Semiconductor Device Modeling

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Lecture – 17
Drift-Diffusion Transport Model: Equations, Boundary Conditions, Mobility and Generation / Recombination

In the previous lecture, we have introduced the Drift-Diffusion model. In this model, there were or rather there are 6 equations.

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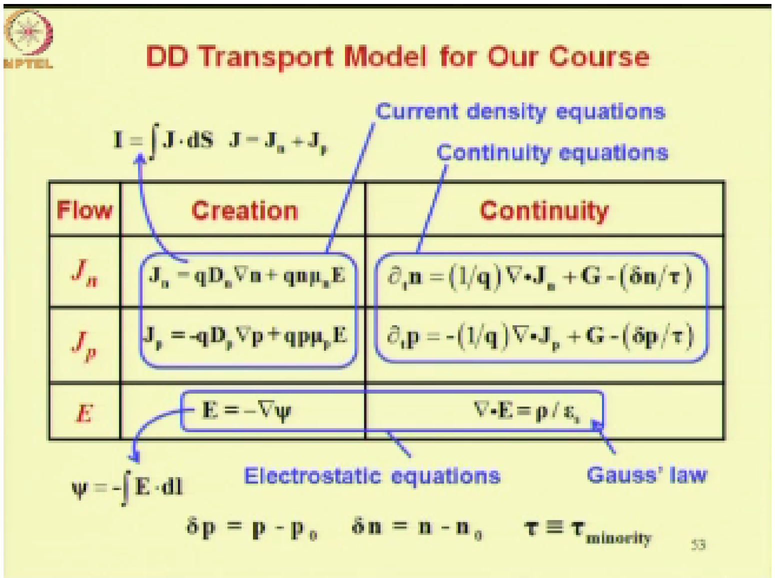

DD Transport Model for Our Course

$I = \int \mathbf{J} \cdot d\mathbf{S} \quad \mathbf{J} = \mathbf{J}_n + \mathbf{J}_p$

Current density equations

Continuity equations

Flow	Creation	Continuity
J_n	$\mathbf{J}_n = qD_n \nabla n + qn\mu_n \mathbf{E}$	$\partial_t n = (1/q) \nabla \cdot \mathbf{J}_n + G - (\delta n/\tau)$
J_p	$\mathbf{J}_p = -qD_p \nabla p + qp\mu_p \mathbf{E}$	$\partial_t p = -(1/q) \nabla \cdot \mathbf{J}_p + G - (\delta p/\tau)$
E	$\mathbf{E} = -\nabla \psi$	$\nabla \cdot \mathbf{E} = \rho / \varepsilon_s$

$\psi = -\int \mathbf{E} \cdot d\mathbf{l}$

Electrostatic equations

Gauss' law

$\delta p = p - p_0 \quad \delta n = n - n_0 \quad \tau \equiv \tau_{minority}$

The 6 equations contain 2 current density equations, 2 continuity equations and 2 electrostatic equations. We can reduce these 6 equations to 3 coupled equations by moving the equations for current density and the equation E = - grad Psi. So the equations of this Creation column into the Continuity column and these 3 equations are the equation for n, p and Psi.

We derive the current voltage characteristic of the device by integrating the current density J which is the sum of the electron current and hole current over the contact area. And the voltage corresponding to this current is obtained by integrating the electric field over the length between the contacts. We have explained that in most cases, the excess carrier concentration of electrons and holes would be approximately equal.

Because the semiconductor regions which are neutral or quasi neutral the excess holes and electrons are generated in pairs. However, to take care of the case isolated instances where the space charge neutrality condition maybe violated, we have retained delta n and delta p as separate symbols rather than using the same delta in both equations. We discussed the boundary conditions, the ideal boundary conditions on n, p and Psi and the non-ideal or general boundary conditions.

And we pointed out that the boundary conditions on n, p and Psi are derived based on sum constraints on the current density at the boundary whether the contacted or non-contacted. Now let us process further on this and then in this lecture we will consider the models for the mobility which is one of the most important parameters of this Drift-Diffusion model. So mobility of electrons and mobility of holes.

As we have pointed out, the diffusion coefficient, Dn and Dp can be obtained from the mobility values using the arsenide relation. Therefore, one does not talk about a diffusion coefficient separately. The other equations we will need are the equations for generation of electron hole pairs and the lifetime. So these equations also we will provide at the end of this module.

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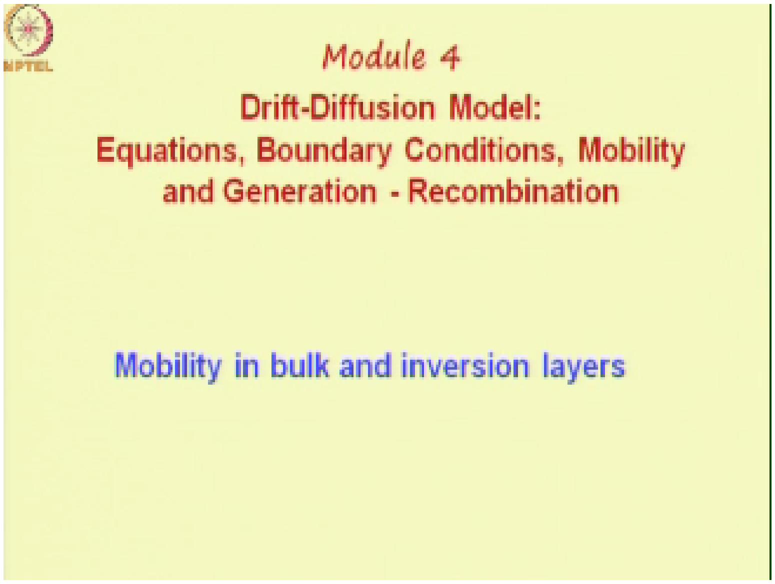

Module 4

Drift-Diffusion Model:

Equations, Boundary Conditions, Mobility and Generation - Recombination

Mobility in bulk and inversion layers

So let us look at mobility in bulk and inversion layers. So when you look at a semiconductor you must separate the semiconductor region into 2 parts the Surface and the Bulk.

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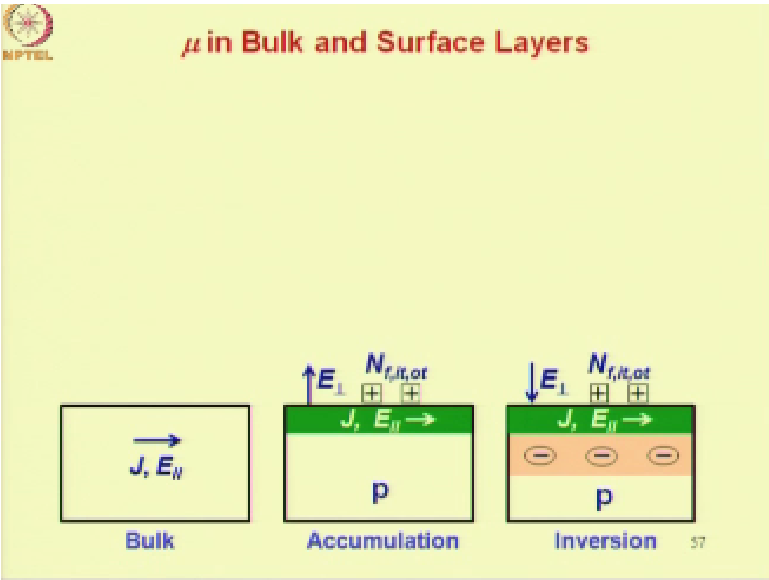

μ in Bulk and Surface Layers

The Bulk is somewhere inside here okay far away from the boundaries semiconductor. Now, we will be encountering 2 electric fields one is parallel to the current flow so the arrow shows the direction of current low and the electric field that is causing this flow, so the electric field which is along direction of the current we shall denote it as E parallel.

On the other hand, when we move to the surface we will find that there will be an electric field which is perpendicular to the current flow. Let us look at the surface. Now what are the occasions when you have current flow at the surface? So here is an example of a mass wet in 2 conditions, accumulation and inversion. So in both these instances you have large concentration of mobile carriers at the surface shown here by this green region.

And current flow can occur therefore near the surface. Now this is where we find the perpendicular electric field denoted as E perpendicular. It is this field that is holding on to these mobile carriers at the surface. So if it is a p type semiconductor and you have an accumulation layer of holes then the electric field will be outward from the semiconductor. On the other hand, if you have inversion as shown here in a p type substrate the inversion occurs due to electrons.

And therefore to hold these electrons near the surface, you will need a field which is coming into the surface. So this is where you see there are 2 electric fields one parallel to the current flow and the other perpendicular to the current flow. So here again you have parallel and perpendicular. In addition, what you have find at the surface is that there are charges and states. Now these charges and states are because of the abrupt change in the boundary from the semiconductor to the insulator in this case.

The insulator here can be vacuum or oxide or anything, in general for a surface. So these charges which are separated into 3 types N suffix f denotes the fix charge and this is denoted by a positive sign with a boundary around it. So the boundary around the positive sign shows that this charge is fixed. So here we have assumed that this region is silicon dioxide okay, but in general the space charge could the fix charge could be negative also for some other insulators.

Then, you have N suffix it that is Interface Trap charge. These are charges trapped at the interface. And you have N ot that is Oxide Trap charge, so you have some charges trapped in the silicon dioxide layer here. We can always replace this silicon dioxide by any other insulator. Therefore, though we call it N ot it is basically a trapped charge in the insulator. Now the polarity of this charges are the same whether it is an inversion of accumulation layer, therefore the same charges are shown here.

Now one more thing that we need to take into account when we are talking about an inversion layer is the presence of the depletion layer beneath. So these are the conditions in the bulk and at the surface. So for the surface we will concentrate on the inversion layer mobility in the inversion layer because most of the mass fit operation is actually involving this inversion layer. Though whatever we discussed can be extended to accumulation layer also.

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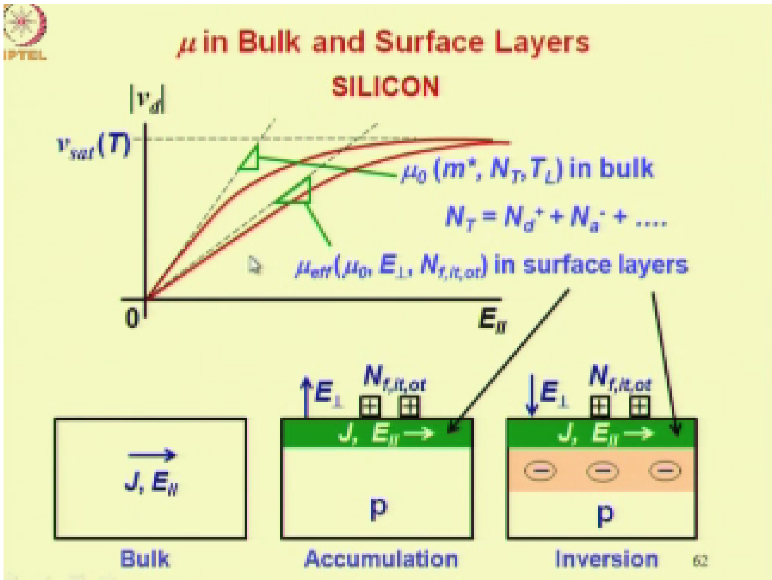

μ in Bulk and Surface Layers

SILICON

Let us concentrate on the Bulk. Here is the drift velocity versus electric field characteristic that we have derived in our earlier module. This electric field now is the E parallel which is along the direction of the current. We have put a modulus over the drift velocity because if you are considering electron the drift velocity in the direction opposite to that of the electric field and so its sign is negative.

2 limits of this drift velocity curve are shown here 1 is the saturation limit and that is indicated by the saturation velocity which we shall see is a function of temperature. And the second limit is near the origin the Quasi equilibrium or Ohmic region where at low electric fields there seems to be a straight line behaviour between the drift velocity and the field. And the ratio of the drift velocity to field is denoted as the mobility and Mu suffix 0 here the suffix 0 indicates low field mobility.

Now since we are in general, going to encounter both parallel electric field and perpendicular electric field we need to understand that when we use the term low field mobility we always mean the field parallel to the current flow. Okay. So it is E parallel. Also note that we have considered a semiconductor such as silicon for which this kind of a velocity field curves applies I mean this shape of the velocity field curve.

For instance, for Gallium Arsenide, we have pointed out that there is an over shot of the velocity okay in the velocity field characteristic so it would be something like this. So your velocity would go up beyond the saturation velocity and then in some region it will fall down to the saturation velocity slowly negative resistance region. So our description of the mobility would be related to the silicon because the silicon devices are more prevalent.

At the end we will also very briefly discuss about the Gallium Arsenide velocity field curve. Now the mobility, the low field mobility is a function of the effective mass of carriers; the total doping total number of ionized impurity atoms which is sum of the positively charged ionized impurities and negatively charged impurities, right. So this is important to note that the mobility depends on the sum total of all the impurities donors, acceptors, traps and everything.

This is unlike the carrier concentration. The majority carrier concentration depends on the net impurity concentration; that is the difference between, the donor impurity concentration and the acceptor impurity concentration whereas the mobility depends on the total impurity concentration. In addition to the impurity concentration you have the dependence of mobility or Lattice temperature as well.

So you would recall that we had said that the electron or hole get scattered by ionized impurities by Phonons and by other carriers, right. So therefore the behaviour of mobility is a function of NT and TL. It depends on effective mass because between 2 collusions the amount of velocity that the electron acquires because of the electric field depends on the effective mass. Lesser the effective mass more the acceleration and more the velocity.

Now let us look at the surface, mobility picture for the surface. For the surface your mobility gets reduced because of additional scattering and that is what shown here. So you see that the initial slope of the velocity field curve has reduced and this is because the additional scattering mechanism which I have come into the picture.

Now, before we discuss the scattering mechanism let us look at the symbolism, the mobility under low parallel electric field conditions in the presence of a perpendicular electric field is called the Effective mobility. So please note that Mu effective this symbol would apply to condition namely low value of parallel electric field and a presence of perpendicular electric field. Okay.

So it is the initial slope of the velocity field curve or slope of the velocity field curve at low parallel electric fields in the presence of perpendicular electric field. Now this effective mobility is a function of the bulk low field mobility Mu0 then the perpendicular electric field and the concentration of charges at the interface such as the fixed charge, the interface trap charge and the oxide trap charge.

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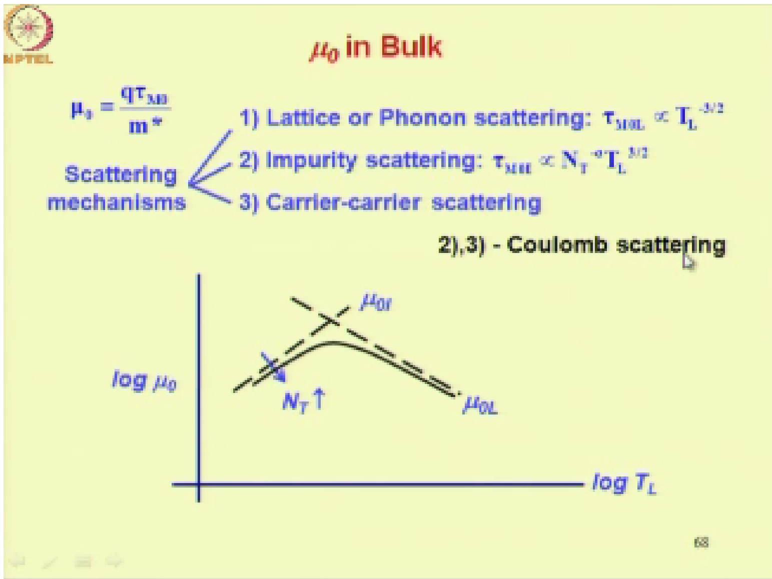

μ_0 in Bulk

$$\mu_0 = \frac{q\tau_{M0}}{m^*}$$

Scattering mechanisms

1) Lattice or Phonon scattering: $\tau_{M0L} \propto T_L^{-3/2}$
2) Impurity scattering: $\tau_{M0I} \propto N_T^{-1} T_L^{3/2}$
3) Carrier-carrier scattering

2),3) - Coulomb scattering

Let us concentrate on the mobility in the bulk and let us see what kind of a model we have for mobility as a function of the total impurity concentration and the latest temperature. The formula for mobility we are rewriting here from our earlier module, the low field mobility Mu0 = times the moment relaxation time close to equilibrium divided by the effective mass. Now we have said that we use the symbol m* when we want to generally refer to electrons and holes.

If you are talking about electrons specifically, we will replace m*/m suffix n and if it is holes it is m suffix p. The scattering mechanisms which affect this mobility are Lattice or Phonon scattering, the Impurity scattering and Carrier-carrier scattering, we appointed this out earlier.

Now quantum mechanism gives us the relation between the moment relaxation time for Lattice scattering.

And the Lattice temperature so this relation is obtained as Tau m suffix Tau suffix M0L is propositional to TL power -3/2. Now since your mobility is proportional to Tau M0 therefore the mobility is also proportional to TL power -3/2, so it decreases as TL power -3/2 for Lattice or Phonon scattering. Now that is what is depicted here in the graph. Now since the relation between Mu0 and TL is a power law.

We have chosen a log Mu0 versus log TL access because on such choice of access the behaviour would appear as a straight line. Repeating the similar procedure for impurities scattering you have the moment relaxation time due to impurity scattering proportional to NT power - alpha multiplied by TL power 3/2. Recall that we had said in our earlier module that impurity scattering will increase with total impurity concentration.

Therefore, the impurity concentration appears in the denominator that is why the negative power alpha. Further, we have also remarked that if the carrier moves very fast past the impurity item then the amount of scattering will be reduced. So you have impurity atom and the carrier is moving very fast then the amount by which the carrier will get scattered would be less.

And therefore, since the thermal velocity increases the Lattice temperature the amount of scattering decreases as Lattice temperature increases for ionized impurity scattering, that is why this kind of a behaviour. Now this is what is depicted here in graph. So the mobility appears to increase as your lattice temperature increases and on a log-log plot this is a straight line because the behaviour is power log.

As you increase the ionized impurity concentration total ionized impurity concentration this line would shift down okay that is what is indicated by the arrow here. Now as far as Carrier-carrier scattering is concerned we have already explained that what matters is scattering of electrons by holes or holes by electrons. And Carrier-carrier scattering affects minority carriers because the minority carriers are surrounded by a large amount of majority carriers.

Scattering of electrons by electrons and holes by holes does not affect the current. Now in general the Carrier-carrier scattering affect on mobility is not so well understood particularly when the injection level is not high and very often its affect is not that significant so we shall not concern our self about a formula for Carrier-carrier scattering mobility here. So combining the Lattice scattering and the Phonon sorry the Lattice or Phonon scattering.

And the Ionized Impurity scattering you get a mobility versus temperature behaviour as shown here, so for very low temperature the mobility increases reach a pick and then falls off. So normally when you are operating around room temperature you would be somewhere here were the mobility falls with temperature because the Phonon scattering or Lattice scattering would dominant.

Now just want to remark that 2 and 3 that is Carrier-carrier scattering and Impurity scattering are both referred to as Coulomb's scattering because in both of these cases the reason for the change in direction of the carrier motion is the Coulomb forces of attraction or repletion between the entity that is scattering and the carrier.

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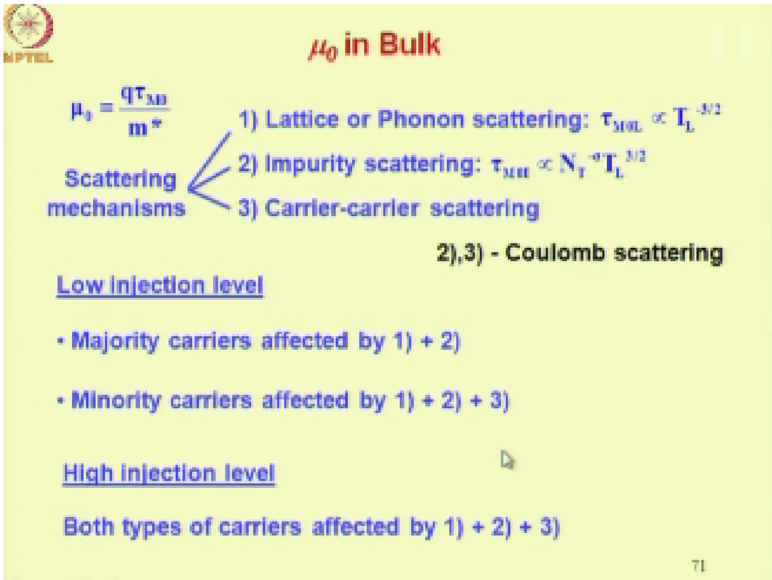

μ_0 in Bulk

$\mu_0 = \frac{q\tau_{MB}}{m^*}$

Scattering mechanisms

1) Lattice or Phonon scattering: $\tau_{MBL} \propto T_L^{-3/2}$

2) Impurity scattering: $\tau_{MBI} \propto N_I^{-1} T_L^{3/2}$

3) Carrier-carrier scattering

2),3) - Coulomb scattering

Low injection level

- Majority carriers affected by 1) + 2)
- Minority carriers affected by 1) + 2) + 3)

High injection level

Both types of carriers affected by 1) + 2) + 3)

Now let us separate the behaviour of mobility into 2 regions of operation namely the Low injection level and High injection level and look at these 2 conditions separately. So when device currents small normally injection levels will be low and when device currents are large injections level could be high. Okay. Now from your first level course you know what injection level means.

The injection level represents the extent to which the majority carrier concentration is disturbed under non-equilibrium conditions. So more specifically the injection level is equal to the excess carrier concentration divided by equilibrium majority carrier concentration. So this ratio excess carrier concentration divided by equilibrium majority carrier concentration if it is more than 10 then you say it is high injection level.

On the other hand, if the ration is less than 1/10 then you say it is injection level is low; in between you have moderate injection level. So in low injection level majority carriers are affected by the Phenomena 1) and 2) that is Lattice scattering and Impurity scattering while minority carriers are affected by all the 3 namely Lattice scattering, Impurity scattering and Carrier-carrier scattering.

In High injection level however, both carriers majority and minority in fact under high injection level since carrier concentration of electrons and holes are almost equal you really cannot identify any particular carrier as majority or minority. So when we use the term majority or minority in the context of high injection level we are actually referring to the semiconductor under equilibrium, right. And then we are using that reference.

So for example if I am taking a p type semiconductor then electrons are majority carriers under equilibrium conditions. So we will say using this nomenclature that under high injection level the majority carrier concentration almost same as minority carrier concentration, right. Whereas strictly speaking we should refer to we should not identify any of the carriers in majority or minority.

Now since both carrier concentrations are high in high injection level they affect each other they scatter each other therefore all the 3 mechanisms of scattering are important. And it will reduce the mobility with the low injection value.

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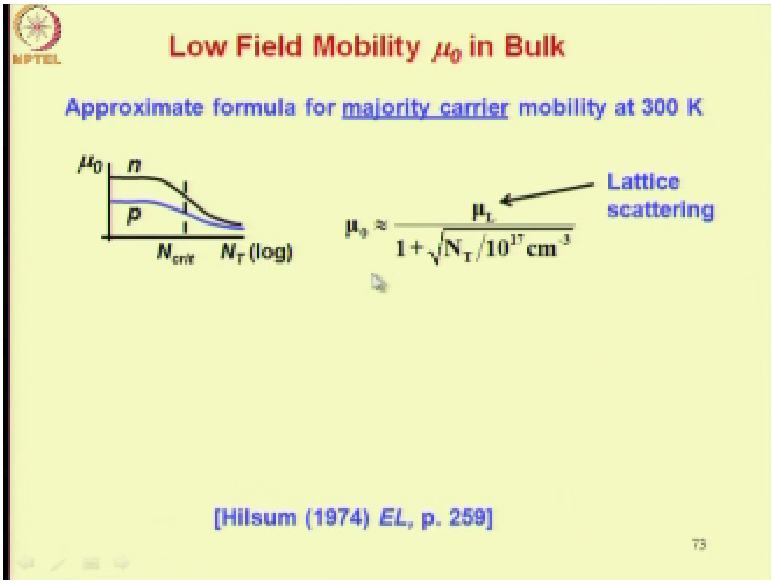

Low Field Mobility μ_0 in Bulk

Approximate formula for majority carrier mobility at 300 K

$$\mu_0 \approx \frac{\mu_L}{1+\sqrt{N_T/10^{17}\,\mathrm{cm}^{-3}}}$$

Lattice scattering

[Hilsum (1974) *EL*, p. 259]

Now let us look at the formulae for majority carrier mobility at 300K. We will look at silicon first. Now by this time it must be clear to you that if you are asked a question such as what is the mobility of carriers in silicon. You know that you will ask a few questions before giving an answer. So you would ask back, “Well, are you talking about majority carrier mobility or minority carrier mobility.

Point number one. Point number 2, you would ask “Are you talking about high injection level or low injection level, are you talking about bulk or are you talking about surface. Right? And only when you know all this conditions then you can talk about what is the mobility. You would also ask what is a doping level right? So please remember that the mobility which is such an important parameter depends on so many conditions the simply.

Because the electron moment in the response to the electric field is affected by so many things present around the electron or a hole, so these facts must be borne in mind. Now generally, it is easier to measure majority carrier mobility then minority carrier mobility. Because, you know that if you take the expression for resistivity the resistivity of a semiconductor which is an easily measurable quantity depends on majority carrier concentration.

The effect of minority carrier concentration on resistivity small therefore in general it is difficult to measure minority carrier mobility's. So unless stated otherwise if people are giving you values of mobility they are most likely giving you values of majority carrier mobility. Now let us look at the behaviour of mobility as a function of temperature according to the formulae.

If you plot mobility as a function of doping were the doping is sketched on the lock scale because you know the doping level varies from 10 power 14 per centimetre cube-- I am talking about the approximate range 10 power 14 per centimetre cube to as high as may be 10 power 19 or 20 per centimetre cube, right. It can even go beyond in some cases. So this is a very wide range evidently you cannot show the behaviour on such a wide range on a linear plot, therefore we have to choose a log scale for the total doping.

On the other hand, in this graph the mobility is shown on a linear plot, a linear scale. So this is important to recognize because when we remember the shape of a curve we should remember it along with the information about the access whether it is a log or semi-log graph or Linear-linear graph. So this is semi-log plot. Now when you look at the shape from the shape you can get some ideas about the expression that would fit the shape.

Now that expression is shown here, in which the numerator Mu suffix L is Lattice scattering. Evidently, this total impurity concentration here is the affect of ionized impurity scattering. Now let us see how this kind of a formula can result from the shape, okay.

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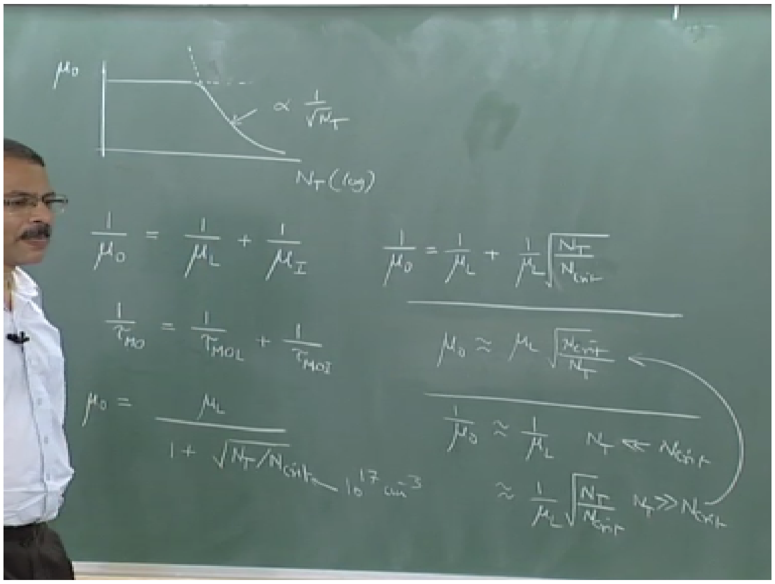

$$\frac{1}{\mu_0} = \frac{1}{\mu_L} + \frac{1}{\mu_I}$$

$$\frac{1}{\tau_{M0}} = \frac{1}{\tau_{M0L}} + \frac{1}{\tau_{M0I}}$$

$$\mu_0 = \frac{\mu_L}{1 + \sqrt{N_T/N_{crit}}} \quad 10^{17}\,cm^{-3}$$

$$\frac{1}{\mu_0} = \frac{1}{\mu_L} + \frac{1}{\mu_L}\sqrt{\frac{N_T}{N_{crit}}}$$

$$\mu_0 \approx \mu_L \sqrt{\frac{N_{crit}}{N_T}}$$

$$\frac{1}{\mu_0} \approx \frac{1}{\mu_L} \quad N_T \ll N_{crit}$$

$$\approx \frac{1}{\mu_L}\sqrt{\frac{N_T}{N_{crit}}} \quad N_T \gg N_{crit}$$

Now, you can separate this into 2 regions, say maybe one region which goes like this and other region which is kind of constant right as a function of doping. Now it proves convenient to develop equations for mobility using the reciprocal. So for example, I can write 1/Mu0 = 1/Mu L that is due to Lattice scattering and +1/Mu I due to ionized impurity scattering. Why?

Because I can write in terms of the moment relaxation time 1/Tau M0 = 1/Tau M0L+1/Tau M0I. This is the moment relaxation time because of Lattice scattering and this is moment relaxation time because of ionized impurity scattering. Now why can I sum up the reciprocals, well it is very simple 1/reciprocal of this time represents the number of scattering events or scattering rate.

Now intuitively, it is very easy for you to recognize that if I have one mechanism of scattering I get a certain scattering rate then if I add another scattering mechanism the scattering rate of this mechanism would add on to the scattering rate that was already there. Now you can ask but how can you just superpose to scattering mechanism and the rates. Yes, strictly speaking it may or may not hold in practice. Okay.

So however, we make an approximation that the scattering rate of a number of scattering mechanisms is the same as the scattering rate of each mechanism construct individually, and then the rates and all summed up, okay. So this is an approximation that we are doing is also refer to as Matthiessen's rule. So since this formula can be recognized to be valid at least approximately valid very easily where the total scattering rate is equal to the sum of the scattering rates of each individual mechanism.

And since the mobility Mu is proportional to the moment relaxation time right corresponding moment relaxation time, this formula follows from this formula. Okay, now once you know this, we can easily get the equation that we have got. So the equation was Mu0-- let me write it here, Mu 0 = Mu L divided by 1+square root of NT by a critical doping it happens to be 10 power 17 per centimetre cube.

Now let us cast this formula in this form in reciprocal form and then it will be very evident how you get the relation. So when I cast it in reciprocal form it will look as follows: 1/Mu0 = 1/Mu L+1/Mu L into NT/10 power 17 or let me write it as in critical, of course with a square root sign. Now you compare this formula and this formula. So what you find is we have written an expression for ionized impurity scattering.

So we have said the ionized impurity scattering goes on increasing as square root of NT and then this is nothing but a concentrate. Okay. And similarly, if you write the fact that 1/Mu I is proportional to square root of NT, now evidently the square root sign the square root behaviour we have to get from quantum mechanics we assume a result. So now we need a proportionality constant when I put an equality sign.

Now that is where the proportionality has been achieved by using the Mu L itself in the coefficient and then choosing an appropriate doping so that the behaviour matches what you derived from quantum mechanism. Okay. So that is how one gets this relation. Now how do you get a relation like square root? So you see here that your mobility is falling and this part of the curve is 1/square root, right.

So when I add this 2 for low values of doping it would be this line and for high values of doping it would follow this. So in other words, you get 1by Mu 0 is approximately 1/Mu L which is independent of doping and that is this line so this is Mu L actually because 1/Mu 0 approximately = 1/Mu L means Mu 0 approximately = Mu L this line. And on the other hand this is for the NT small. So NT much < in critical.

And it is approximately = 1/Mu L into square root of NT/N critical for NT much greater than N critical. So in other words, Mu0 if I write for Mu0 I will get Mu0 is Mu L into square root in critical/NT, this one. So this is this curve. So this curve is proportional to 1/root NT. Now because of the way we are adding up, right.

Because it is reciprocal when this when NT is small this quantity does not hold when NT is large it is this quantity rather than this quantity that is how your curve is asymptotic to this limit for low NT and to this limit for high NT that is how you get this shape and that is how you get this formula. When you transform this formula which is written in the reciprocal form to the form that we want where you directly want an expression for Mu0 instead of 1/Mu0 then you get this. Okay.

Now this approach will be used to write expressions for mobility for various scattering mechanisms. So as we go on adding scattering mechanisms all that is going to happen is you are going to have multiple such terms coming on right hand side in the reciprocal. And this order if you recognize then we can derive the mobility expressions very easily. Now let me show you what are the values, so for Silicon the Mu suffix L right for electrons is 1400 centimetre square per volt second okay that unit, please note it is centimetre square per volt second you can.

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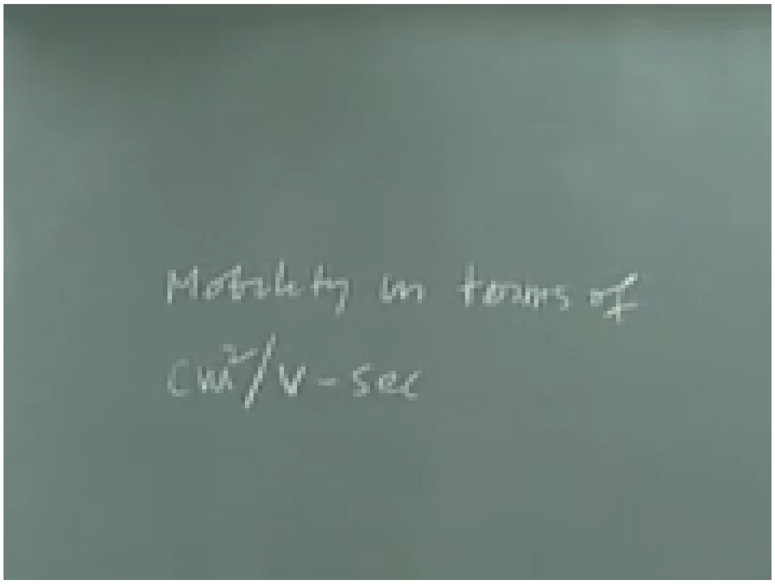

Mobility in terms of

cm²/V-sec

That is not put on the slide. So the unit of mobility is, the value is given or in terms of centimetre square per volts second.

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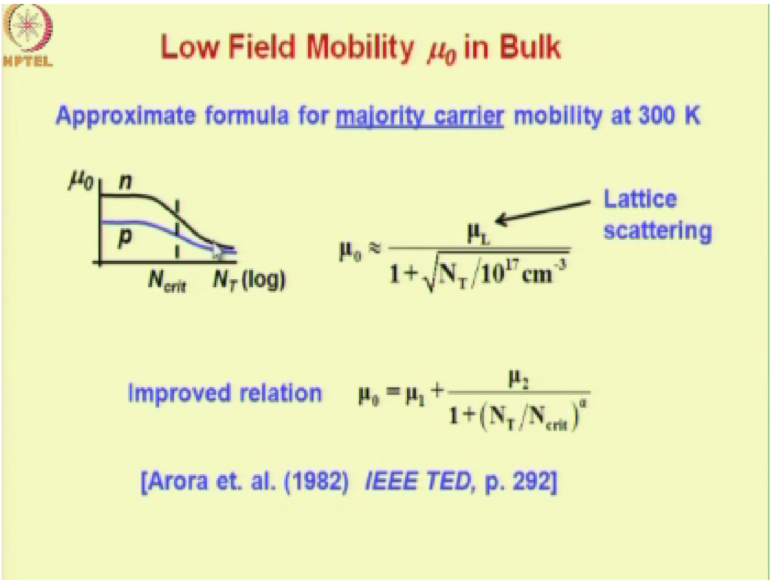

Low Field Mobility μ_0 in Bulk

Approximate formula for <u>majority carrier</u> mobility at 300 K

$$\mu_0 \approx \frac{\mu_L}{1+\sqrt{N_T/10^{17}\,\mathrm{cm}^{-3}}}$$

Lattice scattering

Improved relation $$\mu_0 = \mu_1 + \frac{\mu_2}{1+\left(N_T/N_{crit}\right)^{\alpha}}$$

[Arora et. al. (1982) *IEEE TED*, p. 292]

Now let us look at an improve relation. Now, you see what is found is that for large NT this relation predicts the mobility going towards 0. Okay. Whereas it is found in practise that it would be more appropriate to have a non-zero saturating value because than the curve-- when the expression fits the curve better and that is why people are proposed an improved relation where you add a small mobility term here which is a saturation value for large NT.

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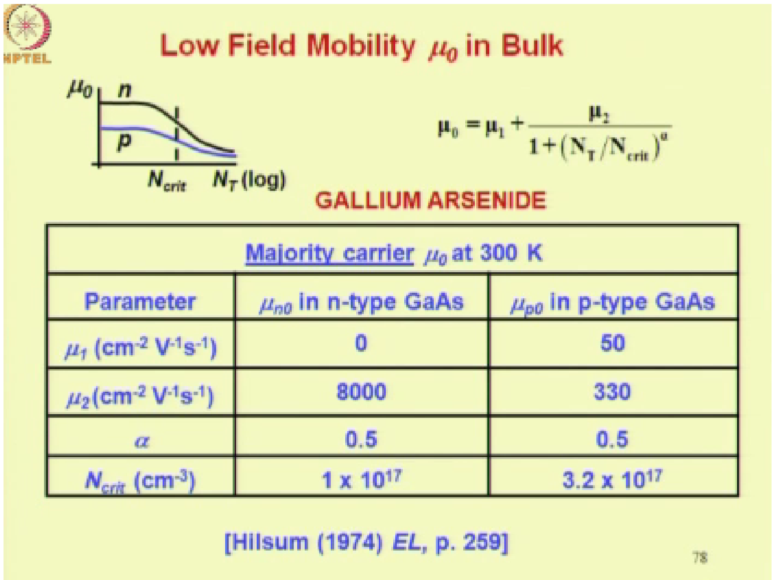

Low Field Mobility μ_0 in Bulk

$$\mu_0 = \mu_1 + \frac{\mu_2}{1+(N_T/N_{crit})^{\alpha}}$$

GALLIUM ARSENIDE

Majority carrier μ_0 at 300 K		
Parameter	μ_{n0} in n-type GaAs	μ_{p0} in p-type GaAs
μ_1 ($cm^{-2}\ V^{-1}s^{-1}$)	0	50
μ_2($cm^{-2}\ V^{-1}s^{-1}$)	8000	330
α	0.5	0.5
N_{crit} (cm^{-3})	1×10^{17}	3.2×10^{17}

[Hilsum (1974) *EL*, p. 259]

Now the values in these formulae are given here. One advantage of this formula as we will see is that it can be used for majority carrier mobility, minority carrier mobility and for silicon, Gallium Arsenide and so on. Right, that is the advantage of this form of the equation. And also it can incorporate temperature dependence. So each of this terms Mu1, Mu2 written here you see the temperature dependent.

So this incorporates both the impurity dependence, impurity concentration dependence as well as temperature dependence of mobility. In case you are taking down this values I will give you some time, I leave the slide on for some time. Now I will-- let me just mention the significant of the N critical okay. So what is the significant of N critical, you see when NT = N critical the mobility is approximately half of the maximum value, right.

If you leave out this-- this Mu1 which is small quantity you can see here say, Mu1 at room temperature is about 88 for electrons in silicon and Mu2 is 1250, right so this really a small value. The value to which the mobility saturates here. So approximately for NT = N critical your mobility falls to half of the maximum value. Okay. So your N critical therefore, on this graph if you see this would correspond to a point your mobility would be half of the maximum.

This point is around 10 power17 per centimetre cube for silicon. It is useful to note some of this values. One can give the values for minority carrier mobility, some people have measured and given these values. Evidently this is curve fitting exercise. So these have been given for 300 K; general results as a function of temperature are not available that readily. Values have been given for Gallium Arsenide as well.

Now you see that the electron mobility in Gallium Arsenide is very, very high compare to the hole mobility. Okay. So that is why Gallium Arsenide devices are mostly based on electron transport. Okay. You do not have something like a CMOS concept that you have in silicon Complimentary mass where you have both N type and P type transistors that is devices in which the current flow because of electrons and as well as holes.

So that maybe a possible in silicon but not in Gallium Arsenide where the hole mobility is really very, very small. On the other hand, the electron mobility of Gallium Arsenide is very high even higher much higher compare to silicon. Therefore, Gallium Arsenide devices are Gallium Arsenide is use for power devices it is used for very high frequency applications and so on, prefer to silicon.

Now note also that the mobility of electrons is always more than that of holes, this has been broadly observed for most of the semiconductors, right. In case of silicon for example, the electron mobility is about 2 to 3 times more than hole mobility. And mobility can fall over a very wide range as they change your doping. For example, for silicon we saw that mobility can fall for electrons.

Let us say from as high as more than 1300 centimetre square per volt second to as low as about 100 centimetre square per volt second when you change the doping from 10 power 14 to 10 power 19 or 20.

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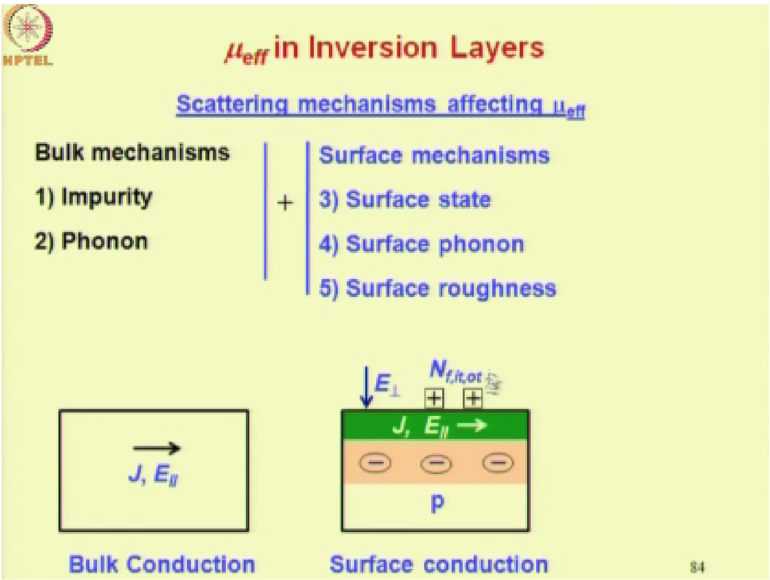

μ_{eff} in Inversion Layers

Scattering mechanisms affecting μ_{eff}

Bulk mechanisms

1) Impurity
2) Phonon

+

Surface mechanisms

3) Surface state
4) Surface phonon
5) Surface roughness

Now let us look at the effective mobility in inversion layers. The scattering mechanisms affecting this mobility. So we are following the same approach that we did for mobility. We shall consider the various aspects in the same order. Now the scattering at the surface includes the mechanisms which take place in the bulk also. Therefore, let us separate the mechanism affecting Mu affecting into 2 parts namely the bulk mechanisms and surface mechanisms.

So the impurity scattering and the Phonon scattering in bulk that affect the surface also, the carriers at the surface also. You have analogues extra scattering mechanisms at the surface. For example, analogues to the impurity scattering you have the surface state because of surface charges so these charges are indicated here. So they scatter the carriers in this surface mobile carrier layer just in the same way as you have scattering because of ionized impurities.

Similarly, the Phonon scattering in the bulk as an Analog surface and that is called the surface Phonon scattering. In additional, you have a mechanism called Surface roughness scattering which is related to the roughness of this surface. Let us show these things with the diagram.

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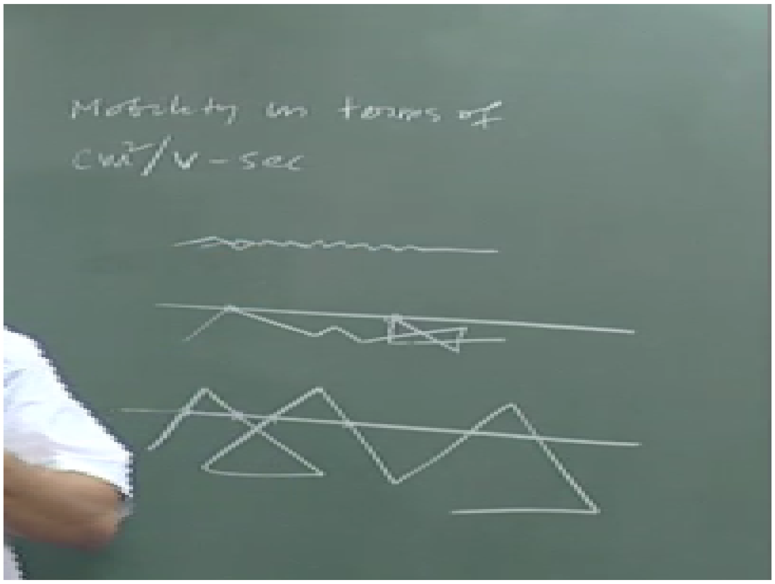

So suppose this is surface we are talking about evidently whenever you are coming near the surface your scattering mechanisms will be more because, construct a situation; suppose I was in the bulk let us say the electron path was something like this; now moment I put a surface I immediately find that there are extra scattering points, right. If the surface was not there then the electron would have gone all the way up to this point.

And then got scattered here only instead of one scattering point now you have 2 here. So clearly the number of scattering points have increased. Now when we say that a surface scatters, now why does it scatter? So at the surface you have Lattice vibrations those are Phonons or you have charges, right. So each of this points when we show that there is a scattering so supposing I show the scattering at the surface like this then each of the points can either be a Phonon, okay or it could be charge.

Now in addition to this, I have shown the surface to be flat at atomic levels it is not that flat so the picture of the surface is actually something like this. Now you can easily appreciate that the number of scattering mechanisms would be more if the surface is rough. Okay. Because the surface area is now much more than what you can get with the flat surface. Another way of looking at the scattering because of roughness is regarded as something like a frication.

If you are moving against a rough surface you know that the resistance from the surface is more the frication is more; so the surface roughness scattering can also be viewed as a friction kind of effect.

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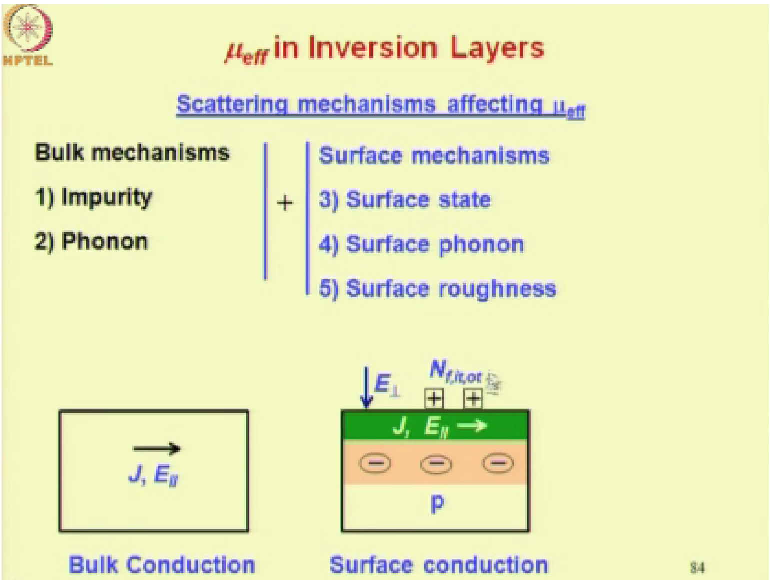

μ_{eff} in Inversion Layers

Scattering mechanisms affecting μ_{eff}

Bulk mechanisms	+	Surface mechanisms
1) Impurity		3) Surface state
2) Phonon		4) Surface phonon
		5) Surface roughness

Bulk Conduction

Surface conduction

Now evidently, all the surface mechanisms would depend on the perpendicular electric field. Why? Because, this field would tend to accelerate the carriers toward the surface and if the carriers are moving away they cannot move away to that distance because here again the carriers will be pulled back toward the surface. So because the perpendicular electric field tends to move the carriers toward the surface accelerates the carriers toward the surface the presence of the perpendicular electric field has an effect on each of the scattering mechanisms.

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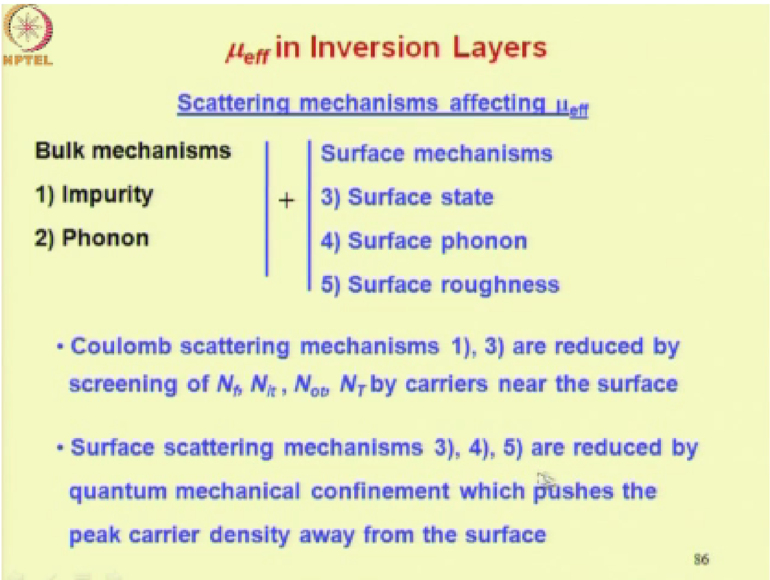

μ_{eff} in Inversion Layers

Scattering mechanisms affecting μ_{eff}

Bulk mechanisms
1) Impurity
2) Phonon

+

Surface mechanisms
3) Surface state
4) Surface phonon
5) Surface roughness

- Coulomb scattering mechanisms 1), 3) are reduced by screening of N_f, N_{it}, N_{ot}, N_T by carriers near the surface
- Surface scattering mechanisms 3), 4), 5) are reduced by quantum mechanical confinement which pushes the peak carrier density away from the surface

Now the Coulomb scattering mechanisms 1 and 3 so impurity scattering and surface state scattering are because of Coulomb force. So these mechanisms are reduced by screening of the charges Nf, Nit, Not and Nt that is the ionized impurity which are there in bulk also by carriers near the surface. Okay. Now let us understand this fact. So these are the charges we will present, let us say here and this is the so called region of the mobile carriers near the surface.

Now in this region you can see that if I consider the mobile carriers in this region these carriers are screened by the carriers above. So if I were to take the affect of this positive charge on the carriers here that would be much less than the affect of this positive charge on this carrier because these carriers will prevent this positive charge from having an effect on this carrier, right. They will terminate some of the field lines.

Let us say if these are negatively charged electrons. Then field line from the positive charge would terminate here it would not come to this point, right. That is why these mobile carriers are set to be screened by mobile carriers above and therefore the affect of these charges on the mobile carriers is less, so this is a so called screening affect. So you have more perpendicular electric field you have more of these charges and therefore you are likely to have more screening affect, right because more mobile carrier is represented.

And therefore this perpendicular electric field its accelerating tendency will be somewhat nullified by or rather this electric field will increase the mobile carrier concentration and increase the screening affect and thereby reduce the affect of this interface charges on the mobility of carriers below. So therefore this screening affect will actually increase the mobility as compare to the case when there is no perpendicular electric field.

Similarly, surface scattering mechanisms all 3 of them 3, 4 and 5 are reduced by quantum mechanical confinement which pushes the pick carrier density away from the surface. Now let us explain that very briefly we will have to discuss this in detail when we talk about the mass affect.

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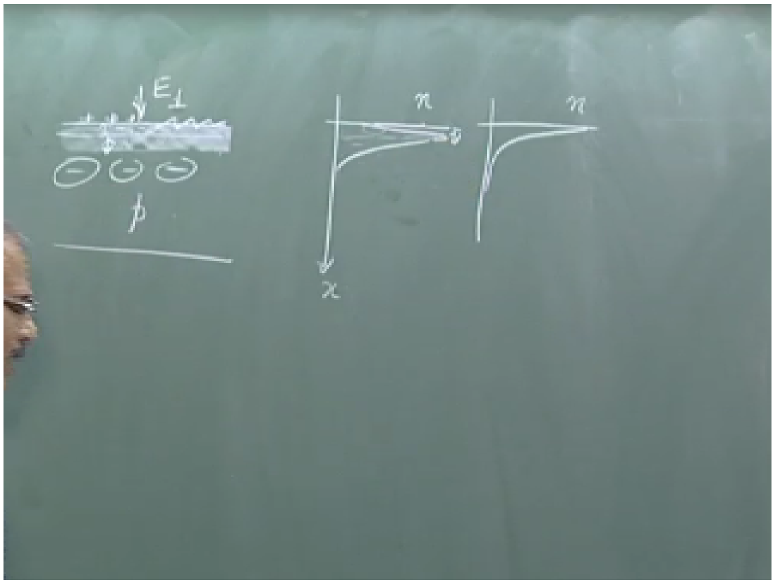

So it turns out that if I plot the distribution of this mobile carrier at the surface because of quantum mechanical confinement the distribution of the mobility of this carriers is something like this, right. And it is not like this which we would so this is in the x direction and what we are plotting let us say electron concentration, okay, let us say P type substrate and it is inversion layer. So beneath you have a depletion layer also, now it is like this, not like this.

So you see the pick is away from the surface by this much amount and that is why the affect of all this interface affects and so on will be reduced because the pick is away, many mobile carriers are away from this surface. Surface roughness affect also will be reduced, right. So if the surface is rough it may have affects on these charges right but not on these which are inside. So that is what is implied here.

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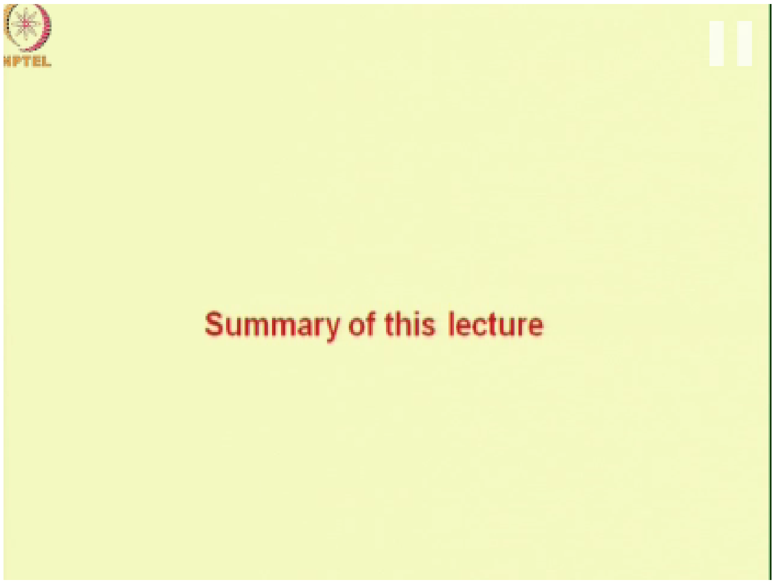

Summary of this lecture

So towards the end of the lecture let us make a summary of the important points. So in this lecture we have began discussion about the mobility which is a very important parameter of the Drift-Diffusion model. So we pointed out that a question such as what is the mobility in silicon or what is the mobility of electrons in silicon, right. Does not make sense,

Because the mobility depends on so many parameters; so many conditions in which the electron is moving that unless you specify whether you are talking about majority mobility, a majority carrier mobility or minority carrier mobility. Are you talking about high injection level or low injection level, are you talking about bulk or are you talking about surface. What temperature is--what is the temperature at which your device is operating.

And what is the ionized impurity concentration or doping concentration in your device? So unless all these information is available you cannot really assign a value for the mobility. We consider some of the formulae that are used to model mobility as a function of doping in the bulk and as a function of Lattice temperature. So we discussed in detail about the mobility in the bulk and we began a parallel discussion about the mobility at the surface and we shall be writing the formulae for the mobility at the surface in the next lecture.