Semiconductor Device Modelling and Simulations
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Lecture - 62
Models and Simulation Concepts

Hello welcome to lecture number 62. We will further continue our discussion on discussing different models and the examples.

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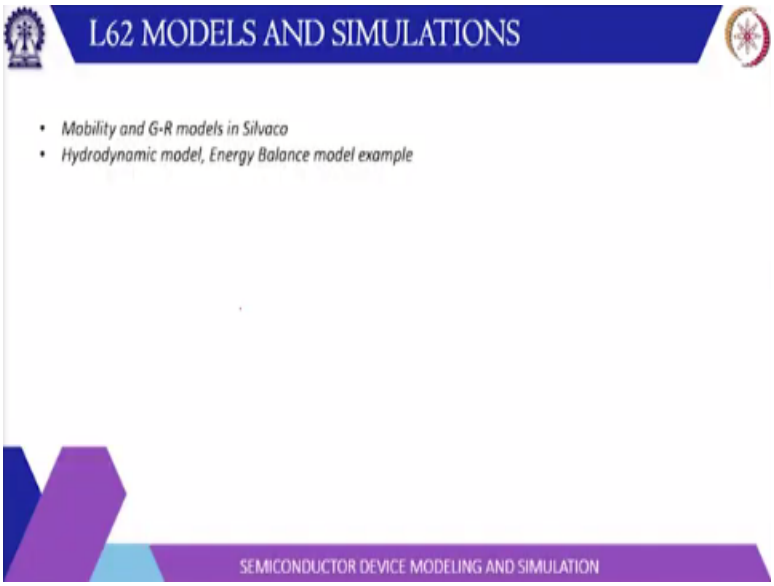

So, in this lecture we are going to discuss the mobility models, the generation recombination models and example with the hydrodynamic and energy balance simulation.

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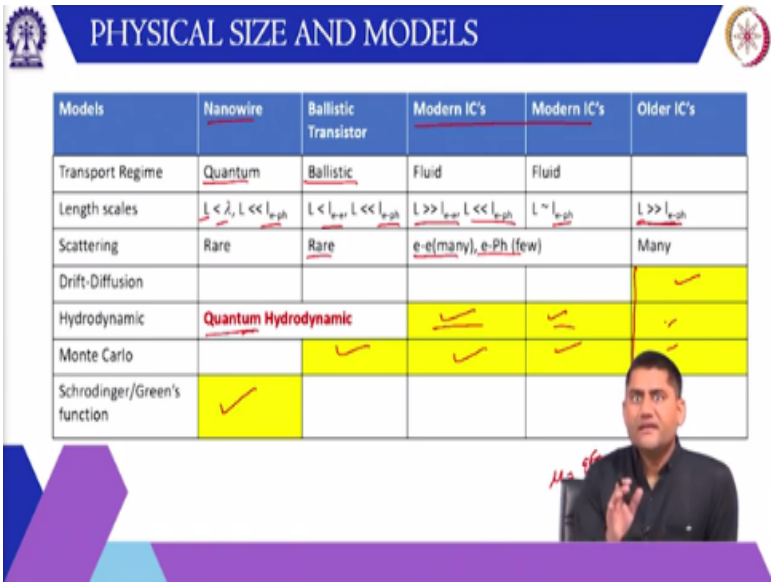

So, this is an important question how do we choose the model. So, model is chosen based on the device dimension. What are the critical dimension of the device? So, for let us say the L is the critical dimension of the device. Now if this length is less than the De Broglie wavelength and it much less than the electron phonon skating length then in that length scale the number of scattering events are quite small.

So, we can either use the Schrodinger equation, Greens function method or we can use the quantum hydrodynamic model and this region is called quantum region and it is usually seen in case of nanowires. Then if we increase the length slightly now length is not smaller than the wavelength the De Broglie wavelength but it is smaller than the electron length or the electron phonon is interaction scattering length.

In this region also the number of scatterings are quite small. So, we do not have to use the Schrodinger equation model but the quantum effect will play a role here also and number of scatterings are small rare. So, this region is called the ballistic region or such transistor are called the ballistic transistors and again we can use the quantum hydrodynamic model or we can use a Monte Carlo model. Monte Carlo model is computationally intensive.

So, it takes lot of memory because we have to track this number of electrons or holes. Now the device size is small here. So, within reasonable time this simulation can complete. So, we can

use the hydrodynamic, quantum hydrodynamic or Monte Carlo model. Then the you know IC's fairly modern IC's where lengths are much larger than this electron-electron scattering length but still much smaller than the electron phonon scattering.

That means electron-electron scattering are many electron phonon scattering are few. Then of course we have to use the hydrodynamic model or the Monte Carlo model they can be used here. So, preferably the hydrodynamic models. Then once the length is crosses the electron phonon scattering length then you can define the average scattering time and you can define this mobility V = Q tau y m because now this scattering length is much smaller than the device dimension.

So, devices already fairly large. So, we can use this statistical property this tau so this is average tau basically. So, here you can use drift diffusion model or if you want to use for certain region of the device, you can use hydrodynamic or Monte Carlo method but for a bigger device, we can work with the drift division model. Now these dimensions are dependent on these scattering lengths and this is scattering lengths are different for different materials as we have seen.

Accordingly, the length scale where we have to use the model. So, in some cases drift division model is sufficient but for other semiconductor we have to use a hydrodynamic model for the same length scale.

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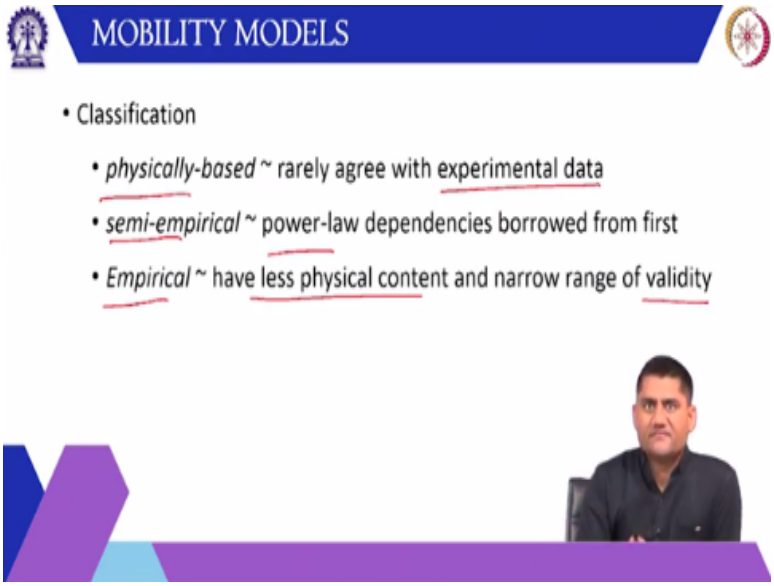

Now we will consider these models one by one we will consider these models. So, first we have considering the mobility models. So, mobility models are basically you can broadly classify them into three categories. One is a physically-based models so they are basically derived from the first principle. For example, mobility they are derived from the scatterings different scattering what is there dependent on phonon scattering ionized impurity scattering and so on.

So, by itself they may not agree with the experimental data. So, we have to have some you know some coefficient we have to include it because each process is different and that the way the device is made this may affect basically the performance. So, second, we come to the same empirical. So, we borrow the dependence let us say scattering is T to the power of 3 by 2 or T to the power - 3 by2 is a empirical dependence.

So, that power dependence is borrowed from the physically based model and then with some parameter we have some empirical model. So, this is valid for given experimental situation and for fairly broad range of validity is there. Then we are totally empirical model so it may have physical meaning or it may not a physical meaning. So, the focus is not on the physics of the device but accuracy and the validity in certain narrow range. So, that is our empirical models basically.

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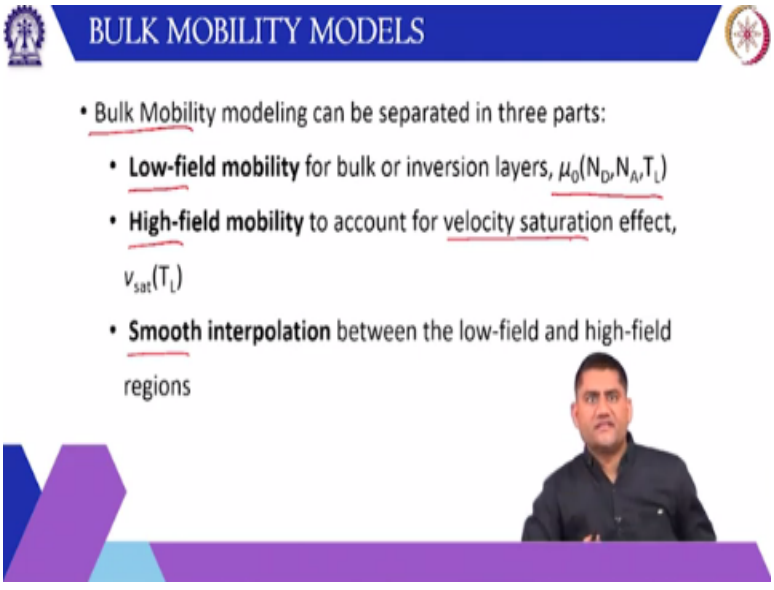

Then we have this bulk mobility. So, bulk mobility is the characteristic of the bulk semiconductor. So, this can be divided into low field mobility, high field mobility or in between. So, for low field we can define mu 0 is a function of the dopants, the lattice temperature. For high field we have to account the value velocity saturation effect because this is a function of lattice temperature and then a smooth interpolation between this low field and high field mobilities.

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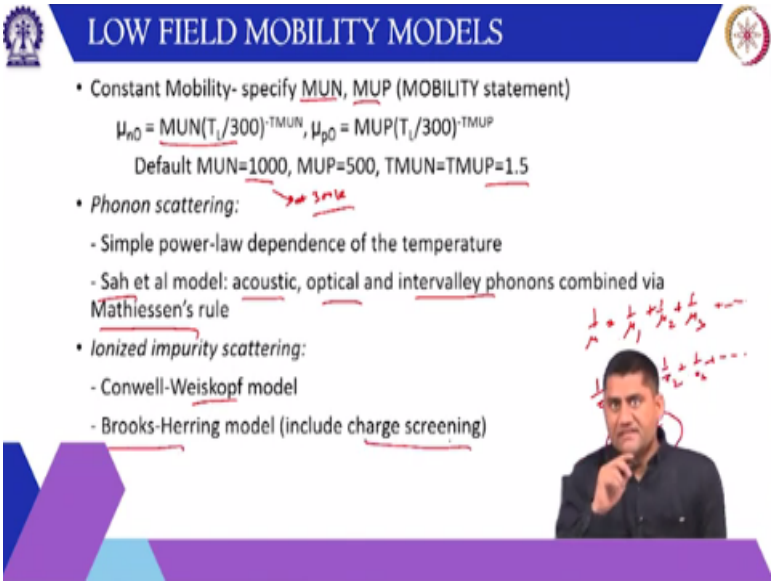

Now you can define the constant mobility. So, just space the parameter MUN and MUP in the mobility statement and by default this is basically so if you see recall the previous lectures example, we said MUN was 1000 by default and then it is at 300 kelvin this value is at 300 kelvin. Other temperature you can calculate it MUN so that is 1000 into T L by 300 to the power – T MUN.

Now T MUN and T MUP are the coefficient the power of dependence that you borrowed from the theory that value is 1.5. Then you can there are models which are dependent on phonon scattering. So, they have simple power law dependence of the temperature. There is Sah et al model which account for acoustic, optical and intervalley phonon. So, all three types of phonon and they are combined by Mathiessan's rule.

Mathiessan's rule says 1 over mu = 1 over mu due to mechanism 1 + 1 over mu due to mechanism 2 + 1 over mu due to mechanism 3 and so on. Or you can say the rate scattering rate is a **(()) (07:45)** basically. So, 1 over tau is 1 over tau due to mechanism is a 1 + 1 over tau mechanism is 2 + 1 over tau mechanism of 3 and so on because mu is q tau by m so mu also add like this. So, it is basically simply adding up the scattering rates.

Then for ionized input scattering there is a Conwell Weiskopf model and there is a Brooks Herring model which include the charge screening also. Charge screening is basically due to this charge each charge will have some screening effect so it will reduce the electric field.

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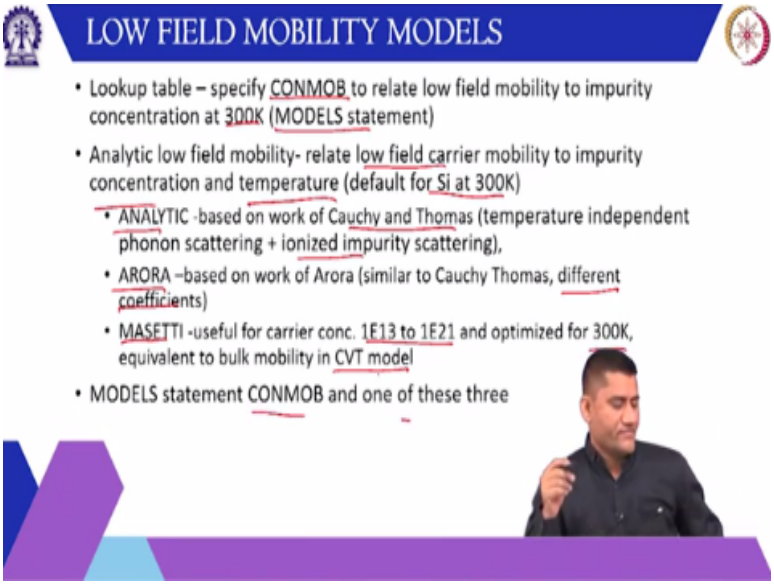

Then you can use models CONMOB which is basically a lookup table-based model. So, that means the values of the mobility are specified in a table and this is valid at 300 kelvin. So, as a function of doping these values are specified. So, it can take these values from the table. So, that is CONMOB basically. So, it relates the low field mobility to the empiric concentration at 300 kelvin and it is invoked by using model statement.

So, you write model CONMOB then this can be combined with other analytical low field mobility model. So, they relate the low field mobility to the impurity concentration and the temperature. So, if you do not set any temperature then default temperature is 300 Kelvin. So, you can have this analytic model which is based on the Cauchy and Thomas so that is

temperature independent phonon scattering and ionization are combined through Mathiessen's rule.

Then there is Aurora model which is based on the work of Arora. So, it is similar to the Cauchy Thomas oriented but the different coefficients are different basically. Then there is a MASETTI model which is useful for a broad range of carrier concentration 10 so 13 to 10 so 21 and it is optimized for 300 kelvin. So, it is equivalent to bulk mobility CVT model. CVT model include the effect of perpendicular field also. So, you can use CONMOB and one of these three model under the model statement.

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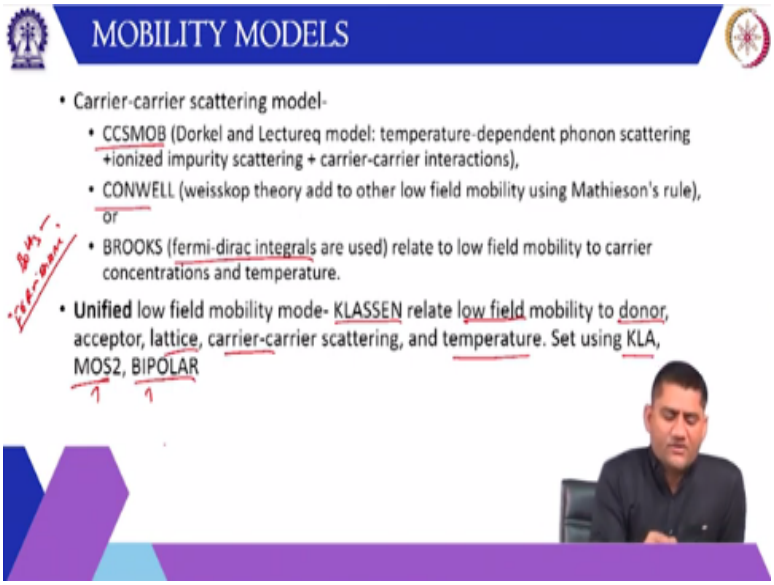

Then in some scenario we need to include the carrier-carrier scattering when they are you know large number of carriers are involved. So, for that you can include the CCSMOB so this is another model name. So, it is based on Dorkel and Lectureq model so it uses the temperature dependent phonon scattering plus ionized input scattering and carrier-carrier interaction. Then we have this CONWELL model.

So, it is Weisskop theory add to other low field mobility using Mathiessen's rules or BROOKS model here they use the Fermi Dirac integrals. By default, Silvaco uses the Boltzmann distribution or if you use this Fermi Dirac term under model statement then it will use the Fermi

Dirac distribution. So, it relate to the low field to carrier concentration and the temperature. Then there are you know some unified models which have a bigger range of variety.

So, one such model is KLASSEN model which read the low field mobility to donor, receptor, lattice, carrier scattering, temperatures. So, it is set using KLA then there are some macros also. So, this MOS2 and BIPOLAR are the macros which include these basic models like KLASSEN model, SRH model. So, these are you have to simply write one macro to include all the relevant models.

So, for bipolar transition simulation if you do not want to write all the model then you can just write the bipolar. So, it will include the models that are required for the bipolar transistor simulator simulation and so on.

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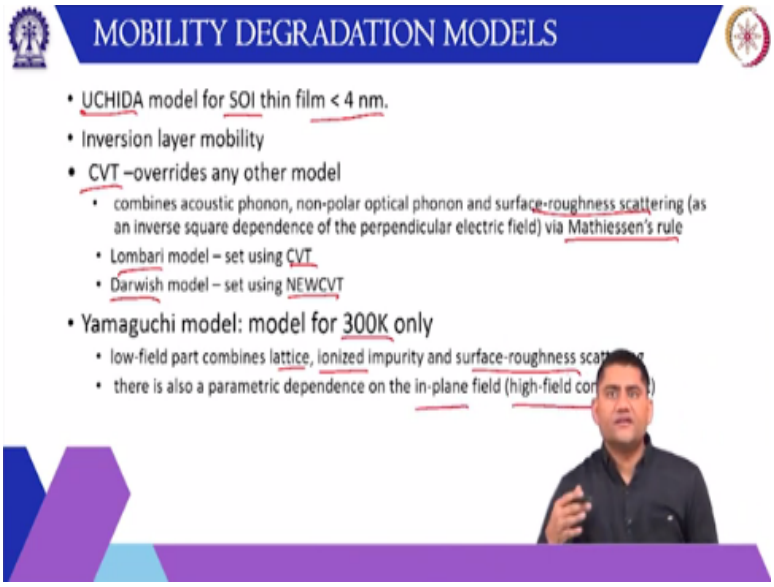

Then there are some specific scenarios like Silicon on insulator where thin film is less than four nanometre. There is a you know mobility degradation so that is model UCHIDA models because there is a you know this is near to the interfaces. So, there will be some scattering from the interfaces then inversion layer mobility you have this CVT model. So, these models have their precedence also.

So, if you specify two models if model A and B are specified and model A have more weight is then model A will be taken off and B will be ignored. So, but how will you know which model is taken? Again, you can see the runtime log file. So, CVT what it does it combines the acoustic and non-polar optical phonon and the surface roughness scattering because that in the inversion layer this surface place are all here.

So, this is NOS scholar dependence of the perpendicular field and by a Mathiessen's rule all these effects are combined or you can use Lombari model or the Darwish model. So, this is set using CVT Darwish is set using new CVT. Then there is a Yamaguchi model so which is valid for 300 Kelvin only. So, here what it does is low field mobility is combined effect of this lattice scattering, ionizing body scattering and surface roughness scattering.

And there is a parameter parametric dependence on the in-plane field and the high field. So, it basically include the field mob effect basically.

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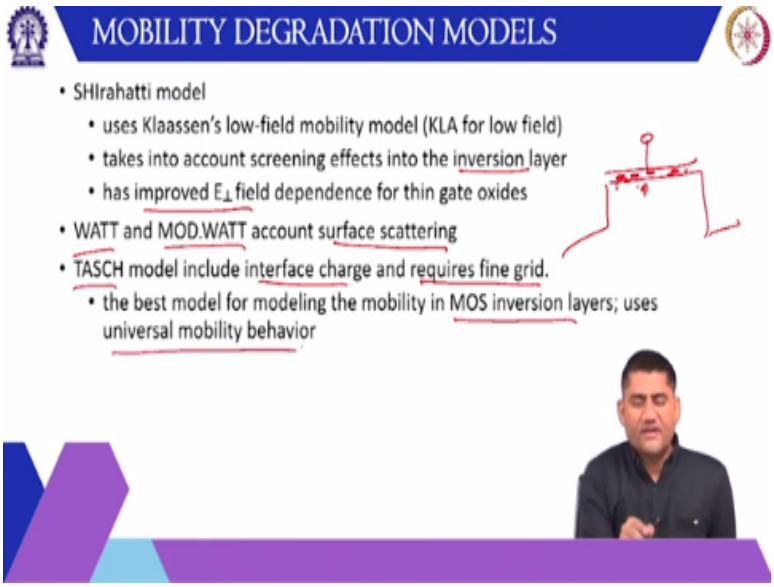

Then there is a SHIrahatti model which uses Klaassen's low field model and takes into account the screen effect into the inversion layer. So, inversion layer effect is taken to account and improved perpendicular field dependence because in MOSFET there is a gate here so there is a perpendicular field also. So, it also affect because this perpendicular field will attract this carries to the interface and they will experience higher scattering from the interface.

So, that perpendicular field dependence has to be taken into account. Then you have this WATT model and modified WATT model they account for the surface scattering then there is a TASCH model which include the interface charge and requires fine grid. Because this interface charge present here will again lead to some kind of you know scattering of these carriers. So, this is used for modelling the most inversion layers and it uses the universal mobility behaviour. You might have heard about universal mobility degradation and so on.

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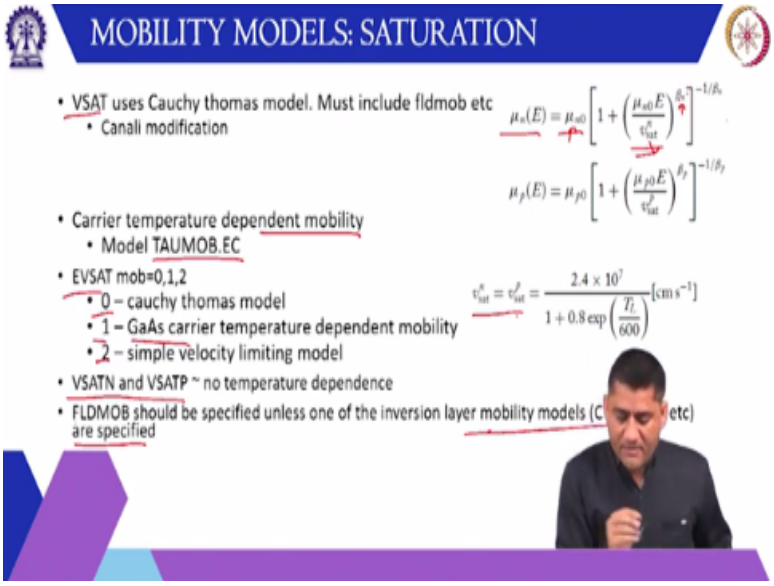

Then to include the saturation effect there are certain you know you can set VSAT which is the saturation velocity and VSAT uses Cauchy Thomas model and it include field model and so on. So, here mobility is basically now mu n 0 + 1 + mu 0 e by VSAT power beta and whole power - 1 by beta. So, this is the parameters VSAT, beta and mu n 0. So, if you set these three parameters you can have a generalized model including the saturation effect.

Then you can also have carrier temperature dependent mobility. So, in the model statement you can have this tau mobility for electron and hole and for other material like gallium arsenide and R so you can have these different scenarios. So, if you set this EVSAT parameter and then if you set to 0 you have Cauchy Thomas model if you set to one then you have gallium arsenate carry a temperature dependent mobility.

Or if you set it to two then simply velocity is limiting model is used basically. So, these are the saturation velocities for electron and hole, they do not have temperature dependence as such unless you model it and FLDMOB should be specified unless one of the inversion layer mobility model are specified. So, saturation velocity you see this is basically these are the parameters. So, if you do not mention VSATN and VSATP then it will use this kind of expression for calculation saturation velocity.

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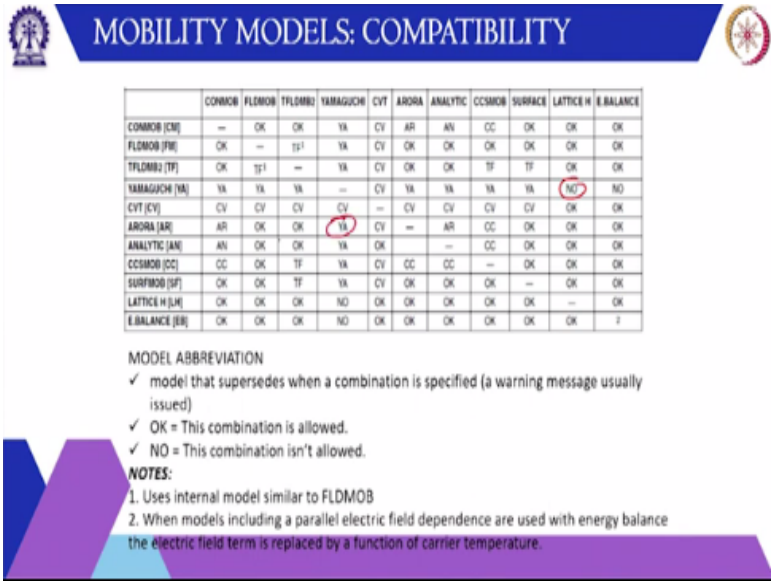

	CONMOB	FLDMOB	TFLDMB2	YAMAGUCHI	CVT	ARORA	ANALYTIC	CCSMOB	SURFACE	LATTICE H	E.BALANCE
CONMOB (CM)	--	OK	OK	YA	CV	AR	AN	CC	OK	OK	OK
FLDMOB (FM)	OK	--	TF[1]	YA	CV	OK	OK	OK	OK	OK	OK
TFLDMB2 (TF)	OK	TF[1]	--	YA	CV	OK	OK	TF	TF	OK	OK
YAMAGUCHI (YA)	YA	YA	YA	--	CV	YA	YA	YA	YA	NO	NO
CVT (CV)	CV	CV	CV	CV	--	CV	CV	CV	CV	OK	OK
ARORA (AR)	AR	OK	OK	YA	CV	--	AR	CC	OK	OK	OK
ANALYTIC (AN)	AN	OK	OK	YA	OK		--	CC	OK	OK	OK
CCSMOB (CC)	CC	OK	TF	YA	CV	CC	CC	--	OK	OK	OK
SURFMOB (SF)	OK	OK	TF	YA	CV	OK	OK	OK	--	OK	OK
LATTICE H (LH)	OK	OK	OK	NO	OK	OK	OK	OK	OK	--	OK
E.BALANCE (EB)	OK	OK	OK	NO	OK	OK	OK	OK	OK	OK	--

Then this is the summary of these mobility models and it shows the compatibility. So, whether two model can be used or not if ok then they can be used if no then that combination is not allowed. So, for example air is a lattice heating is for 300 kelvin. So, you cannot use with lattice heating model and that is true for any model which is valid for 300 kelvin only. Then there are two models then which one will have a higher precedence.

For example, Arora model and Yamaguchi model then Yamaguchi model will be used then CVT model will be used and so on. So, CVT you see it has higher precedence and it can use that is temperature energy balance because it is a temperature dependent model and so on.

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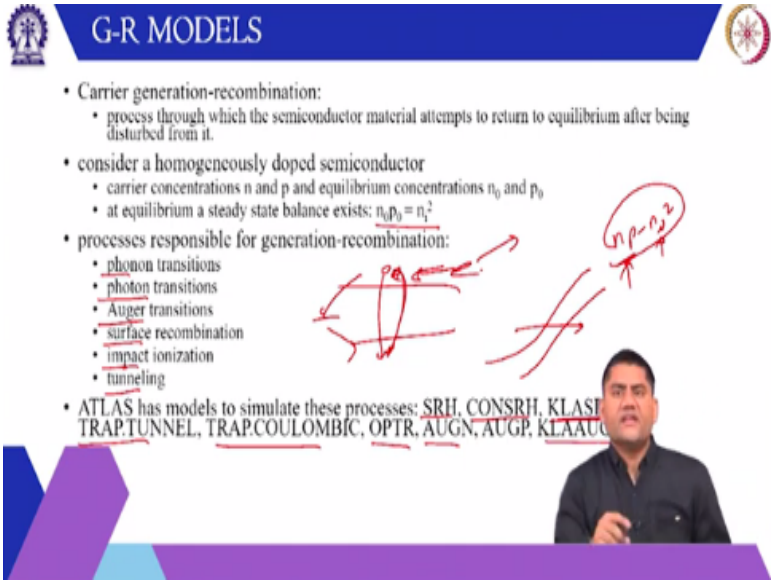

Then you have this generation recombination models. So, carrier generation recombination is a process through which you know semiconductor return to the equilibrium after being disturbed. So, if the number of carriers is increased that means there is a insertion of carriers then what will happen? They will try to recombine and come back to the original carrier concentration level and if you somehow extract the carrier, you deplete the carriers then there will be net generation.

It all depends on the difference n p - n i square. So, if n p - n i square is positive that means there will be net recombination. And if n p - n i square is less or negative then there will be net generation because this n p is the recombination term and n i is called the equilibrium value. So, there are various ways that in which this takes place. So, consider a homogeneous heat of semiconductor then carry a consultation they have n and p and in equilibrium if you see this n and p = n i square.

And equilibrium electron hole concentration is called n 0 and p 0. Now the process that are responsible for this generation recombination you can have phonon transition. So, that means from the bandage this electron can go here emitter phonon or electron can go from balance band to conduction band and absorb a phonon or it can associate by photon which is radiative recombination of generation.

You can have AUGN so the energetic particle can affect this transition surface recombination through the surface state. They can make a transition like this. Impact ionization so the energetic particle again hits it. And the difference between AUGN and impact is that AUGN is mostly this particle may make a transition emitter energy and electron takes away that energy. In Impact ionization the energetic electron hits this particle and make a transition.

So, there is a fundamental difference between the two and there can be tunnelling also. So, if there is a band bending somewhere then this electron can make a transition make a tunnelling from one side to another side and Atlas has this model to simulate these properties. So, for generation recombination you can use SRH model. SRH is softly read all recombination or if you use SRH model with consultation dependent parameters then you have this CONSRH.

So, consultation dependent SRH or if you use classes model a model with you know broad validity then you have this CONSRH. You can use TRAP, TUNNEL, TRAP, COULOMBIC, Optical generation recombination or AUGN electron hole, class and hole recombination. So, these models are available basically.

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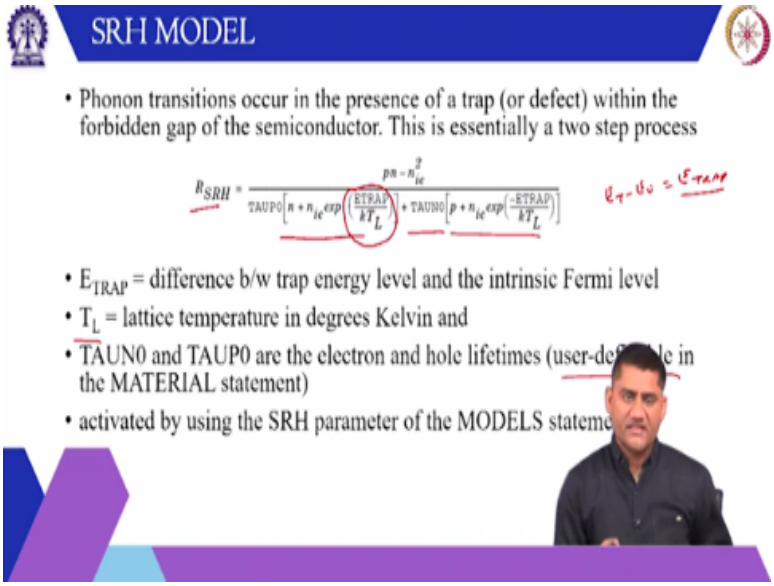

Now in SRH model we have already dragged this expression that recombination rate is n p - n i square divided by tau p times n + n 1 tau n times p + p 1. So, this is essentially two step process. Now E TRAP is the trap energy level and here it is taken with respect to the intensinsic energy

level. So, instead of writing E t - E i that is defined as E TRAP. So, if E TRAP is 0 then this is most efficient trap energy level.

And then T L is basically the lattice temperature in kelvin and tau n 0 tau p 0 the electron whole life times. They can use it you can define them in the material statement and they are activated using the SRH parameter of the model statement.

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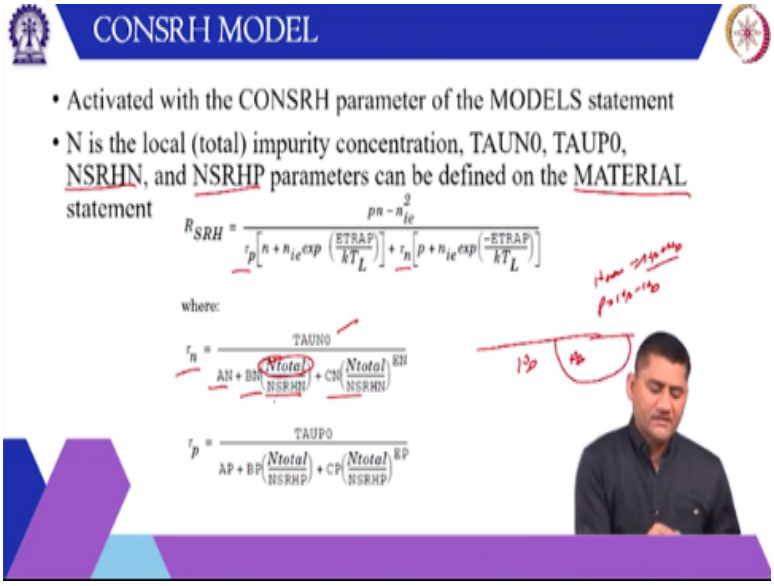

In concentration dependent SRH model tau n and tau p are not constant but they are dependent on the temperature. So, now tau n is tau n dot divided by a + b + c times n, n is basically total number of dopants. So, in a certain region your let us say doping is n d then n total become n d. Now you make a value with n doping so it is compensated doping. So, number of carriers the holes will be n a - n d if n is more but the impurity concentration will be n a + n d because now impurities are more basically.

So, this is n total here. So, it depends on the impurity consultation. So, again these parameters NSRHP, NSRHN they can defined on the material statement. So, it is basically some value you know which basically normalize this total number of dopant concentration. So, basically now this tau n and tau p are not constant with respect to the doping. But their function of the doping concentration.

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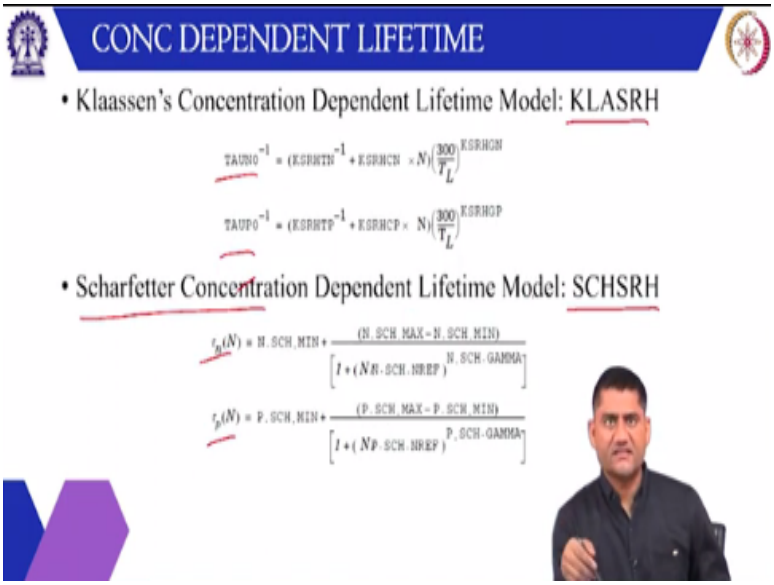

Then your Klaassen's concentration dependent lifetime model. So, instead of CONSRH you can use KLASRH then the expression for tau n and tau p is different. So, we have separate expressions then similarly Scharfetter concentration dependence. So, this is SCHSRH here the mod the expression for tau n and tau v actually changes. So, the basic model is still same n p - n i square y tau n + tau p some parameters.

But the way we define this tau n and tau p we have different models basically CONSRH, KLASRH or SCHSRH and so on.

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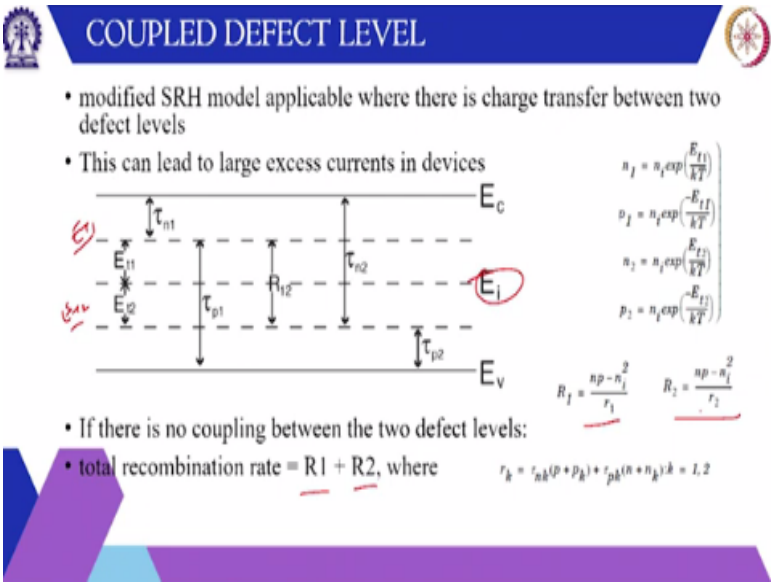

Then Atlas also allows us to have couple defect levels. So, there may be two defect levels so let us say this is E t 1 let us say this is E t 2. So, E trap 1, E trap 2 again they are defined with respect to the intrinsic energy level E i. And then if there is no coupling then you can just add R 1 + R 2 will be the total recombination rate. R 1 is a recombination rate due to trap 1, R 2 is a recombination rate due to trap 2.

And it is you know n p - n i square by R 1 and P - n square by R 2 and so on. If they are coupled then the third term will appear here.

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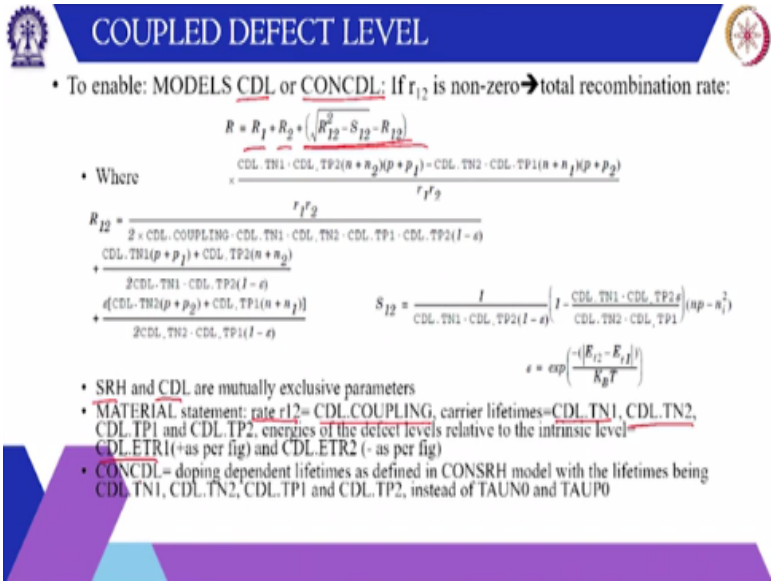

So, this will be square root of R 1 square - S 12 - R 12. So, this is a complicated expression given in the manual but you can drive it if you like. So, here some key point that I would like to tell you. You can use CDL couple defect level or concentration dependent couple defect level. So, the difference is basically in concentration dependent. These parameters are concentration dependent and if R 12 is non-zero then the total recombination will be R 1 + R 2 plus this effect of the coupled parameter.

Now you can use either SRH model or CDL model they are mutually exclusive and in the material statement the rate R 12 is CDL dot coupling. So, that R 12 you can define through this parameter. And the carrier lifetime are now instead of tau n and tau p we have CDL dot TN1 and

CDL dot TN2. Similarly for whole TP1 and TP2 and then you can also define this energy levels ETR1and ETR2.

And in concentration dependent CDL the lifetimes are defined in a similar way that are defined for concentration dependent SRH model.

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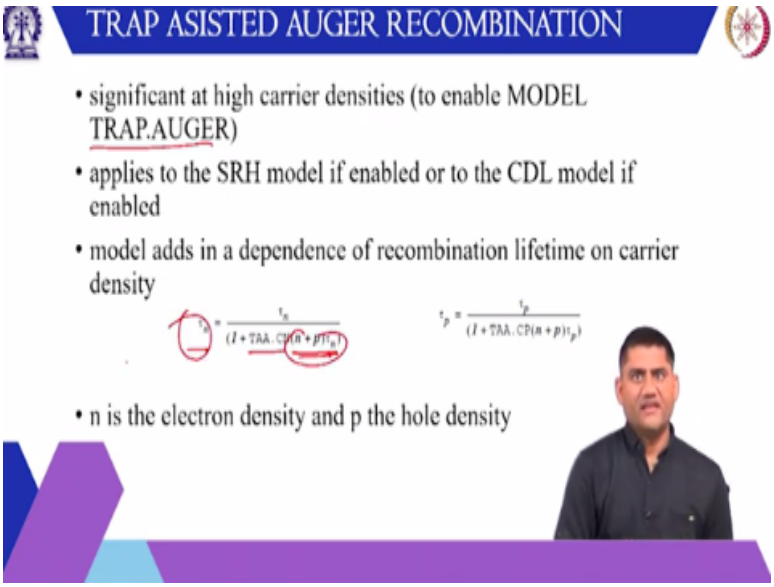

So, you can also have the strap asisted Auger recombination. So, it is significant that higher carrier densities to enable you have to use trap dot Auger and is applies to the SRH model if enabled or the CDL model is enabled. Model includes the dependence of carry lifetime on carry density. So, now tau n is basically one over some coefficient + n + p times tau n. So, this is basically now lifetime is dependent on the carrier concentration.

And that is especially the nature of Auger recombination. So, if the concentration is more the lifetime is less basically. So, both the lifetimes electron and whole lifetimes and then coefficient can be different.

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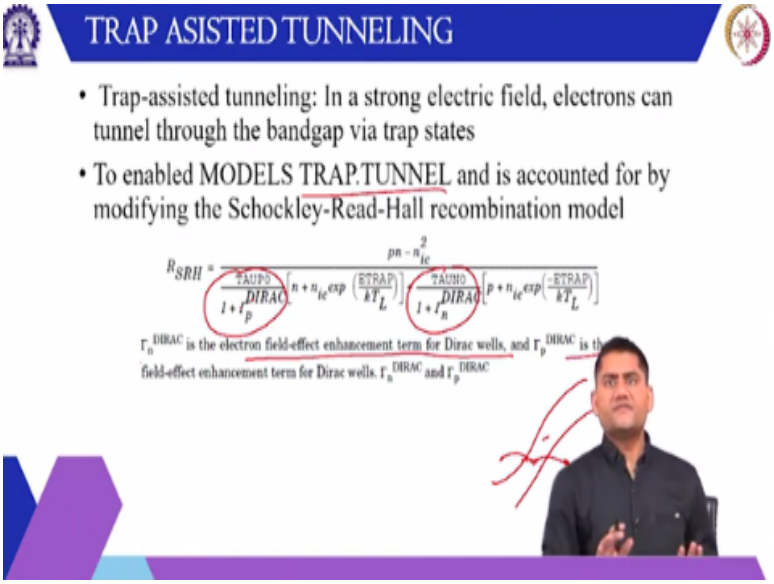

Then you can also have trap asisted tunnelling. So, this basically is in a strong electric field then electron can tunnel through the bend gap by a trap state. So, let us say this is some you know bend structure they are trap State here. So, electron can make a transition like this and they can you know this thickness. Now this length is reduced for them. To enable this model, we have to use trap dot tunnel in the model statement and then this is slightly modified.

If you see the tau n and tau p there is one more extra factor one plus you know gamma trap p. Now gamma trap is electron field effect enhancement term for trap wells and for holes basically. So, these factors can be taken into account and they can be used to model the trap assisted tunnelling.

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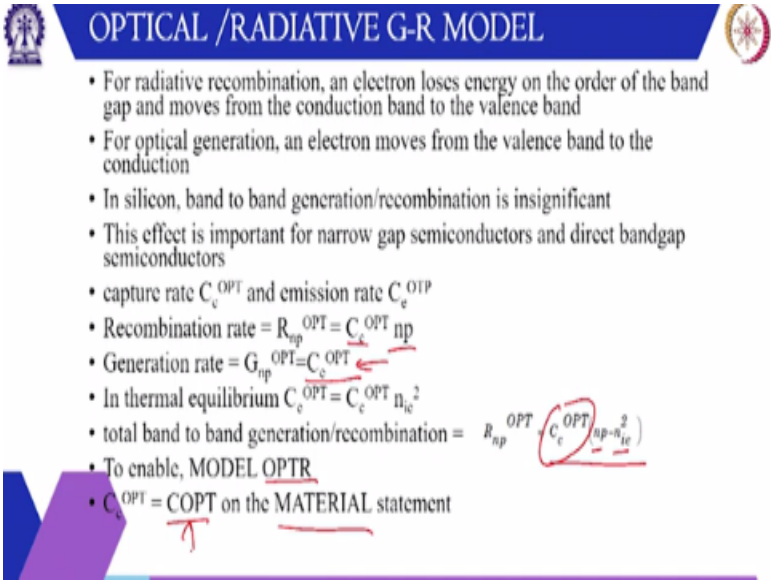

Similarly, for optical or radiative generation recombination model you have to set this OPTR parameter under the model statement and the coefficient can be set on the material statement. So, this is C optical and the way generation recombination rate is defined. So, the RECOM the generation rate is C e times C OPT. So, this is basically is the parameter C OPT and the recombination is C c OPT times NP.

So, if you equate them then you will get you can get the relationship between C and C c O P T and in total band to when generation recombination becomes generation recombination minus generation. So, that will be C c OPT - n p - n i square. So, you have to only specify this C OPT so which is specified using material statement. So, this parameter can also be specified and for this you have to assess that you know it is a direct band gap, indirect band gap you know which model to use so that is user's choice basically.

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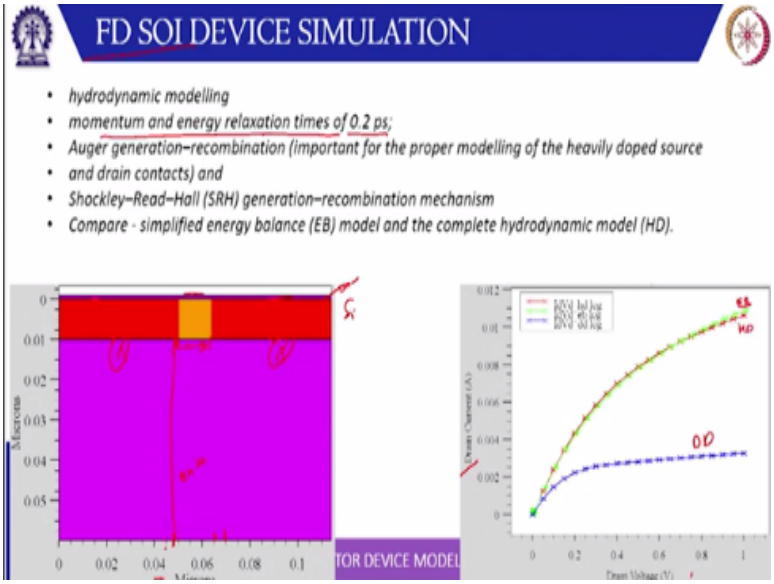

Now here we have taken one example. This is basically an example of fully depleted SOI. So, this is oxide and this is silicon layer then on top you have this again oxide is there and then there we have the source drain and the gate. Now this length is pretty small here you can see this one goes from some 4.04 micron so this is around 50. So, something like around 50 and this is around 67, 65 something. So, I think it is 14 nanometre.

So, in hydrodynamic model the momentum and relaxation time have to be set so which are chosen around 0.2 Pico second here. Generation recombination is important here that is basically to model this heavily doped regions. These red regions are heavily dropped source and drain regions and Shockley Read Hall generation recombination mechanism is used. And what we have to do basically?

Here we are comparing the effects of hydrodynamic model, energy balance model and the depth division model. So, you can see here this is the IV curve for the drain current versus the drain voltage and this is from the drift diffusion model and this green is for energy balance and this is for hydrodynamic model the red one. Now how do we proceed it?

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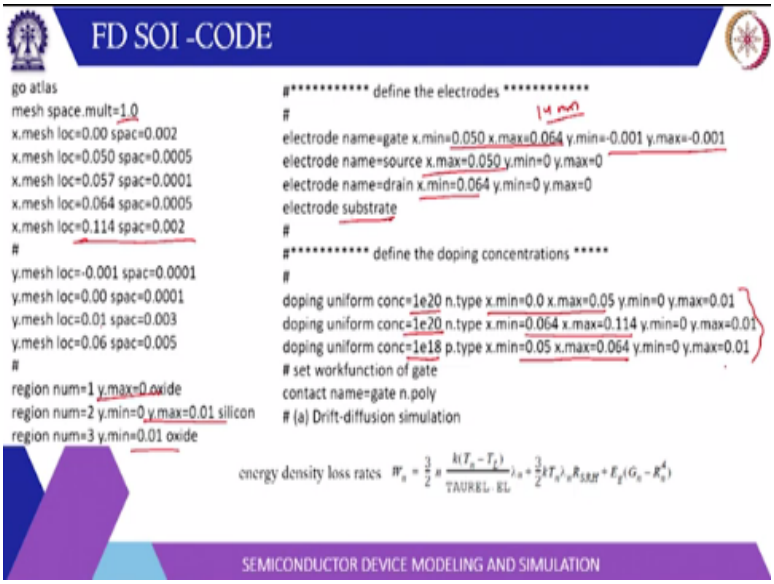

This is the code again taken from the textbook. So, here we write go Atlas then Mesh, mult one then this is a location. Now you see here it is the spacing actually very small. So, you see here this one is around 0.0005 that means it is around 0.5 nanometre so that is 5 angstrom. There is a spacing here that means it is the reason where you have some junction basically. So, from 0 to 05, 057, 064 and 114 then Y is vertical one so - 0.012200 then 0 to 0.1 and 0.6.

Now region num is oxide y max is 0 so that means from top to zero is oxide. So, you can see here this top layer is oxide here this top layer then from 0 to 0.01 is silicon. So, 0 to 0.01 this is silicon here this region is silicon here this is oxide here and this is also oxide. And then Y min 0.01 that means from 0.01 onwards is offside. Then we have to find the electrode so gate is defined from 0.05 to 0.064.

So, that is 14 nanometre long is the channel and Y you mean Y max is the this - 0.001? Then source is from 0 to 0.05 and drain is from 0.064 to n. So, there is a source here left side right side is a drain and this is the 14 nanometre length is the gate length and then electrode substrate. Nothing is mentioned here so this is basically the bottom then doping is there 1 e 20 in the source region 0 to 0.05, 1 e 20 0.064 to 0.114 that is a drain region.

And then 1 e 18 in the channel region and Y is limited same because that is this region will actually be depleted. So, it is called fully depleted silicon on insulator then the gate contact is not

ohmic you have written. You have not written the work function. But you have written the material name poly silicon n-type polysilicon. So, it will take up the work function of n type polysilicon.

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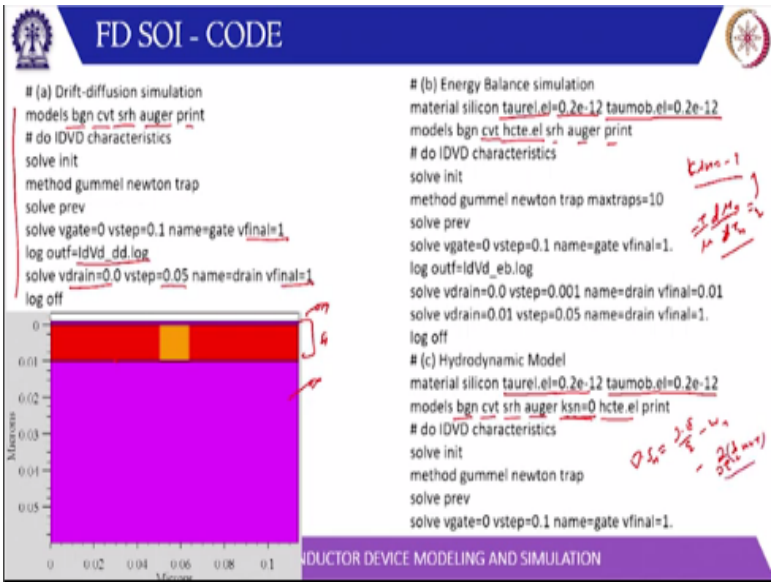

So, now to simulate the drift diffusion model this is a part of the code. So, model band gap, CVT, SRH or Auger and print. So, solve initial then method Gummel Newton trap then solve previous solve vgate = 0 in the vstep of 0.1, vfinal is 1 and then you plot this log file. And solve vtrap in this type of 0.015 the final and log off. So, this is for the drift diffusion model and you see these are the models that are included here then you go to energy balance.

So, energy balancer differences we have mentioned the hcte.en. So, that means now we are not included a whole year because this is n channel because this n channel means these electrons are the carrier and then for the relaxation time, we have set it to be 0.2 picosecond. So, that is the electron relaxation time and the tau mobility for electron 0.2 that is - 12 and then other model is CVT that includes a perpendicular field dependence and then others are SRH or Auger so on.

Then again same thing to calculate the IV characteristic and then in the hydrodynamic model these parameters are similar. Tau relaxation length for electron, tau mobility for electron and band gap narrowing, CVT, SRH, Auger. There is another parameter ksn which is set to 0 here

which will take care of in the energy balance case this. If you set the case and two by default value of ksn is - 1 so that means it is energy balance model.

If you set ksn 20 then it becomes hydrodynamic model. So, what is ksn here? ksn is basically this says d mu by dt this is T by mu times d mu by dt. So, it is basically the dependence of the mobility on the temperature. So, if this is set to - 1 then it is energy balance if it is set to zero that means mobility is not dependent on the temperature it is constant then it is called hydrodynamic model and then of course you have sct.el print.

So, this only difference here between the energy balance and hydro dynamic models because energy balance model basically considers this energy density the flux of the energy density that is delta dot s del dot s is how much energy is going out. So, this energy flux density which is the energy generated so J times e by q then - w n w n is the energy density loss rate then - d by dt of 3 by 2 n k t.

So, there is a energy of the electron due to the temperature so the temperature is changing this will be t n the subscript n. So, this basically solved and in this the parameters are used relating the mu and t. So, that parameters are set using this parameter this term called ksn.

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Now you can also extract out from the structure file the velocities of the carriers. Now they do not appear directly but you can find out that I is equal to q n times V. So, if you want to find the V is I by q n so you can write current answer is J here. So, this J will be you know divided by a so this will be J a times this thing. So, area is constant so velocity will be this and scaled by some factor. So, it will be current density divided by electron concentration times the electron charge.

So, you can see here that in drift diffusion model is more or less constant then for energy balance you have this green curve then green slightly for hydro dynamic the change is actually quite large. So, if you change these scattering, the relaxation times or the source drain doping that means you are changing the series resistance basically for the source and drain you can find out these effects under these simulations.

And you can find out how much difference is appearing in these simulations. So, you can compare the performance of this drift diffusion energy balance and hydrodynamic models using the code discussed here.

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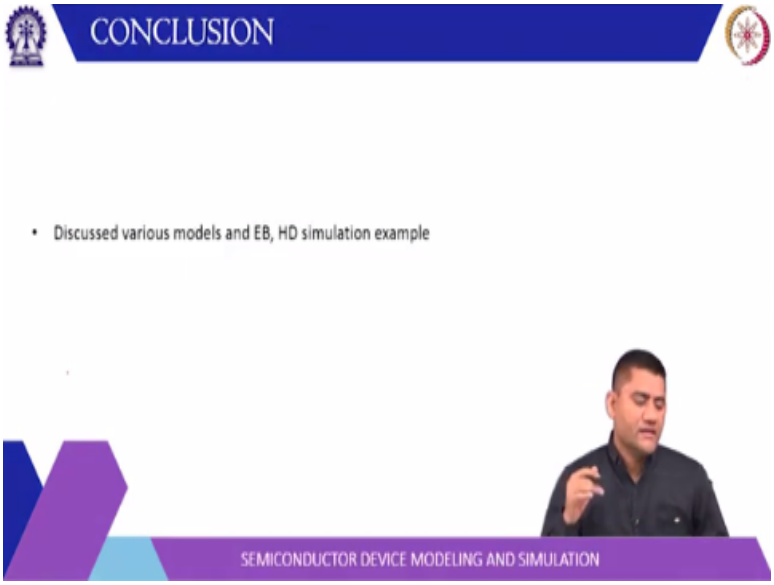

So, we have discussed the various models that are available in SILVACO related to the mobility, the generation recombination, optical generation and we have discussed one example concerning the energy balance and the hydrodynamic model. Thank you very much.