Processing of Semiconducting Materials
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Lecture - 8
Diffusion and Ion Implantation – II

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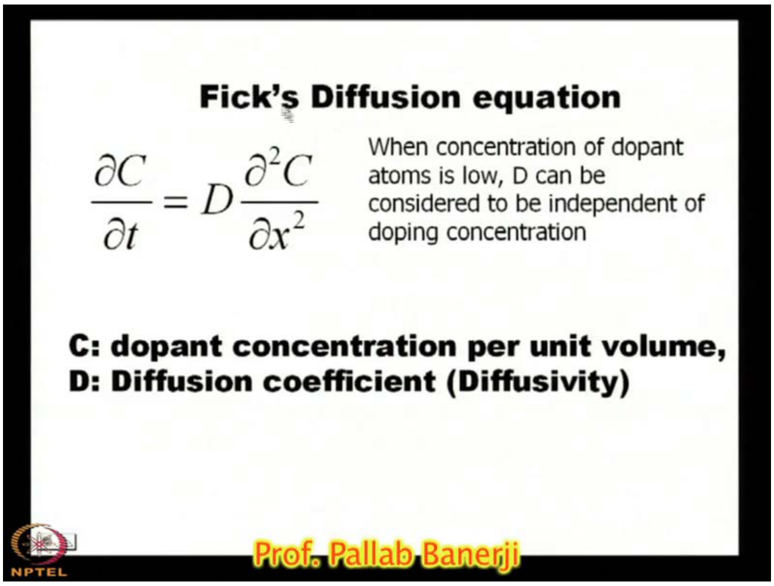

Fick's Diffusion equation

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

When concentration of dopant atoms is low, D can be considered to be independent of doping concentration

C: dopant concentration per unit volume,
D: Diffusion coefficient (Diffusivity)

Let us start our discussion on the Fick's diffusion equation. Fick's diffusion equation that means, when the concentration of dopant atom is low, D can be considered to be independent of doping concentration. What is D? D is the diffusion coefficient or diffusivity. D is known as the diffusion coefficient or diffusivity.

And when D is independent of doping concentration not always, remember I shall show you some cases, where D is not independent of doping concentration. It very much depends on the doping concentration. And, if this is the case then we can express the concentration with the diffusion coefficient by this relation. So, this relation will give you the concentration, time, distance, and diffusivity. It is very good relation; which can give you their profile of the diffusion. I shall show you.

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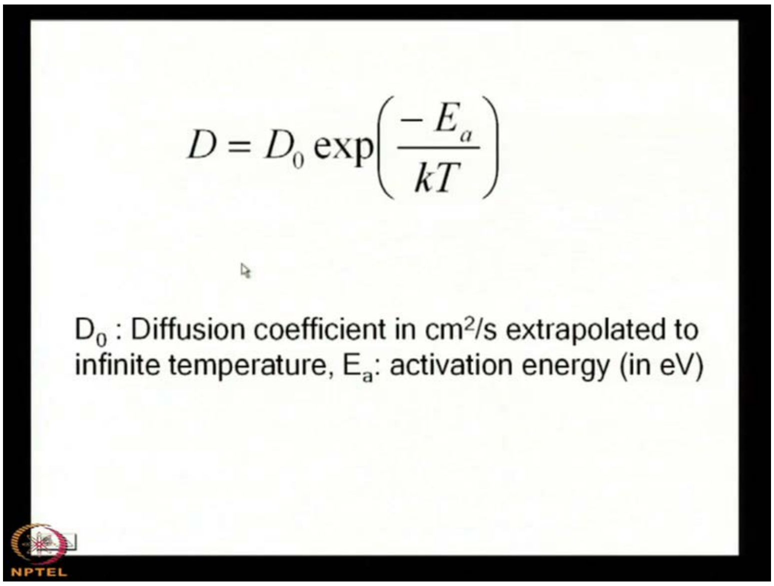

$$D = D_0 \exp\left(\frac{-E_a}{kT}\right)$$

D_0 : Diffusion coefficient in cm^2/s extrapolated to infinite temperature, E_a: activation energy (in eV)

And then the D or the diffusivity can be expressed as D 0 which is known as the diffusion coefficient extrapolated to infinite temperature diffusion coefficient extrapolated to infinite temperature. And, this expression will give you the activation energy D equals to D 0 exponential minus E a by k T. Now, what is activation energy? Activation energy is the energy required for diffusion, required for diffusion required for diffusion and the diffusion can be vacancy or interstitial. So, from the value of this energy E a, from the value of this energy you can say whether it is a diffusion process, the whether the diffusion process is due to the vacancy or it is due to the interstitial.

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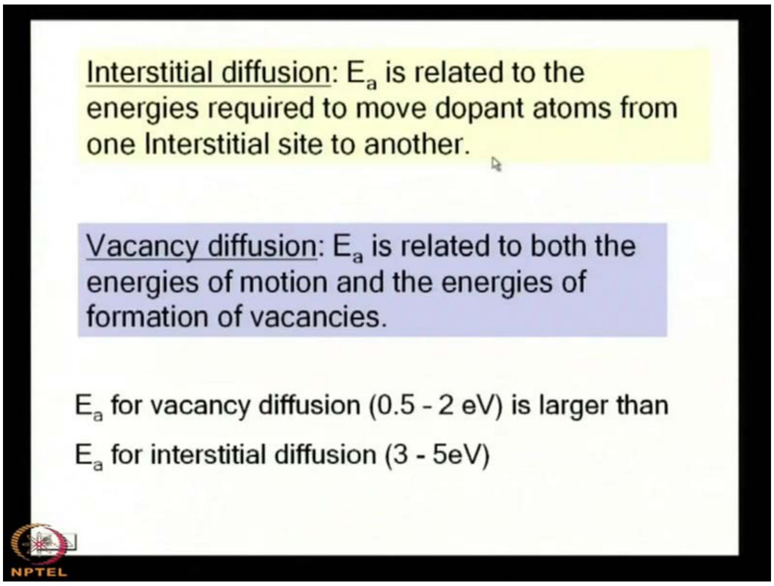

Interstitial diffusion: E_a is related to the energies required to move dopant atoms from one Interstitial site to another.

Vacancy diffusion: E_a is related to both the energies of motion and the energies of formation of vacancies.

E_a for vacancy diffusion (0.5 - 2 eV) is larger than

E_a for interstitial diffusion (3 - 5eV)

Interstitial diffusion: E a is related to the energies required to move dopant atoms from one interstitial site to another one interstitial site to another. That means if this is your interstitial site.

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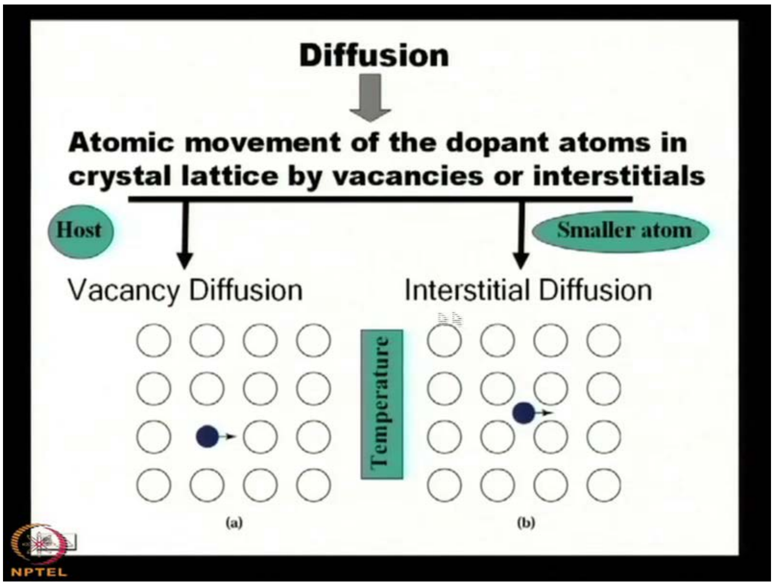

Diffusion

Atomic movement of the dopant atoms in crystal lattice by vacancies or interstitials

This is one site then it will move to here or it will move to their then from here to there and so on and so forth. So, the energy required for its movement from one, one interstitial site to another it is the activation energy for interstitial diffusion. For vacancy diffusion it is related to both the energies of motion and the energies of formation of vacancies. First we have to create the vacancy and then there will be the movement of the impurity or the dopant atoms. You see that the activation energy for vacancy diffusion is 0.5-2 electron volt and is larger than E a for interstitial diffusion the value interchanges. This value will be 3-5 electron volt for vacancy diffusion; and interstitial diffusion it will be 0.5-2 electron volt.

So, the vacancy diffusion the activation energy for vacancy diffusion which is 3 - 5 electron volt, it is larger than the interstitial diffusion which is 0.5 - 2 electron volt. So, that means if you plot the activation energy that you can calculate. You can calculate the activation energy then from the value of the activation energy you can infer whether it is an interstitial or it is vacancy diffusion. Where the impurity is residing? Where the which is the position the impurity atom is occupying? That can be predicted from the value of the activation energy.

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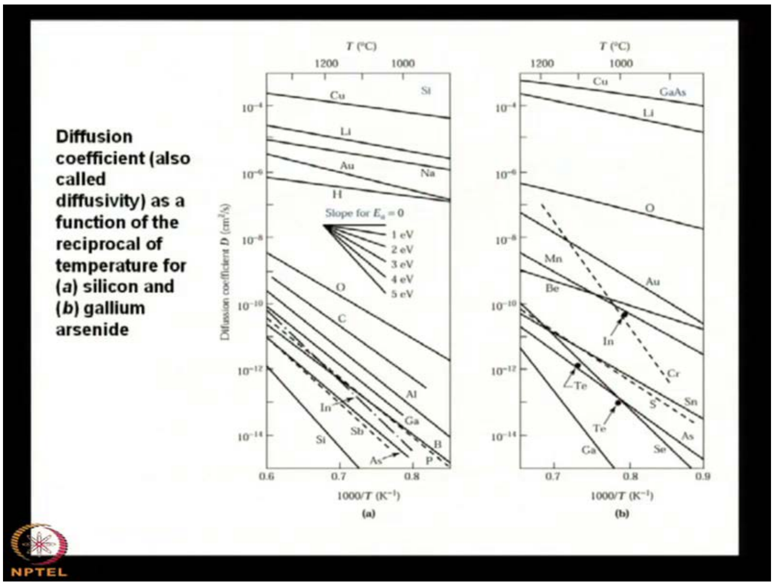

Diffusion coefficient (also called diffusivity) as a function of the reciprocal of temperature for (*a*) silicon and (*b*) gallium arsenide

So, activation energy in that sense is very important parameter. Then, use sees that we have plotted the diffusion coefficient, which is also known as diffusivity. As a function of the reciprocal of temperature for silicon and gallium arsenide it is silicon and it is gallium arsenide. On the y-axis you have diffusion coefficient in centimeter square per second. And, on the x-axis it is reciprocal of temperature usually it is denoted by 1000 by T 10 to the power 3 by T.

And, from the slope you see that what you find? That for silicon you see it is copper. So, what is the slope of copper? It is less than arsenic or phosphorus the slope, the slope here is less. And, you see that the slope will give you the activation energy, because if you plot if you take this equation D equals to D 0 exponential minus E a by k T.

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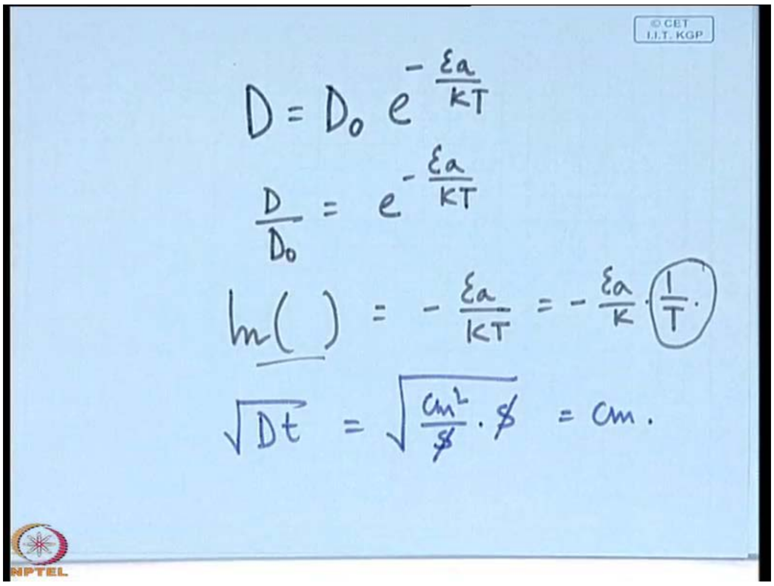

$$D = D_0 \, e^{-\frac{E_a}{kT}}$$

$$\frac{D}{D_0} = e^{-\frac{E_a}{kT}}$$

$$\underline{\ln(\ )} = -\frac{E_a}{kT} = -\frac{E_a}{k} \cdot \boxed{\frac{1}{T}} \cdot$$

$$\sqrt{Dt} = \sqrt{\frac{cm^2}{\cancel{s}} \cdot \cancel{s}} = cm.$$

So, if you plot 1 by T then what will happen? D equals to D 0 e to the power minus E a by K t or D by D 0 equals to e to the power minus E a by k T, if you take log on both sides, then what you will get? ln this is equals to Minus E a by k T. So, that is equals to minus E a by k into one by T. So, if you plot this with 1 by T then the slope will give you the minus E by k that means from the slope you can calculate the activation energy. What is k? k is nothing but Boltzmann constant that you know. It is a it has it is very standard; it has a value you know 1.3 into 10 to the power minus 23. So, from the curve from this slope you can calculate the activation energy. So, if you know the activation energy then you can say whether it is a fast diffusion, it is a slow diffusion. Those things you can predict.

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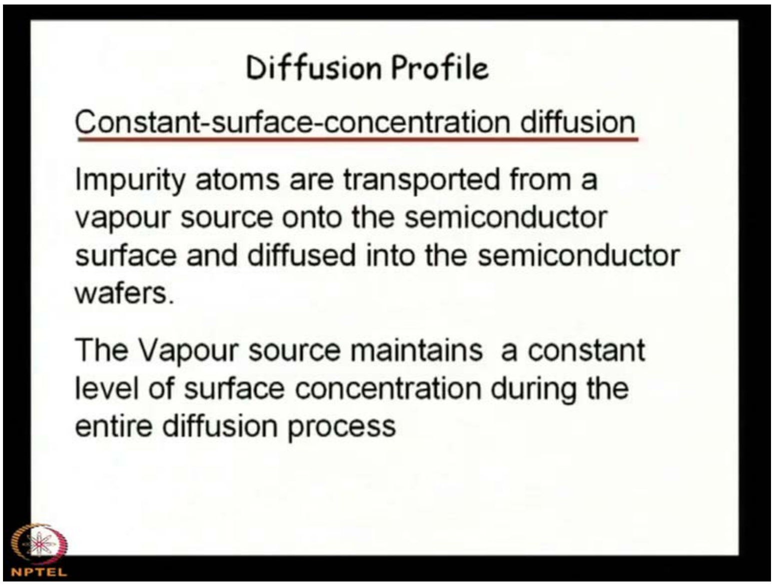

Diffusion Profile

Constant-surface-concentration diffusion

Impurity atoms are transported from a vapour source onto the semiconductor surface and diffused into the semiconductor wafers.

The Vapour source maintains a constant level of surface concentration during the entire diffusion process

Then if I come to the point of diffusion profile. The diffusion profile will be different for different cases. And, we shall discuss two important things, one is the constant surface concentration diffusion. Please write down constant surface concentration diffusion. In this case that is case one. Just you write down that title constant surface concentration diffusion.

In this case impurity atoms are transported from a vapor source onto the semiconductor surface and diffused into the semiconductor wafers. The vapour source maintains a constant level of surface concentration during the entire diffusion process. That means if you diffuse for 1 hour; through 1 hour the concentration at the surface will be same. The concentration at the surface will be same for the whole one hour.

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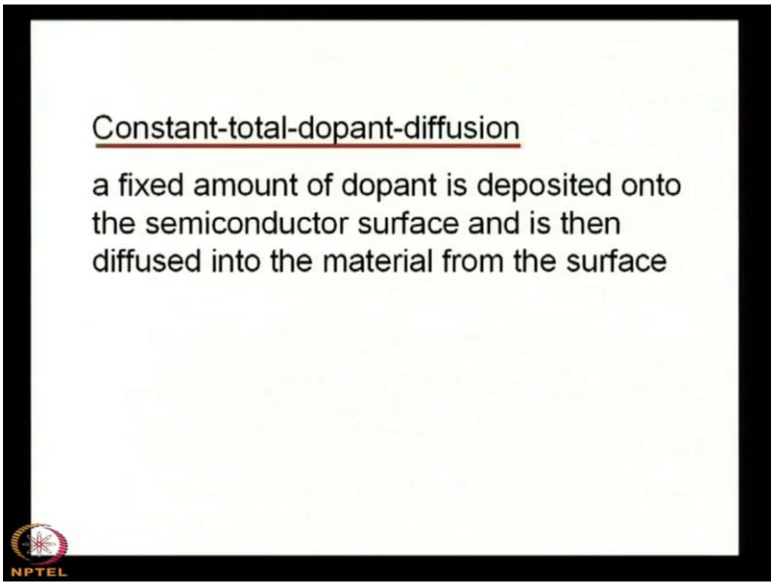

Constant-total-dopant-diffusion

a fixed amount of dopant is deposited onto the semiconductor surface and is then diffused into the material from the surface

Another case is this one please writes down constant total dopant diffusion constant total dopant diffusion. Here you see that a fixed amount of dopant is deposited onto the semiconductor surface and is then diffused into the material from the surface. So, what is the difference between these two cases? 1 is the constant total dopant diffusion and another is constant surface concentration diffusion.

For constant surface concentration as the name implies the surface concentration is same. And, for constant total Dopant diffusion the surface concentration is not same. With time the surface concentration varies basically decreases reduces because a fixed amount of dopant is deposited on to the semiconductor surface, and is then diffused into the material from the surface. So, you are not supplying continuously you are not supplying continuously.

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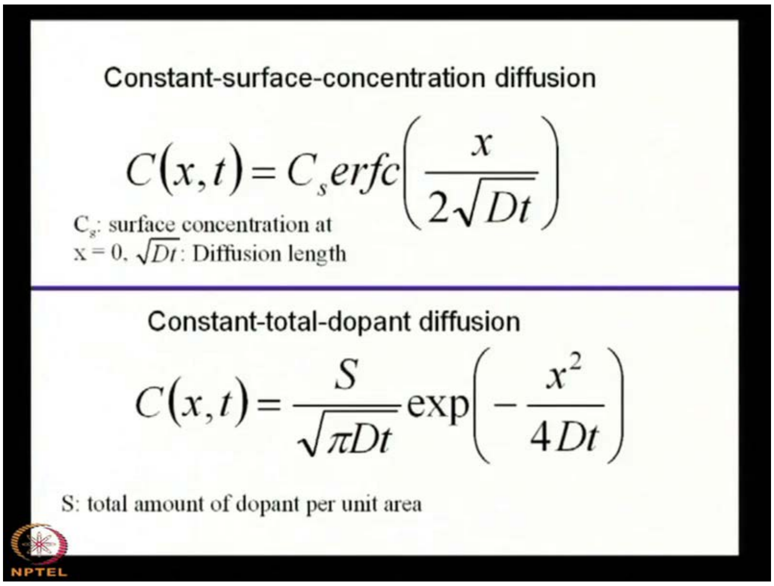

Constant-surface-concentration diffusion

$$C(x,t) = C_s erfc\left(\frac{x}{2\sqrt{Dt}}\right)$$

C_s: surface concentration at
x = 0. $\sqrt{Dt}$: Diffusion length

Constant-total-dopant diffusion

$$C(x,t) = \frac{S}{\sqrt{\pi Dt}}\exp\left(-\frac{x^2}{4Dt}\right)$$

S: total amount of dopant per unit area

So, there are 2 cases and the expression of the diffusion for the 2 cases is different. You see that for constant surface concentration the concentration at any instant of time C(x, t) is equals to C suffix s; s is the surface concentration at x is equals to 0. Then error function complimentary error function x by 2 root over of D t; this root D t is the diffusion length root D t is the diffusion length. Because what is the unit of diffusivity or diffusion coefficient? Centimeter square per second then you multiply by second then centimeter square by second into second. Second goes away it is centimeter square root over. So, it is centimeter.

So, basically root D t is the diffusion length. Root D t it is equals to root over of centimeter square by second multiplied by second; second goes out. So, it is centimeter. So, this is basically the diffusion length; root D t is the diffusion length. And, this is error function and I will show you how the error function looks like if you plot it along x, y. It is like say the exponential function. You know the exponential. And, if you talk about the constant total dopant diffusion, then the diffusion profile is given by s by root over of pi D t. What is S? S is the total amount of dopant per unit area. That means S is put initially S is not changing. Then from S as the time passes the diffusion is taking place.

So, that is the constant total dopant diffusion. And, see what is the difference between these 2? In the next case in the 2 nd case that means when the constant total dopant diffusion is concerned. That means you are not supplying the concentration of dopant continuously then it is given by the exponential function. And, if you supply continuously then it is an error function. So these are two differences.

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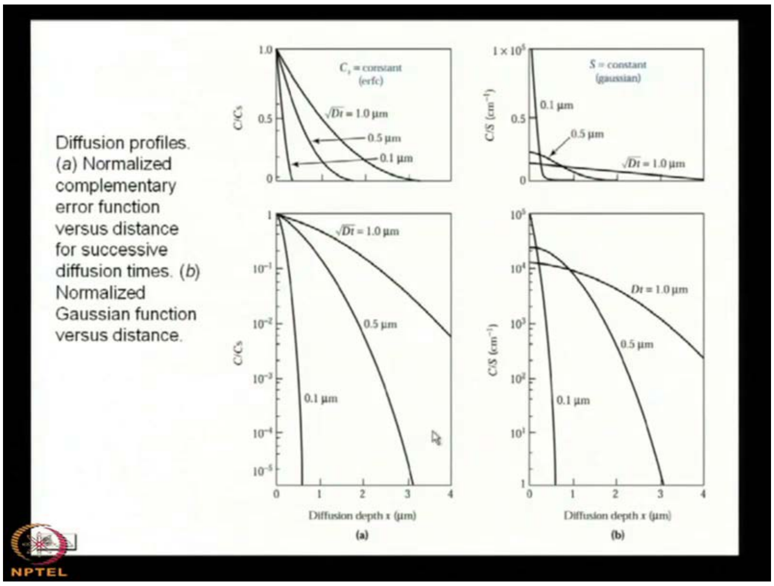

Diffusion profiles. (a) Normalized complementary error function versus distance for successive diffusion times. (*b*) Normalized Gaussian function versus distance.

And, if I plot it you see that the in the first case that means the complimentary error functions the when it is plotted it looks like this type of a figure. That it is C by Cs versus the diffusion depth x that means root D t; on the x-axis it is root D t. And, here it is Gaussian that means exponential something, it is Gaussian. It is also plotted in the x-axis you see that there is a diffusion depth. So, you find from this curve that root D t that means what is root D t? It is a diffusion length.

So, diffusion length you see that it is 1 micron, then it is 0.5 micron, it is 0.1 micron. It is it depends on the time D it depends on the time. Why because we have considered here the D is independent of the concentration. In this case we have considered that D is independent of the concentration. You see what we have written here? You see D is independent of doping concentration D is independent of doping concentration. So this is basically with time.

And, at the onset of our discussion we have mentioned that temperature and time are the main thing which controls those 2 parameters control the diffusion inside the material. And, the depth is controlled by the temperature and the time. So, here you see that the time is different. And, for different value of t you will get different doping depth. That means for t1 it is say 0.1 micron, 0.1 micron from what From the surface, 0.1 micron from the surface. So, if you have started with a 300 micron thickness wafer.

So, that means at the top 0.1 micron it is p then the rest is n-p-n junction. Then if you take the second case it is 0.5 micron. That means from the surface 0.5 micron is say p layer and the rest is n layer. If you have started with a n type semiconductor wafer and you have doped the material with p type. In the third case you see that it is 1 micron. So, that means from the surface is x is 0; from the surface 1 micron is the p layer and the rest is n layer. So, this is the plot.

Now, this is for the constant surface concentration diffusion. That means when you are supplying the same concentration at the surface for the whole duration of doping. If your doping is taking place for 1 hour, throughout 1 hour you will supply the same concentration at the surface. Say the surface concentration you have fixed at 10 to the power 18 per C for 1 hour it will remain at over 10 to the power 18 at the surface. That you can see from here also C by C s is 1.

So, in all the cases it starts from 1, it is normalized curve. So, from for it starts from 1 in all the cases, but in this case you see that it is not same. It is 1 into 10 to the power 5 then it reduces to something say 0.2 then 0.3 etcetera into 10 to the power 5 see that the surface concentration is not same, surface concentration changes. So, this is the difference.

Now, diffusion length; diffusion length means the penetration depth basically inside the material. How long it penetrates from the surface? So, you have this diffusion depth is the basically the material the material is 300 micron thick on the x-axis say it is totally 300 micron. And, it is the surface; 0 is the surface from 0 what is the depth? So, that is here we have used the term diffusion depth.

Student: Sir, depth is there.

No no diffusion length is separate thing. Diffusion depth here it here we should use the term diffusion depth. Yes, not diffusion length. Diffusion length is a different thing.

Student: (( )).

No no. What is that means? That is related to the without collision how far it can go between two successive collisions? The length between two successive collisions that is not important here. It is not important in this case.

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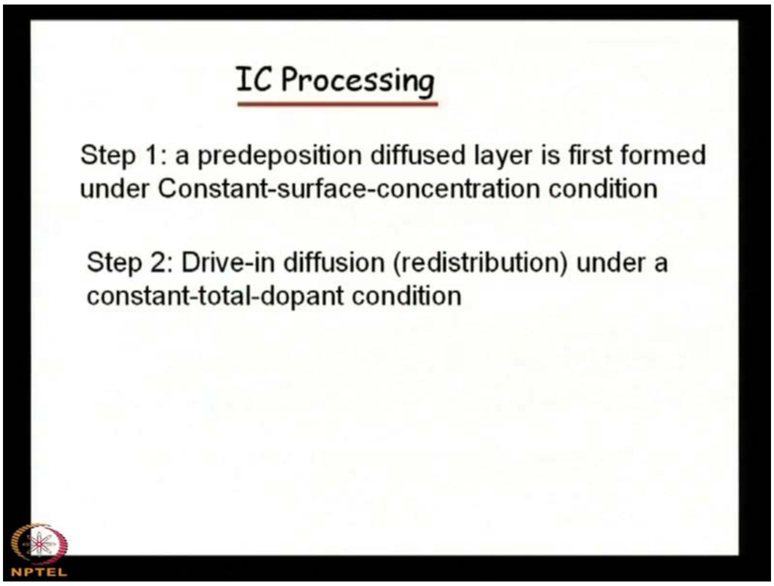

IC Processing

Step 1: a predeposition diffused layer is first formed under Constant-surface-concentration condition

Step 2: Drive-in diffusion (redistribution) under a constant-total-dopant condition

Now, in almost all IC processing; IC means the integrated circuit. For IC processing, step 1 is, it is a two step process. For step 1: a predisposition diffused layer is first formed under Constant-surface-concentration condition. So, that means when a wafer is doped for IC fabrication; IC means integrated circuits. Then, there generally two steps are used. In the first step constant surface concentration conditions is used for a predeposition diffused layer. And, then in step 2 the Drive-in-diffusion under a constant total dopant condition.

That means first we use it the constant surface concentration say for half an hour we use constant surface concentration. That means constantly we are supplying say 10 to the power 18 surface concentrations for half an hour then you remove that source. Now, what is the concentration? 10 to the power 18 then you heat. Drive-in. Drive-in means you would like to drive the impurity atoms inside the silicon wafer. Drive in means basically you would like to drive the atoms. So, why this step 2 is important? You see that if you compare these 2 figures you will find that though the surface concentration is constant; in this case the depth diffusion depth is small compared to the 2 nd case. You see if you compare these two thing then here the diffusion depth is larger here the diffusion depth is larger.

So, for large diffusion depth if you want that it penetrates deep inside the material. Then first you make a predeposition using this one and then Drive-in using this one. Drive-in means the atoms will move inside the material; you would like to drive inside the material. So, that it can penetrate through higher depth larger depth.

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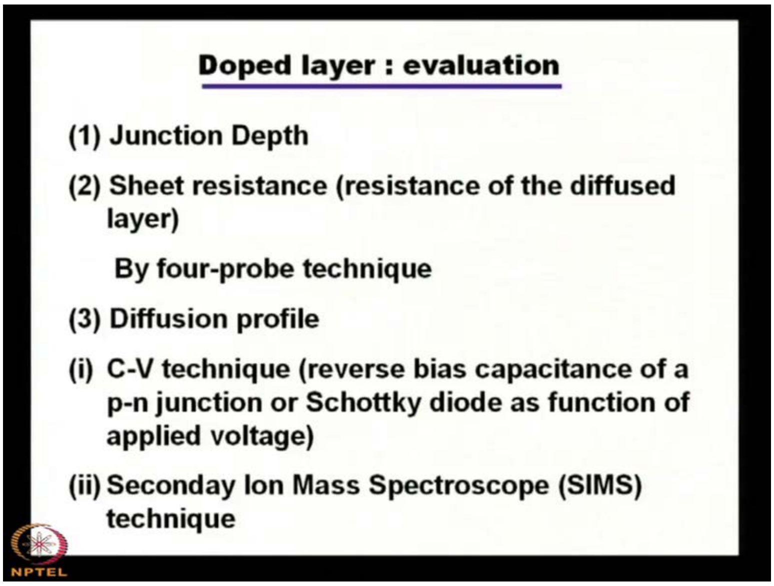

Doped layer : evaluation

(1) Junction Depth

(2) Sheet resistance (resistance of the diffused layer)

By four-probe technique

(3) Diffusion profile

(i) C-V technique (reverse bias capacitance of a p-n junction or Schottky diode as function of applied voltage)

(ii) Seconday Ion Mass Spectroscope (SIMS) technique

So, 2 steps are generally used for IC processing. Now, after the diffusion is made. Suppose this is your wafer and you have made some diffusion say one micron or 0.5 micron whatever the depth be. Then how you evaluate the thickness or the material? How far it has penetrated? What is the depth? What is the carrier concentration? What is the resistivity of the doped layer?

So, evaluation is required because without evaluation you cannot say very confidently that your doping is a valuable one or your doping can be used for some device processing. How you will know? So, there are three important measurements which are done to evaluate a doped layer. One is the junction depth: maybe it is 0.1 micron or 1 micron or 2 micron whatever be the junction depth first you have to measure the junction depth. Second you have to measure the sheet resistance; resistance of the diffused layer and it is made by four- probe technique.

One of the groups have already performed the experiment using four- probe techniques. We shall discuss in this class also in detail about the four probe technique. For time being you consider that four- probe technique is used to measure the resistance of the semiconducting layer. Why we say it as a sheet resistance? Why we use it as a sheet resistance?

It is because if you consider that it is 300 or 400 micron thick then point one or 0.2 or 0.5 or 1 micron of the surface can be considered as a sheet. Considering that the doping is uniform throughout the area surface area. Then you can consider that it is composed of 2 sheets. One is at the top 1 micron doped and the rest is another kind of doping basically it the wafer. So, that is why the sheet resistance the resistance of this sheet of the doped layer.

So, that is why the term is used here as a sheet resistance. That sheet resistance is calculated that means the resistance of the diffused layer and the diffusion profile that means that trajectory whether it is uniform or not. So, that is the diffusion profile and that profile can be done by two methods. One is known as the C-V technique or capacitance voltage measurement C-V capacitance voltage. That means you form a p-n junction or a Schottky diode then you measure the capacitance of the diode as a function of the reverse bias as a function of applied voltage in the reverse bias.

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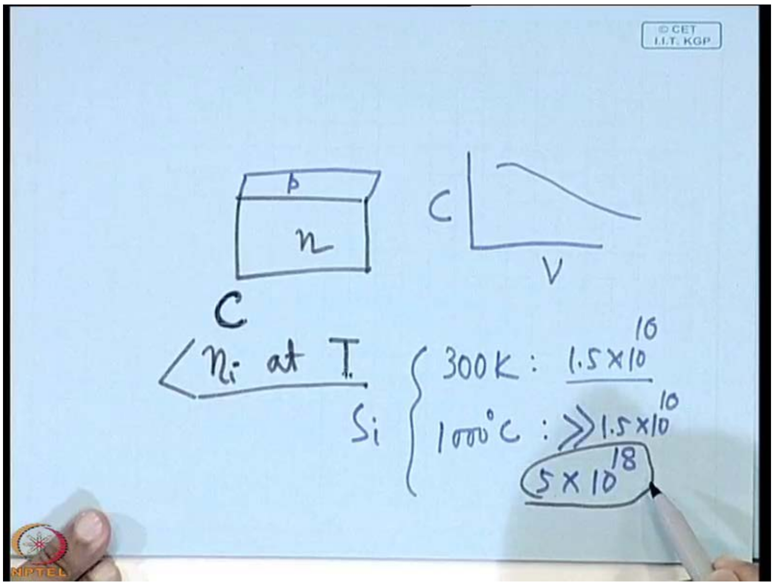

Then, you can plot C versus V that means, you take a material say you have started with a n type material this is 300 micron thick. Then a p type material of one micron thick you have doped using diffusion technique. So, it is a p-n junction, it is a p-n junction there the capacitance of this p-n junction because you know that when there is a junction it will give rise to some capacitance when there is a junction it will give rise to some capacitance any connections also. Suppose we have made a contact with the metal then that contact will give you some capacitance also right.

So, this p-n junction will give you some capacitance junction capacitance. We shall discuss those things in detail when we come into the topic of say a p-n junction diode etcetera. In this cases what will happen? You plot C along y-axis and V along x-axis. So, using a C-V meter that is a capacitance voltage meter it is available you measure the junction capacitance. So, that you can have some plots say any kind of plot you can get; from that plot you can calculate the diffusion profile. Another technique is the Secondary Ion Mass Spectroscopy, Secondary Ion Mass Spectroscopy technique (SIMS), SIMS Secondary Ion Mass Spectroscopy.

So, this is very précised technique and using this SIMS you can show the trajectory of the impurity atom inside the material how it moves and this is also used. So, you see that there are 3 important parameters which must be evaluated. One is the junction depth one is the junction depth, another is the sheet resistance, and third one is the diffusion profile. Now, these two parameters that is sheet resistance and diffusion profile. We has discussed how to measure them though not in detail, but some idea you have received. Now I am giving you the idea of measurement of junction depth. How the junction depth is measured?

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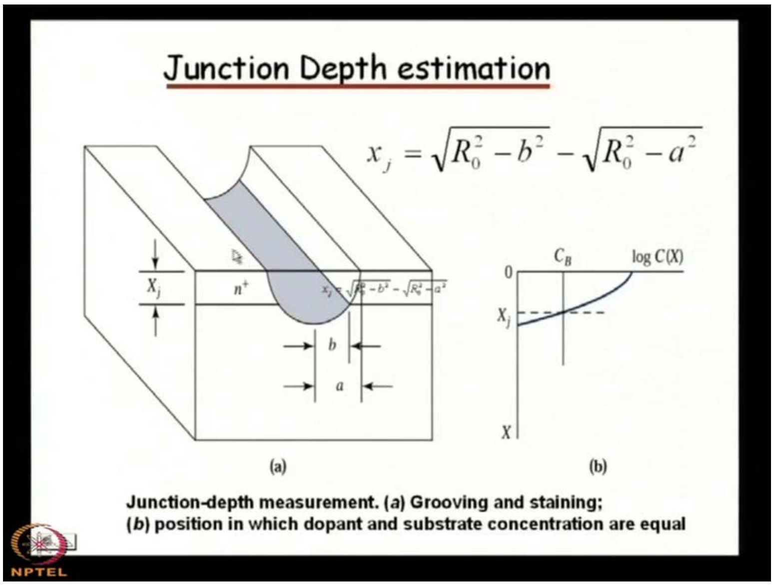

Junction Depth estimation

$$x_j = \sqrt{R_0^2 - b^2} - \sqrt{R_0^2 - a^2}$$

Junction-depth measurement. (*a*) Grooving and staining; (*b*) position in which dopant and substrate concentration are equal

See this is n type layer this is n plus means heavily doped say obviously this is p type. We have started from a p type then it is n type layer. Then what is done a grooving is done grooving is done. Grooving means what is grooving?

Student: Cutting surface.

Yes. Cutting or removing the material by using a tool say a drill machine using a drill machine you can groove a very small trench, cutting a very small trench. So, a groove is done using some tool and then staining is done. Staining basically is coloring, a solution is used and you put the solution then what is the difference? The difference will be that n type region and p type region the color will be different using the stain the color of the 2 regions will be different. So, you can see how long the p type layer or n type layer is there, because as you go from n layer to p layer the color will be different using the stain.

Now, if this is a that means from the centre of this material to the edge the grove it is a. And, if the coloration is at up to b then using this formula you can calculate the junction depth. Now, what is R0? R0 is the dimension of the tool. So, if it is a drill bit then it is the dimension of the drill bit that is equals to your R0. So, you so putting these value you can calculate the junction depth. And see that if you plot log C versus X, what you will find that up to the junction the carrier concentration is decreasing from say this point to that point. And, what is CB? CB is the carrier concentration of the wafer you have started with in a wafer the carrier concentration is constant.

So, if we have started with a wafer of say 10 to the power 17 cc then up to 3000 micron it was 10 to the power 17cc. Then you have made some diffusion say 1 micron. So, the carrier concentration of that 1 micron and below 1 micron will be different because just at the junction below 1 micron what should be the carrier concentration? The carrier concentration of the margin wafer, it will be the carrier concentration of the margin wafer.

We have started with the carrier concentration of the surface till 1 micron depth you have changed using diffusion, but below 1 micron it is the normal wafer of 300 micron. So, this CB this CB is nothing but carrier concentration of the substrate. So, that means if this, is the substrate. So, this dotted line is the junction that means from 0 to x j it is the junction if you consider from the top it is the junction. So, this junction can be measured using grooving and staining right.

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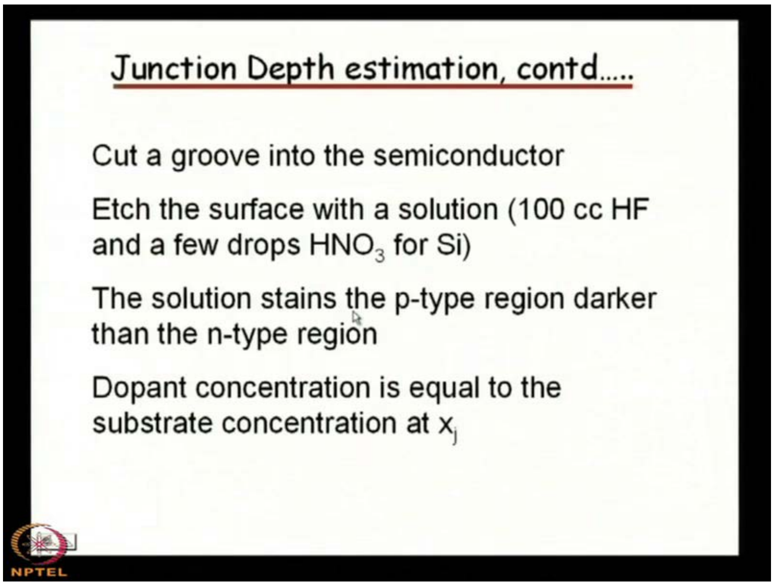

Junction Depth estimation, contd.....

Cut a groove into the semiconductor

Etch the surface with a solution (100 cc HF and a few drops HNO_3 for Si)

The solution stains the p-type region darker than the n-type region

Dopant concentration is equal to the substrate concentration at x_j

So, these are the processes I have enumerated cut a group into the semiconductor h the surface with a solution. The solution is 100 cc HF and a few drops HNO 3 for silicon. For Germanium it will be different; for gallium arsenide it will be different. That means the staining solution the staining solution is different for different semiconductor. For silicon it is 100 cc and a few drops HNO 3, 100 cc HF. So, you mix that will put the in the surface the solution stains the p type region darker than the n type region the solution stains the p type region darker than the n type region.

So, it is n type region this portion is n type. And, inside it is the p type region after grooving. So, the p type region is darker than the n type region. Dopant concentration is equal to the substrate concentration at x j that I have shown you that at x j the dopant concentration and the surface concentration will be the same. That means just dig a tunnel dig a tunnel from the surface mob through 1 micron till 1 micron you will get your diffusion profile. As you complete it 1 micron your normal wafer or the substrate will be there. And, the carrier concentration will be given by the substrate carrier concentration.

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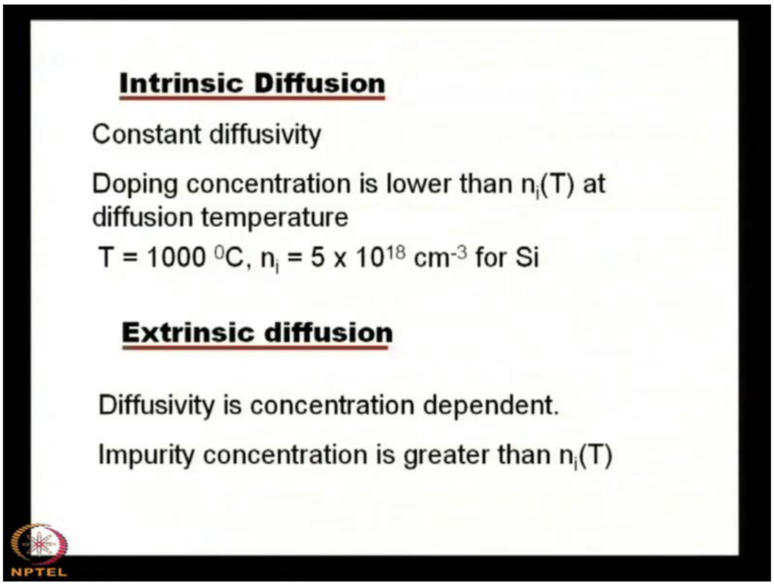

Intrinsic Diffusion

Constant diffusivity

Doping concentration is lower than $n_i(T)$ at diffusion temperature

$T = 1000\ {}^{0}C$, $n_i = 5 \times 10^{18}\ cm^{-3}$ for Si

Extrinsic diffusion

Diffusivity is concentration dependent.

Impurity concentration is greater than $n_i(T)$

Now, this diffusion can be of two types: one is intrinsic another is extrinsic. Intrinsic diffusion means the diffusivity is constant and the doping concentration is lower than n i at diffusion temperature. Let me explain this term intrinsic diffusion means when n i at T and the concentration is less than n i at T. That means the concentration of the doping is less than n i at T; n i at T means, n i is the intrinsic carrier concentration. What is the intrinsic carrier concentration of silicon?

Student: 1.5 into 10 to the power 10.

1.5 into 10 to the power 10 per cc, at what temperature? Room temperature that may 300 T k 300 k yes. 300 kelvin. Now, if you increase the temperature now if you increase the temperature. So, what to what will be the value of n i? The intrinsic carrier concentration also increases it is a function of T it is a function of T. If say at 300 k if say at 300 k it is

1.5 into 10 to the power 10. So, at 1000 degree centigrade it will be very very greater than 1.5 into 10 to the power 10 right.

So, if this carrier doping concentration if the doping concentration is lower than n i at T. That means at diffusion temperature what should be the n i then it is known as intrinsic diffusion otherwise it is known as the extrinsic diffusion. For extrinsic diffusion remembers that diffusivity is concentration dependent. Until now we have considered that diffusivity is not concentration dependent we have considered that that diffusivity is not concentration dependent, but if the diffusion is extrinsic then the diffusivity is concentration dependent.

Now, intrinsic diffusion you see that the carrier concentration at 300k is 1.5 into 10 to the power 10 1.5 into 10 to the power 10. At 100 degree C it is very greater than 1.5 into 10 to the power 10. What is the value? The value is 5 into 10 to the power 18. This is all for silicon it is 5 into 10 to the power 18. So, that means, if you want to dope silicon at 1000 degree centigrade remember the processing temperature is 1000 degree centigrade; then up to 5 into 10 to the power 18 carrier concentration it is intrinsic. If you dope with more than 5 into 10 to the power 18 at this particular temperature then it will be then it will become extrinsic diffusion.

So, it depends entirely on the temperature. If your temperature of processing of doping temperature is 1000 degree centigrade, so you can go up to 5 into 10 to the power 18 for silicon. If it exceeds then it is known as the extrinsic diffusion and in that case diffusivity is concentration dependent. That means as the concentration changes diffusivity also changes but we have not considered that thing earlier.

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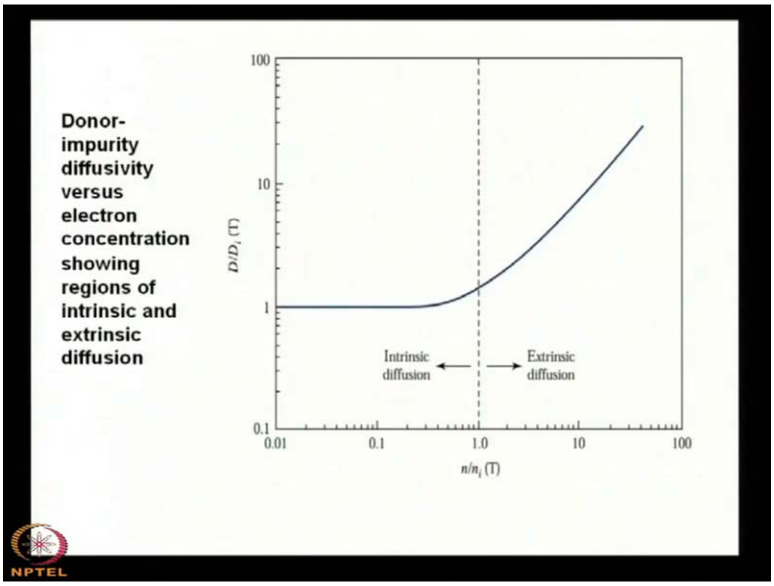

Donor-impurity diffusivity versus electron concentration showing regions of intrinsic and extrinsic diffusion

Yes. This is the donor impurity diffusivity versus electron concentration showing regions of intrinsic and extrinsic diffusion. You see that up to 1 that means D and D I (T); D i (T) is the temperature T is the temperature, D i (T) is the intrinsic diffusivity at that temperature. Till 1 it is intrinsic as soon as it exceeds 1 it is extrinsic diffusion. That means till 5 into 10 to the power 18 it is intrinsic; as it exceeds 5 into 10 to the power 18 it becomes extrinsic.

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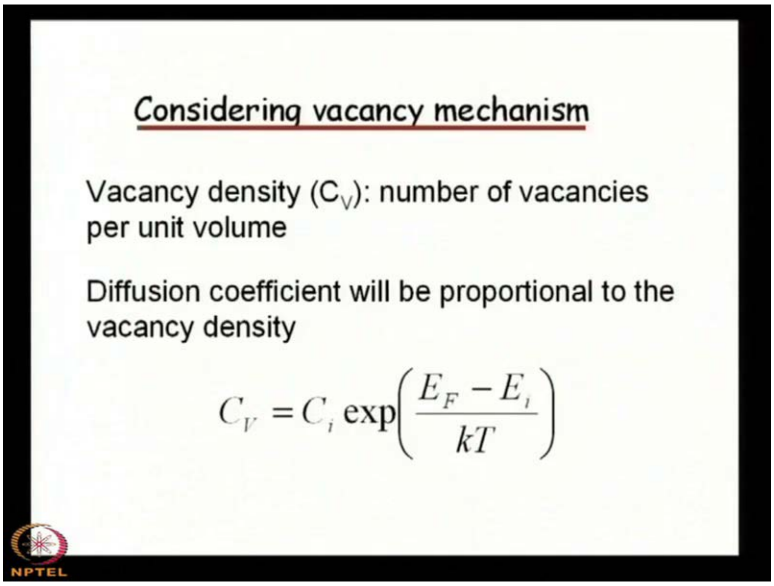

Considering vacancy mechanism

Vacancy density (C_V): number of vacancies per unit volume

Diffusion coefficient will be proportional to the vacancy density

$$C_V = C_i \exp\left(\frac{E_F - E_i}{kT}\right)$$

Now, as the doping is related to the creation of vacancy. If you have more vacancy more and more impurity atom can move into the material because either they will occupy the vacancy position or the interstitial position. Let us consider that they are occupying the vacancy position. Considering the vacancy mechanism; vacancy density is a number of vacancies per unit volume. And, diffusion coefficient will be proportional to the vacancy density that is very important consideration, that the diffusion coefficient is proportional to the vacancy density.

So, CV that means the vacancy density is equals to C i exponential EF minus E i by k T. This type of expression we have already deduced in case of the calculation of the carrier concentration using Fermi level etcetera; can you remember n 0 p 0 equals to n i, p i equals to n i square n i square. So, during that derivation we have this type of mathematics we have used. So, the vacancy density which is the number of vacancies per unit volume it is related to the carrier concentration by this expression.

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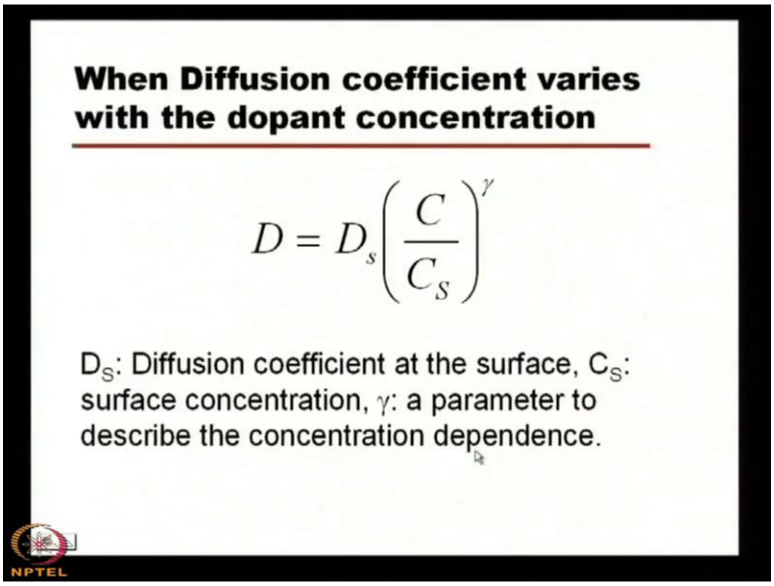

When Diffusion coefficient varies with the dopant concentration

$$D = D_s \left(\frac{C}{C_S} \right)^{\gamma}$$

D_S: Diffusion coefficient at the surface, C_S: surface concentration, γ: a parameter to describe the concentration dependence.

Now, when diffusion coefficient varies with the dopant concentration. That means extrinsic case remembers extrinsic case then it is D equals to D s C by C s to the power gamma. What is C? C is the concentration of the dopant and C s is the concentration at the surface and it is to the power gamma means it is a function of the concentration. That means D is a function of the concentration gamma a parameter to discuss the concentration dependence. When gamma equals to 1, then what happens? When gamma equals to 1 then it is the intrinsic case when gamma equals to 1 then it is the intrinsic case, when gamma is greater than 1, then it is extrinsic case.

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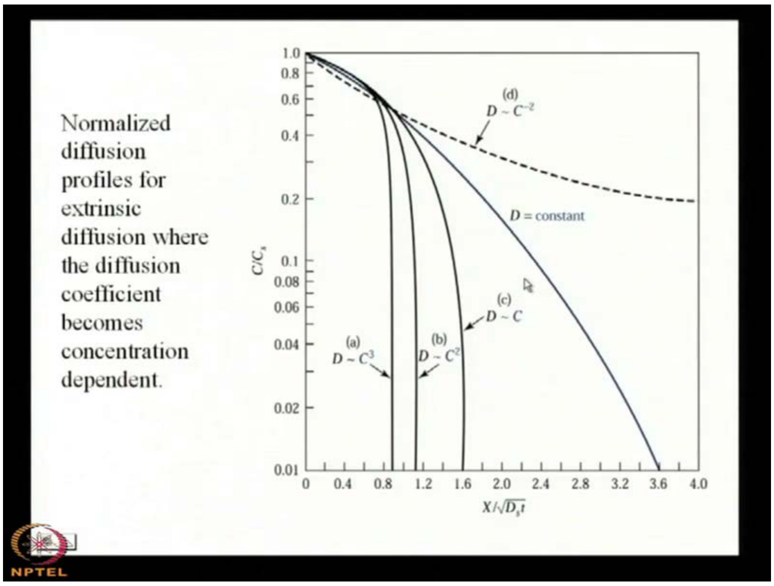

Normalized diffusion profiles for extrinsic diffusion where the diffusion coefficient becomes concentration dependent.

Here you here we have plot the normalized diffusion profiles for extrinsic diffusion where the diffusion coefficient becomes concentration dependent; it is X by root Ds t. You see that curve a, curve a is obtained when the diffusivity varies as the cube of the concentration number. Then curve b, when diffusivity varies as the square of the concentration that means when gamma is 3, when gamma is 2, for curve c the gamma is 1. That means it is the error function it is basically, the error function curve we have shown when it is not concentration dependent. Let me quickly go to that curve. Yes. This curve you see.

This is the error function curve this error function curve means when it is not dependent with the concentration here it is dependent with the concentration. So, when gamma is 1 that means D is a function of C only. So this is the normal curve that should be but depending on the value it can change. Another thing is C when gamma changes at minus 2 when gamma is equal to minus 2, C to the power minus 2 then it becomes concave. These curves are convex type of design this is the concave curve. And, you see that this is applicable for gold or copper in silicon. If you diffuse gold or copper in silicon you will get this type of a profile.

So, depending on the concentration depending on the material these curves changes. So, these are not very uniform thing it changes with the gamma. So, these we have already discussed yes. You see that diffusion in silicon boron and arsenic gamma is 1. When gamma is 1 that means which curve this curve gamma is 1 means this curve C this curve. For gold and platinum gamma is minus 2 concentration profile has concave shape you see that the concentration profile is concave that is the dotted line.

And, for phosphorous it is C square D is proportional to C square. So, you see that it is this type of curve this b type it is very sharp and steep fall is there steep fall is there. If there is a steep fall then what you can predict that it will not move through much distance inside the material because it is the distance in the x-axis it is the distance. So, if this is the very steep fall then the distance will be less; that means the junction will be shallow junction.

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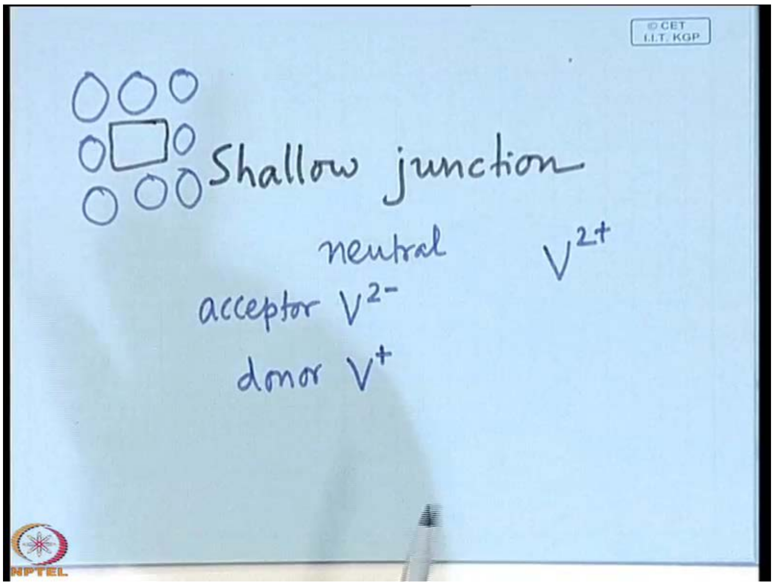

The junction will be shallow junction shallow junction. The junction will not be very depth very deep.

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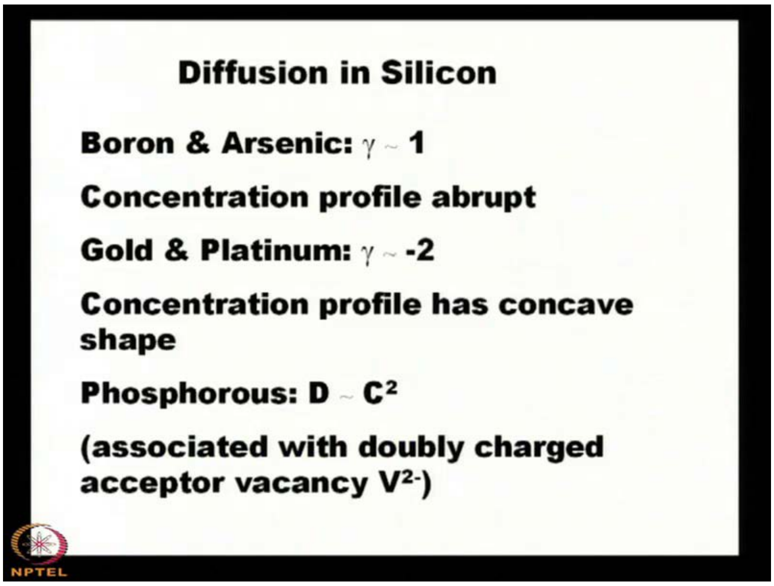

Diffusion in Silicon

Boron & Arsenic: $\gamma \sim 1$

Concentration profile abrupt

Gold & Platinum: $\gamma \sim -2$

Concentration profile has concave shape

Phosphorous: $D \sim C^2$

(associated with doubly charged acceptor vacancy V^{2-}**)**

Now, another thing is that for phosphorous it becomes the diffusivity becomes a function of C square that means the square of the concentration. And one line I have written you see that associated with doubly charged acceptor vacancy doubly charged acceptor vacancy. Now, what is the meaning of this term doubly charged acceptor vacancy? You see that when there is a vacancy when there is a vacancy, this vacancy, this is vacancy this vacancy can be neutral do not think that the vacancy is always neutral it can be neutral it can be doubly charged acceptor vacancy. That means V 2 minus it can be V 1 V plus it can be V 2 plus.

So, different types of charged can be associated with the material associated with the vacancy, vacancy can be neutral it can be acceptor vacancy. This is an acceptor vacancy, this is a donor vacancy, it is donor vacancy, it is acceptor vacancy. Here 2 minus that means doubly charged it is singly charged donor vacancy. So, different kinds of charged state can have a vacancy. So, depending on the charged state the association of the impurity atom will be different.

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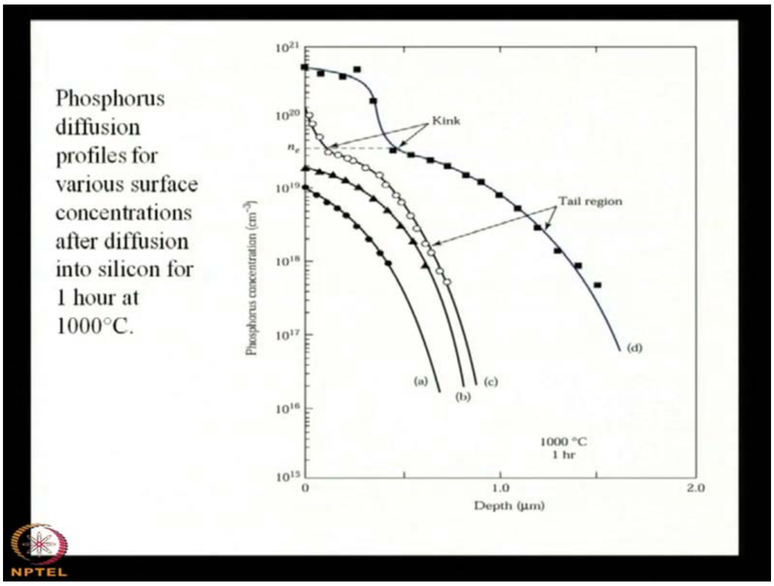

Phosphorus diffusion profiles for various surface concentrations after diffusion into silicon for 1 hour at 1000°C.

You see that in this curve I have shown you the phosphorous diffusion profile for various surface concentrations. The surface concentration is different 10 to the power 19 then 10 to the power 20, 10 to the power 21, it is say 1 into 10 to the power 20. And, sorry it is 10 to the power 19. And, say it is how much? It is 1 into 10 to the power 19 etcetera.

Now, you see that with different surface concentration the diffusion depth is different. This a curve, curve a that means the curve which is the lowest one in this present figure; it is the error function curve. Then as you go on increasing the surface concentration it deviates that means from intrinsic it is becoming extrinsic from intrinsic it is becoming extrinsic.

And, if you go further away from 10 to the power 19 in this particular case of silicon for 1 hour at 1000 degree centigrade. What is the meaning of this term? That means you are doping silicon with phosphorous by diffusion at 1000 degree centigrade for 1 hour. And, you see that there is a kink at ne, ne is the carrier concentration. And, at ne you will find that there is a kink. So, there is deviation there is deviation from the original curve which is the error function.

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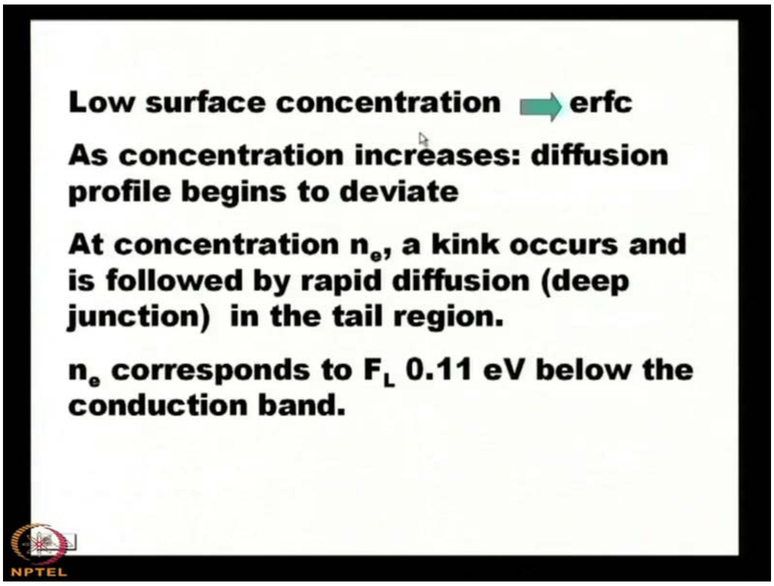

Low surface concentration → erfc

As concentration increases: diffusion profile begins to deviate

At concentration n_e, a kink occurs and is followed by rapid diffusion (deep junction) in the tail region.

n_e corresponds to F_L 0.11 eV below the conduction band.

And, why there is a kink in this case. Kink is because at concentration ne a kink occurs and is followed by rapid diffusion that is deep junction in the tail region. You see rapid diffusion that means rapid diffusion means, this is the tail region it is the rapid diffusion. And, this deep junction deep junction means? If you can calculate this portion you will see it is more than 1 micron, it is 1 micron and this tail is more than 1 micron, it is 1.5 micron.

So, if you compare with this figure it is less than 0.5 micron and it is greater than 1.5 micron that means it has penetrated deep inside the material. So, as a surface concentration increases there is a kink. And, after kink there is a rapid diffusion in the tail region which gives you the deep junction deep impurity level that means it is well below the surface layer. And, when low surface concentration is there it is the error function at as concentration increases diffusion profile begins to deviate we have seen. And, this ne that means where the kink occurs you see that it corresponds to fermi level 0.11 electron volt below the conduction band. What is the implication of this term? 0.11 electron volt below the conduction band.

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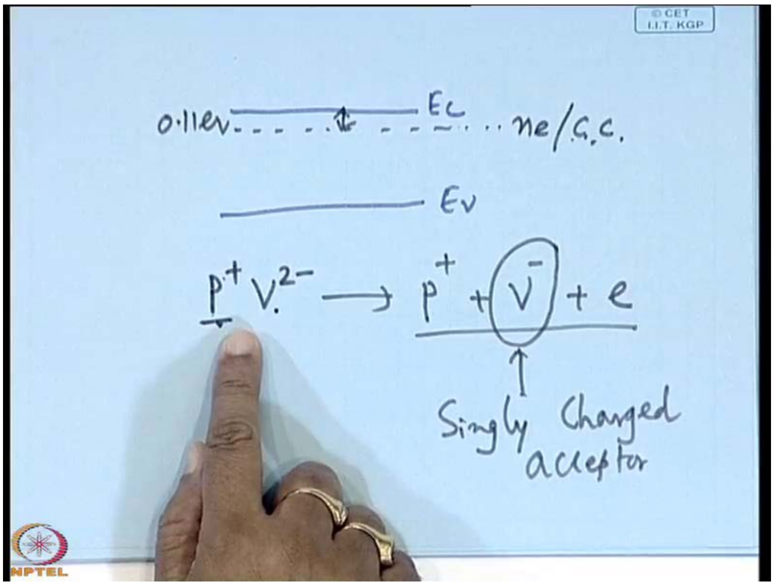

You see that we have already discussed that the situation say it is your conduction band edge, it is your valence band edge. And the position of the fermi level will give you the concept of the doping concentration. If it is in the middle then what is the doping concentration it is intrinsic. Then as it go towards the bottom of the conduction band that means no no that means It is increases the electron concentration increases the electron concentration increases.

Now, suppose this is electron concentration ne per cc that means there is a Fermi level. These Fermi level will give you the value of ne and it is 0.11 electron volt below the conduction band. It is 11.11 electron volt below the conduction band. At this conduction band energy for at this fermi level what happens actually. It dissociates the vacancy along with the phosphorous atom they form a couple then at this energy they dissociates.

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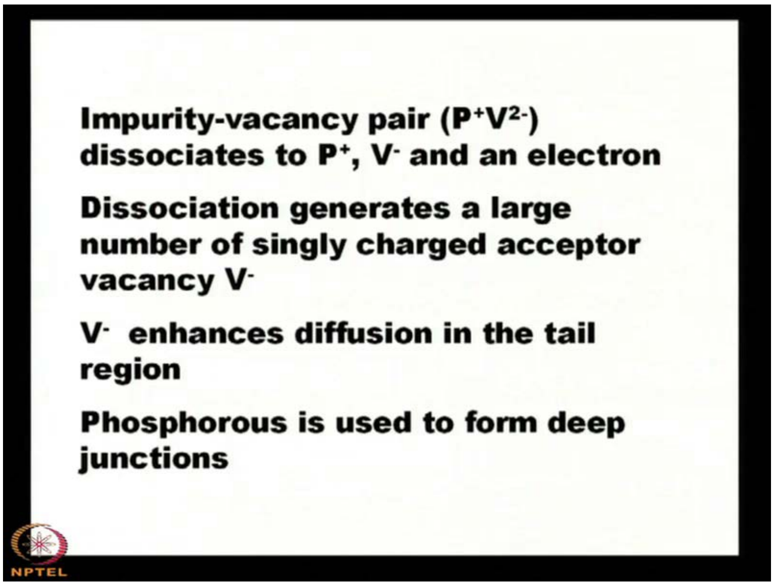

Impurity-vacancy pair (P^+V^{2-}) dissociates to P^+, V^- and an electron

Dissociation generates a large number of singly charged acceptor vacancy V^-

V^- enhances diffusion in the tail region

Phosphorous is used to form deep junctions

They dissociates into what? Impurity vacancy pair dissociate to phosphorous ion. Then this is singly charged vacancy acceptor and an electron. That means this is this P plus V 2 minus. How we get it? We get it from the occupation of the phosphorous in the vacancy P plus V 2 minus.

That means the phosphorous atom was in the vacancy having doubly charged acceptor. These dissociates into these species. What you see? That this is what is this this is singly charged acceptor singly charged acceptor. So, as it dissociates because of the effect of dissociation you will get many singly charged acceptor. So, if there is singly charged acceptor what it implies the diffusion will be more diffusion will be more. There is a vacancy basically this is singly charged acceptor. What is singly charged acceptor? This is the charged state of the vacancy. So, that means first the phosphorous, occupies a doubly charged site and at energy 0.11 electron volt it dissociates. It dissociates into electrons and V minus that V minus is a singly charged acceptor.

So, now for each of this case you will get V minus sites. So, if there are many V minus sites. So, that means the diffusion will be very rapid it will attract more and more phosphorous. So, under such a circumstance what will happen? The diffusion will be very fast, there will be rapid diffusion and it will go deep inside the material and there will be no kink. The kink comes for this reason only then the kink breaks away because kink is due to this P plus V 2 minus. Kink is due to this thing at this concentration ne which is due to 0.11 electron volt below the bottom of the conduction band. And, as it get the energy at that energy what happens? It dissociates into electron singly charged acceptor and phosphorus ion.

This will enhance the diffusion. So, that means I can tell you that singly charged V minus that means the acceptor enhances diffusion in the tail region. And, phosphorus is used to form deep junctions, that means there must be taker phosphorus is there, but who will take phosphorus inside the crystal lattice. Inside the crystal matrix there must be some host. Who is the host? V minus is the host in this case.

Since the host is there so phosphorous will diffuse very rapidly and deep junctions will be formed if we use phosphorous. So, that means there are several considerations. What is your purpose of doping? If your purpose of doping is to form the deep junction you use phosphorous in silicon. If it is shallow junction then the consideration is different. So, depending on your purpose you have to choose the right material the temperature and the time. So, this is all about the diffusion. And, one thing I must add till now we have discussed about silicon.

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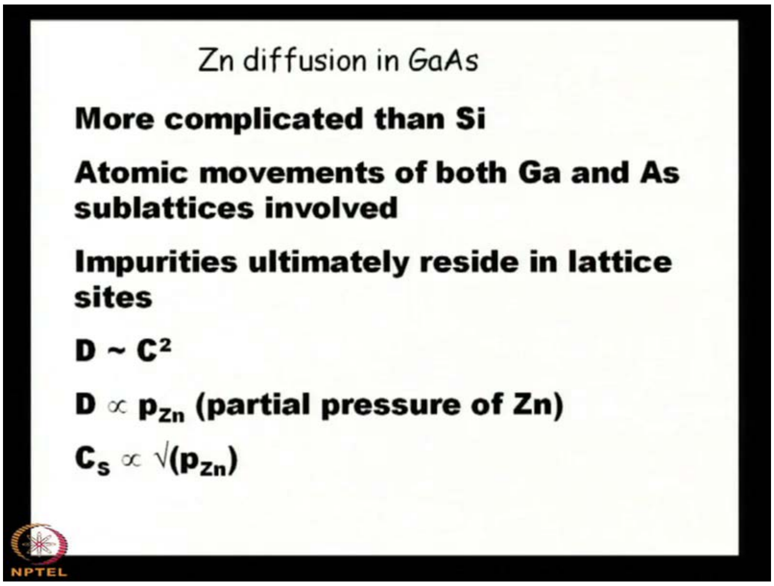

Zn diffusion in GaAs

More complicated than Si

Atomic movements of both Ga and As sublattices involved

Impurities ultimately reside in lattice sites

$D \sim C^2$

$D \propto p_{Zn}$ (partial pressure of Zn)

$C_s \propto \sqrt{(p_{Zn})}$

Now, what will happen to gallium arsenide? Because normally we give the examples of silicon and gallium arsenide. One is the elemental semiconductor, another is the compound semiconductor. When you see that zinc diffusion in gallium arsenide it is more complicated than silicon. Why it is more complicated than silicon? Because in silicon matrix only silicon is involved atom of silicon is involved. Here both gallium and arsenic sub lattices are involved. Impurities ultimately reside in lattice sites where the impurity will go it ultimately. We will use the lattice site either the site of gallium or the site of arsenic either the site of gallium or the site of arsenic.

So, now you see that zinc diffusion in gallium arsenide it becomes p type. First thing you remember that it becomes p type and the diffusivity varies as C square not C or C cube generally it varies as C square. And also diffusivity is proportional to the partial pressure of zinc We have discussed about the partial pressure. And, the surface concentration is proportional to the square root of the partial pressure right. So, if you put you will see that basically D proportional to C square that means the curve will be steep it will not do very deep inside the material, it is steep.

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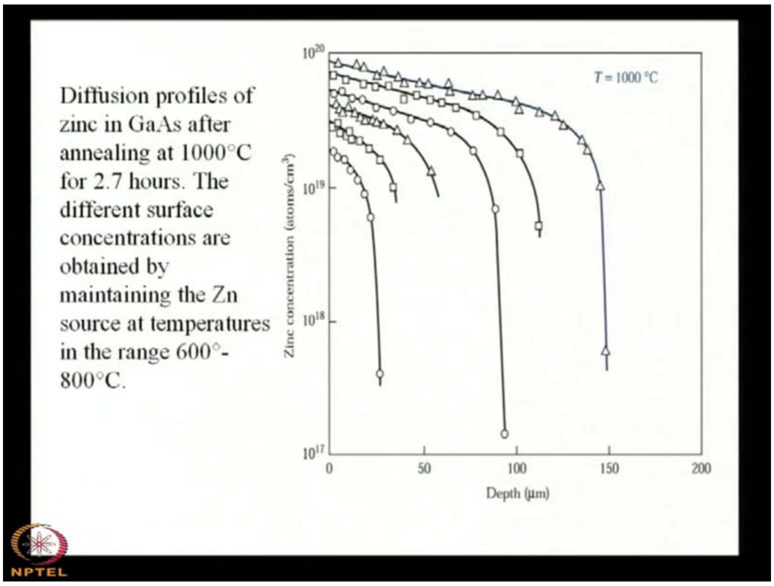

Diffusion profiles of zinc in GaAs after annealing at 1000°C for 2.7 hours. The different surface concentrations are obtained by maintaining the Zn source at temperatures in the range 600°-800°C.

And, it is the profile you see that the profile because of various surface concentration. It is the diffusion profiles of zinc in gallium arsenide after annealing at 1000 degree centigrade for 2.7 hours. It is different for different surface concentration and temperature. So, now we can conclude for today’s lecture. That generally you need a site either it it will be the vacancy or it will be interstitial. And, the energy is much for the vacancy type diffusion not for interstitial site diffusion. For interstitial site diffusion the condition is that the atom will be dimensionless than the, the atomic dimension of the crystal lattice host, host crystal lattice.

So, thank you for today again we shall assemble on Thursday.