries could be contacted or non contacted. So you can do the exercise that we just not discussed separately for each of these situations. As we will find part A in which you tabulate factors for creation and continuity of Jn, Jp, and E will translate to equations in the quantitative modeling. And boundary condition will translate to the boundary conditions in quantitative modeling.

Similarly, these 2 ways referred to the solution step.

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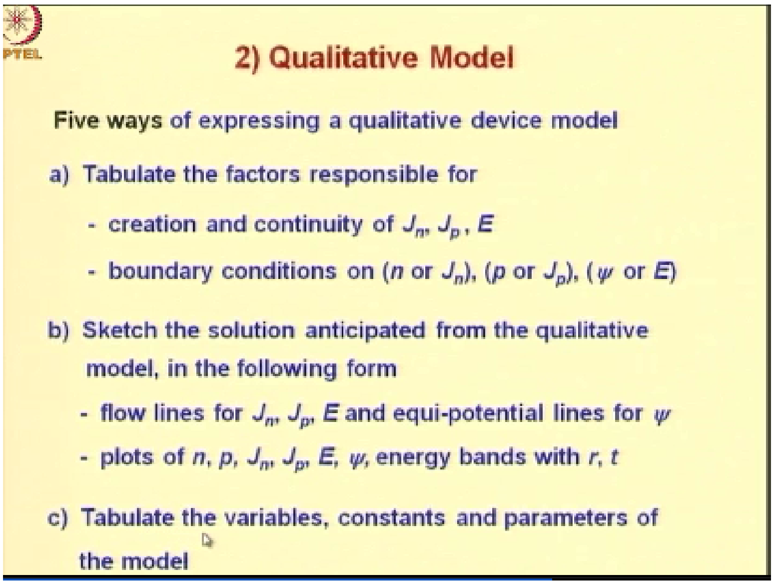

2) Qualitative Model

Five ways of expressing a qualitative device model

a) Tabulate the factors responsible for
  - creation and continuity of J_n, J_p, E
  - boundary conditions on (n or J_n), (p or J_p), (ψ or E)

b) Sketch the solution anticipated from the qualitative model, in the following form
  - flow lines for J_n, J_p, E and equi-potential lines for ψ
  - plots of n, p, J_n, J_p, E, ψ, energy bands with r, t

c) Tabulate the variables, constants and parameters of the model

Finally, the fifth way we can express our qualitative device model is that we can tabulate the variables constants and parameters of the model.

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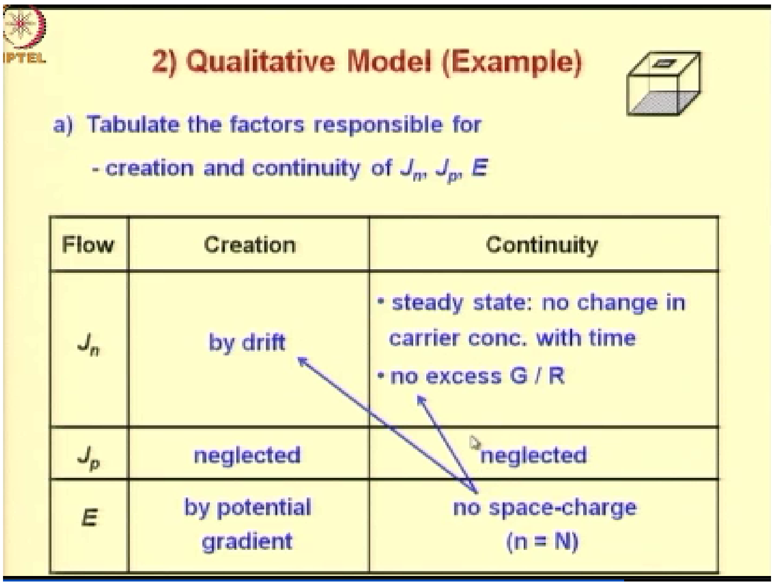

2) Qualitative Model (Example)

a) Tabulate the factors responsible for

- creation and continuity of J_n, J_p, E

Flow	Creation	Continuity
J_n	by drift	• steady state: no change in carrier conc. with time • no excess G / R
J_p	neglected	neglected
E	by potential gradient	no space-charge (n = N)

Let us illustrate the steps of qualitative modeling with examples of spreading resistance. So the first step is tabulate the factors responsible for creation and continuity of Jn, Jp and E. So here we have a table. The first column of the table are the flows Jn, Jp and E and the other 2 columns have information regarding the creation of this flows and the continuity of these flows. Now the first important thing that we know about our device model and bias conditions is that there is steady state implying that no change in carrier concentration with time.

This information enters into the continuity cell of the electron current density. It would also enter into the continuity cell of the hole current density, but as we have remarked earlier we neglect the contribution of holes to the device phenomena in spreading resistance. Ours is an N step semiconductor. Now regarding the electric field, we assume that it is created by potential gradient and as far as continuity is concerned we assume that there is no space charge.

So there are no positive or negative charges in the local volume of the device to increase or decrease the electric field lines. Consequently, the electron concentration would be equal to the dopant concentration. Since we have neglected the contribution of holes. A consequence of no space charge approximation is that the current flow occurs only due to drift. You see this is a uniformly doped semiconductor.

And therefore no space charge implies that electron concentration is uniform and therefore there can be no diffusion current. That is why the current is only due to drift. Another consequence of no space charge assumption is that the electron concentration is equal to the equilibrium value and therefore there is no excess generation or recombination of carriers and this information enters into the continuity cell of the electron current density.

It would have entered into the continuity cell of the hole current density as well, but we have neglected the hole current.

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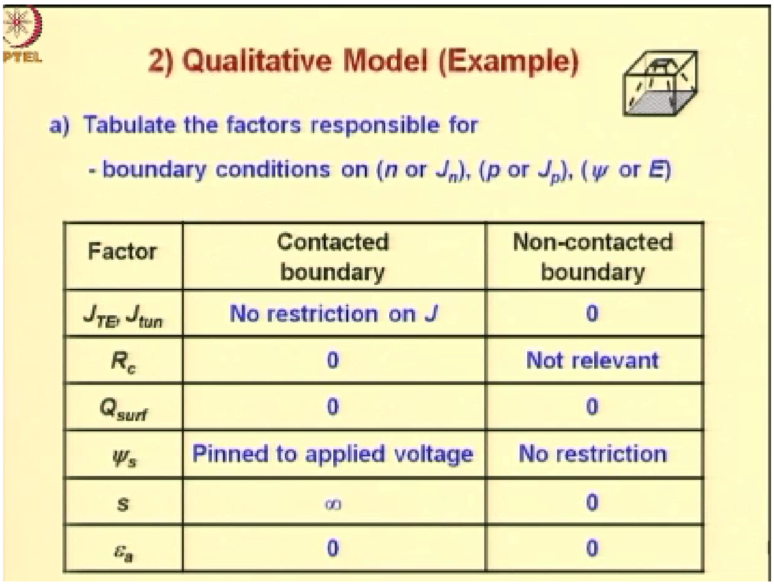

2) Qualitative Model (Example)

a) Tabulate the factors responsible for

- boundary conditions on (n or J_n), (p or J_p), (ψ or E)

Factor	Contacted boundary	Non-contacted boundary
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

The next step tabulates the factors responsible for boundary conditions. Now the factors that affect the boundaries are the following. Please recall the discussion of the drift diffusion model in an earlier module, module number 4 there we have listed all this factors and discuss the boundary conditions in detail Thermionic emission and tunneling current contact resistance, surface charge, surface potential, surface recombination velocity.

And the ambient dielectric constant that is the constant of the dielectric constant of the region surrounding the device. Now for our case we will assume that at the contacted boundaries there is no restriction on J. So we do not bother whether the current is Thermionic emission or tunneling. The current can always vary as dictated by the applied voltage. The contact resistant is 0.

There is no surface charge and the surface potential is pinned to the applied voltage. This means if I apply voltage V to the top contact the potential of this surface would be V with respect to the bottom contact which should be assumed to be at 0 potential. The surface recombination velocity is assumed to be infinite which means the carrier concentrations are equal to the equilibrium values at the contacts.

Finally, ambient dielectric constant assume to be 0 which is not really true in practice because you know that the ambient if his vacuum has a dielectric constant of one. However, we will assume it to be 0 which means no field escapes from the device. For non contacted boundaries similarly we assume that no current escapes from the non contacted regions and therefore Jte and J tunneling are 0.

The contact resistant is not relevant for non contacted boundary. Surface charge will assume to be 0, ideal surface. Surface potential we assume no pinning and no restriction so it all depends on how the potential gets distributed in the device. We do not assume any imposition from the surface side. Surface recombination velocity is 0 which means no carriers are moving towards the surface to recombine there. Finally, the ambient dielectric constant is 0.

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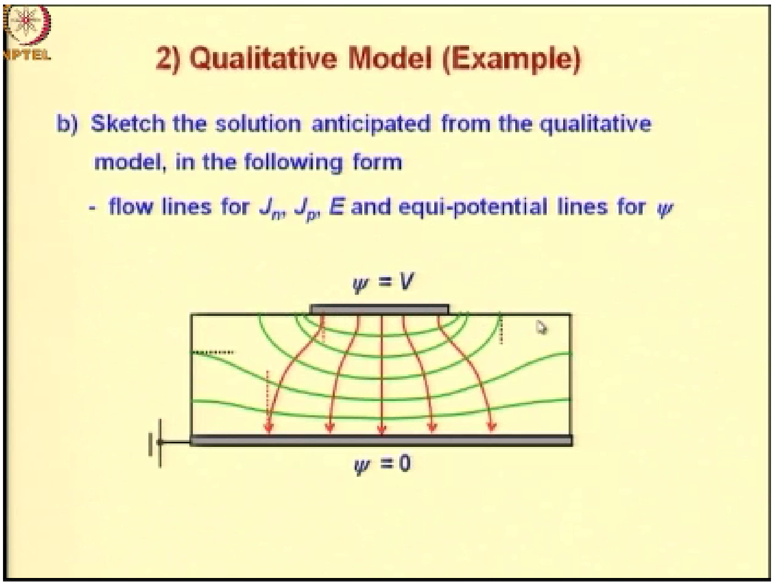

2) Qualitative Model (Example)

b) Sketch the solution anticipated from the qualitative model, in the following form

- flow lines for J_n, J_p, E and equi-potential lines for ψ

Sketch the solution anticipated from the qualitative model in the following form. Flow lines of Jn, Jp and E and equi-potential lines for psi. Now once we know the factors at the boundaries we can sketch the flow and potential lines. So the current flow lines can be sketched as shown in this figure with this red lines. The feature of this flow lines is that they emanate perpendicular to the contacts and terminate perpendicular to the contacts.

What is the reason for this? The reason for this is electric field is perpendicular to the contact both for top as well as bottom contacts and why is the electric field perpendicular because these are equi-potential electrodes there cannot be an electric fields in the lateral directions along these electrodes. So we can sketch the potential lines or equi-potential lines which are perpendicular to the current flow lines and they will appear something like this.

So the potential lines or equi-potential lines emanates perpendicular to the non contact surfaces. You can see that here as well as on the sides here. What is the reason? The reason for this is that the electric field is perpendicular to the equi-potential lines and we have said that the ambient dielectric constant is 0. Therefore, no field can escape normal to the surface into the ambient and since normal electric field is 0 electric field at non contacted surface can only be lateral.

You will also see that the equi-potential surfaces are closer to each other near the edges of the smaller contacts.

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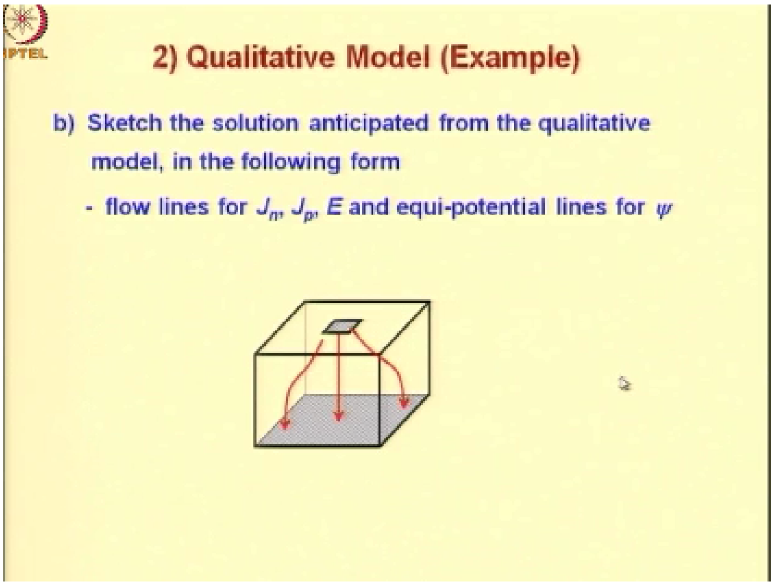

2) Qualitative Model (Example)

b) Sketch the solution anticipated from the qualitative model, in the following form

- flow lines for J_n, J_p, E and equi-potential lines for ψ

Now you can show the picture in 3 dimensions also. So far we have been showing in 2 dimensions of cross section, in 3 dimensions the flow lines will look something like this. The drawing of equipotential surfaces is difficult because the equipotential which are lines in 2 dimensions become surfaces in 3 dimension. So drawing of equipotential surfaces is a little difficult and therefore they are not shown here.

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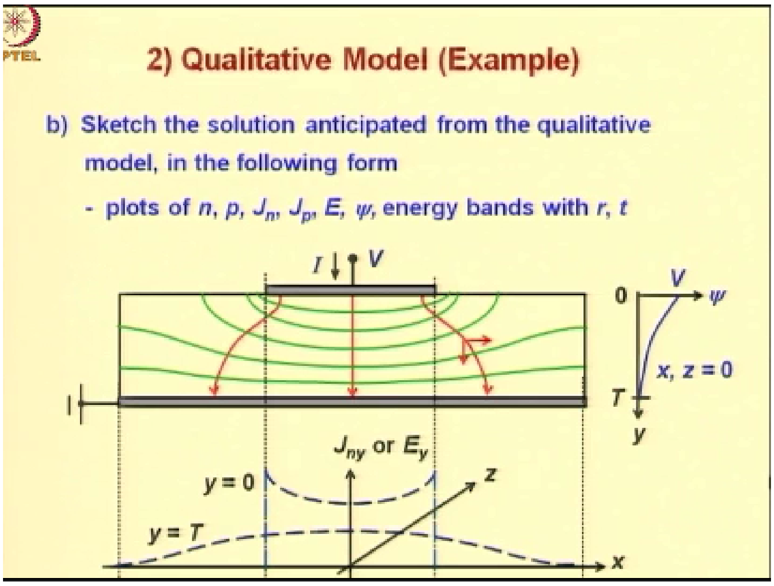

2) Qualitative Model (Example)

b) Sketch the solution anticipated from the qualitative model, in the following form

- plots of n, p, J_n, J_p, E, ψ, energy bands with r, t

Let us go to the next step that is sketching the solution anticipated from the qualitative model in the form of plots of carrier concentration, current density, electric field and potential and energy bands. Now we shall not draw the energy bands in our spreading resistance case because the energy bands are not important for working of the spreading resistance. It is a simple situation where we need not invoke the energy bands to understand the operation.

Wherever energy bands are important such as bipolar transistor or diode or MOSFET we will sketch the energy band diagrams. Similarly, we are not sketching the electron and hole distributions as a function of distance because we are assuming electron and hole concentration are uniform. To sketch the current densities and electric field and potentials we begin from the potential and field or current flow line picture.

We are not going to plot anything regarding the hole current density because hole current density is assumed to be negligible. Let us set up the coordinate system. This is X direction the vertical direction is Y directed from top contact to the bottom contact. T is the distance between the 2 electrodes and Z direction is perpendicular to the plane of the diagram. So the origin is located here at the center of the top electrodes.

So suppose we are trying to plot Jny that means we are plotting this vertical component of Jn. The lateral component is Jnx. We will plot Jny I will leave it to you as an exercise to plot Jnx. So we setup the coordinate system below the resistor. The vertical axis is Jny since it is drift current Jny also reflects the electric field in a Y direction Ey. And Y = 0 that is along this top electrode as a function of X is what we are plotting. Jny or Ey would have a shape such as this.

The magnitude is increasing towards the edges because the potential lines crowd near a sharp edge and the electric field is higher and therefore the current density also is higher that explains why the current density is higher at the 2 edges as compared to the center of the contact and Y =T however the shape of the current density distribution is opposite to that at Y = 0.

Here as you move towards the edges the current density falls down to 0. This is because you can see from the flow lines that as you move away from the center the length of the flow line goes on increasing and therefore the electric field at this point near the bottom contact goes on decreasing because if you integrate the electric field along this line which is also the electric field line then you should get the voltage V as length of the field line increases.

The average electric field along the line decreases because the integral over the length is V remaining constant. Therefore, at the bottom contact the current density is maximum at the center because the flow line is straight and has minimum length here and then it goes on decreasing. The potential psi inside the device along the center line look something like this. So it falls from V to 0 however it is not linear.

The rate of fall is more near the top contact and slows down near the bottom contact. It is because D psi/Dy or dou psi/dou Y represents the Y direction electric field and since the potential lines or equi-potential lines are crowded together near the top contact. The electric field is higher near the top contact then near the bottom contact.

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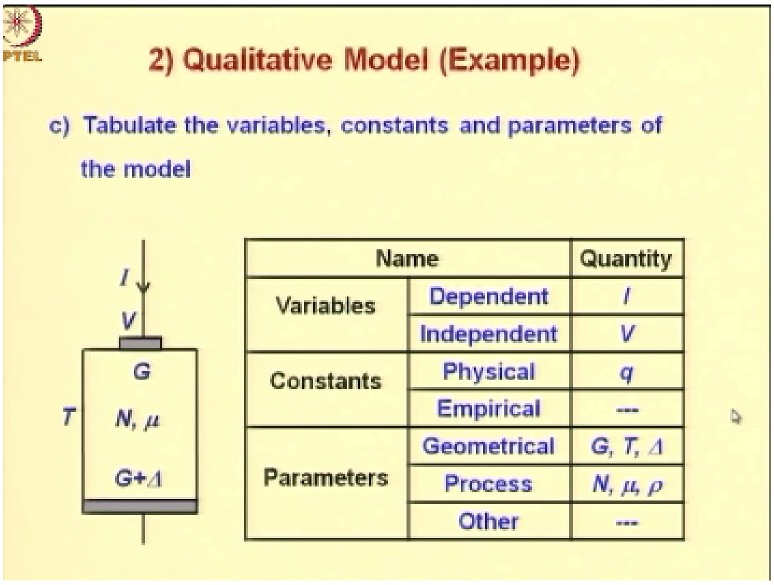

2) Qualitative Model (Example)

c) Tabulate the variables, constants and parameters of the model

Name		Quantity
Variables	Dependent	I
	Independent	V
Constants	Physical	q
	Empirical	---
Parameters	Geometrical	G, T, Δ
	Process	N, μ, ρ
	Other	---

Finally let us tabulate the variables constants and parameters of the model. So here is the diagram showing the current I flowing into the resistor the voltage V has been applied. The distance between the contact is T and length of the top contact is G and that of the bottom contact is G+delta both contacts are assumed to be square. The concentration of dopant N type dopant in N and the mobility of carriers is mu.

Now these are all the quantities that will be involved in modeling. So let us separate them into variables constants and parameters. So variable can be dependent or independent. In our case the dependent variable is the current and independent variable is the voltage. In general, when we are trying to model device characteristics we apply a voltage to setup a current this is true for almost all the devices.

Therefore, in general, in our device modeling exercise, the current will be a dependent variable and voltage will be an independent variable. Constants can be of 2 types physical and empirical. In our case Q is an example of a physical constant. It is a constant because it does not change with situations. There are no empirical constants in our case. Parameters can be geometrical process or other.

Gt and delta are geometrical parameters here and process parameters are those which are affected by the process or decided by the process. So the doping concentration depends on the doping process. Similarly, mobility is a function of doping and other parameters such as defects in the resistor therefore their process is dependent. Rho is the resistivity which depends on n and mu and therefore this is also a process parameter.

Now parameters which cannot fit into either geometry or process are normally called other parameters. In our case there are no other parameters. So when we talk about parameter extraction we are talking about extraction of geometrical and process parameters please understand that. We are not talking about extraction of constants. So we should not regard all quantities in or all quantities associated with the device as parameters.

We should separate the variables, constants and parameters and parameter extraction involves only extraction of those quantities which are called parameters. We do not extract constants or variables.

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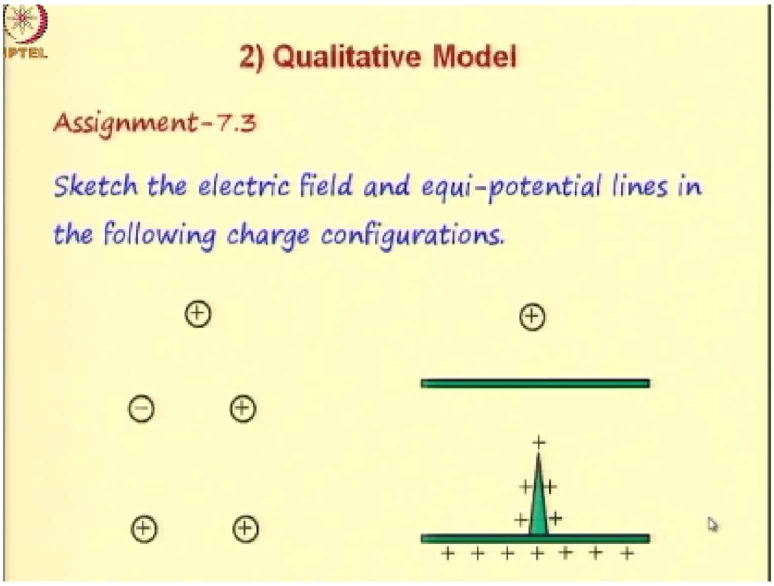

2) Qualitative Model

Assignment-7.3

Sketch the electric field and equi-potential lines in the following charge configurations.

So we have come to the end of this lecture a few assignments. Sketch the electric field and equi-potential lines in the following charge configurations. A single positive charge a negative and a positive charge it is a dipole separated from each other and then 2 positive charges separated from each other. A positive charge located at a distance from an electrode, a thin sheet and finally a thin sheet with a sharp protrusion in the middle.

And we will assume that this entire sheet with a protrusion is positively charged. You are supposed to draw the field and potential lines for these cases.

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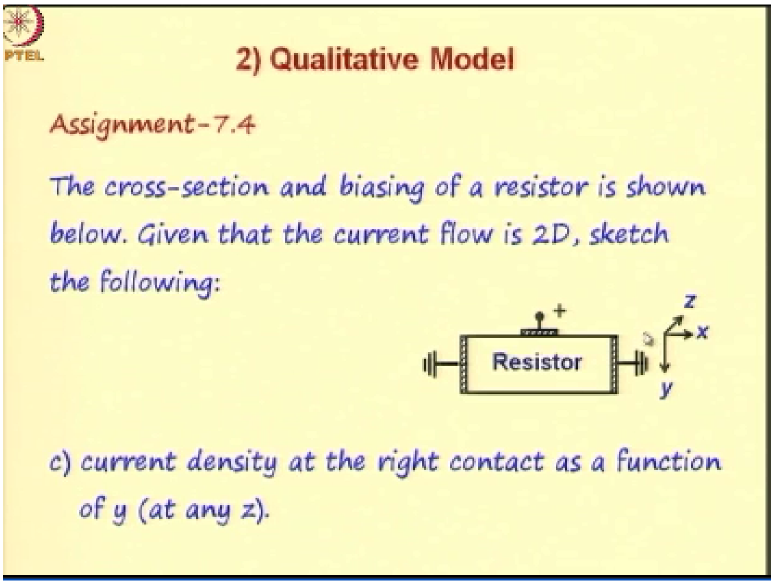

2) Qualitative Model

Assignment-7.4

The cross-section and biasing of a resistor is shown below. Given that the current flow is 2D, sketch the following:

c) current density at the right contact as a function of y (at any z).

Next assignment the cross section and biasing of resistor is shown below. So this is a resistor in which you have a small contact on the top horizontal contact and the other contacts are on the sides of the resistor. Given that the current flow is 2 dimensional sketch the following top view and 3D view of the structure. Current flow and equipotential lines within the device stating the boundary conditions employed and finally current density at the right contact as a function of Y at any Z. So at this contact as a function of Y.

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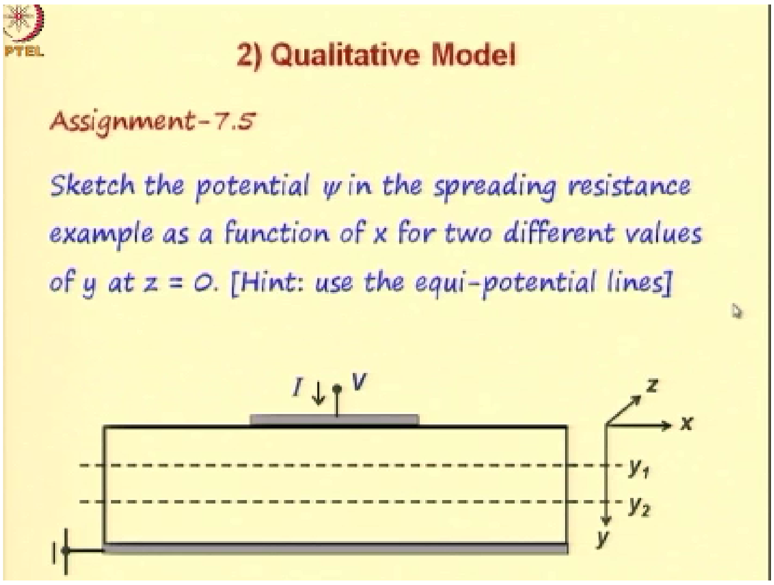

2) Qualitative Model

Assignment-7.5

Sketch the potential ψ in the spreading resistance example as a function of x for two different values of y at $z = 0$. [Hint: use the equi-potential lines]

Assignment 7.5 sketch the potential psi in the spreading resistance example as a function of X. X is the lateral direction for 2 different values of Y at Z = Z. So hint use the equipotential lines.

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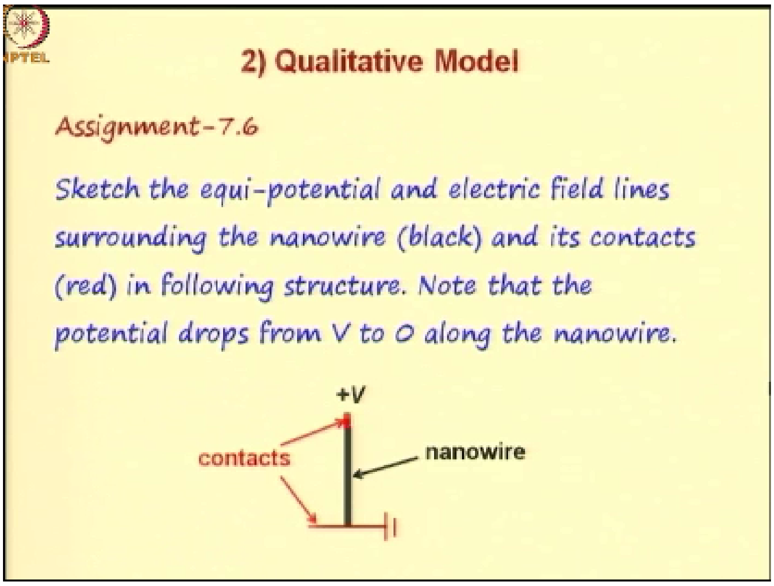

2) Qualitative Model

Assignment-7.6

Sketch the equi-potential and electric field lines surrounding the nanowire (black) and its contacts (red) in following structure. Note that the potential drops from V to 0 along the nanowire.

Another assignment here is a nanowire that is a wire of very, very small diameter over bottom surface which is fairly large which is grounded. So the top of the wire is contacted with a positive voltage and you are supposed to sketch the equi-potential and electric field lines surrounding the nanowire which is black in color and its contacts which is red in color in the following structure.

Note that the potential drops from V to 0 along the nanowire. So potential is continuously dropping that has to be taken into account when you sketch your field and potential lines.

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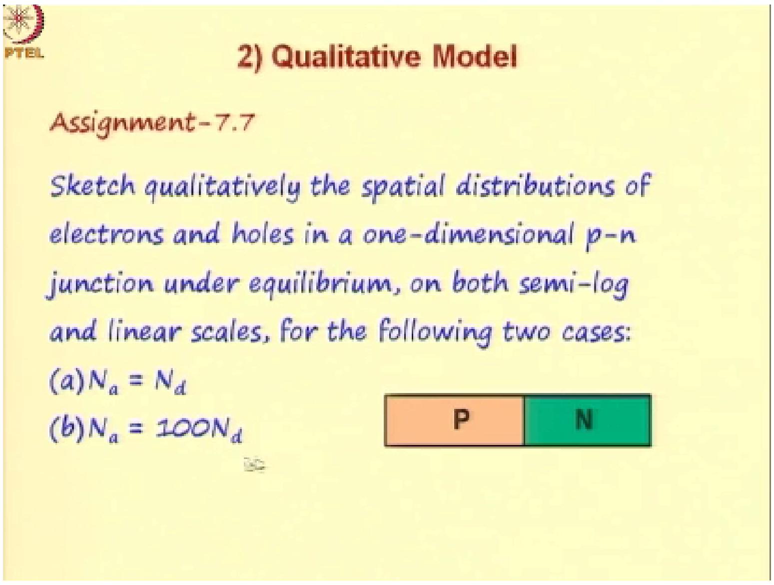

2) Qualitative Model

Assignment-7.7

Sketch qualitatively the spatial distributions of electrons and holes in a one-dimensional p-n junction under equilibrium, on both semi-log and linear scales, for the following two cases:

(a) $N_a = N_d$

(b) $N_a = 100N_d$

Sketch qualitatively the spatial distributions of electrons and holes in a 1-dimensional P-n junction under equilibrium on both semi-log and linear scales for the following 2 cases. Na = Nd and Na is 100 times Nd. So this is an example of a grossly asymmetric junction. So Na =

Nd is a simple case. You would have done it in the first level course, follow the same approach and construct this more involved situation and more interesting situation where one side doping is 100 times the other.

Now with that we have come to the end of the lecture. Let us make a summary of the important points. In this lecture, we began a discussion of the steps in which the model for any general device can be derived. So we said there are9steps abbreviated as SQEBASTIP and we considered the first 2 steps of this modeling procedure namely visualization of the structure and characteristics to scale that is step number 1 and step number 2 qualitative modeling of the device.

We emphasized why visualization to scale is very important and what happens if you do not visualize structure and characteristics to scale. In qualitative modeling we pointed out what are the different ways in which we can express the results of qualitative understanding. We shall continue with the other steps of device modeling procedure in the next class.