

Fabrication of Silicon VLSI Circuits using the MOS technology
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Lecture 20
Ion Implantation

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$R = \frac{1}{2kN} E_0^{1/2} \approx 20 \sqrt{E_0} \text{ \AA}$

We have used $k_{si} = 2 \times 10^{-16} \text{ eV}^{1/2} \text{ cm}^2$

And again $R_p = \frac{R_{es}}{1 + \frac{M_2}{3M_1}}$

Some Data:

	Z	M
1. Phosphorous	15	30.973
2. Arsenic	33	74.92
3. Aluminium	13	26.98
4. Boron	5	10.82
5. Indium	49	114.82
6. Silicon	14	28

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Anyway we were looking for implants and let us go back a little bit. We said that the, if the implanted energy is more than E_c or less than E_c , then the stopping will be either nuclear or by electronics, electronic stopping. And we will be able to calculate the range from that formula. Okay, typically it is also found that the range may not be in the direction of ions where they come actually straightway. They will be somewhere randomly situated. So there is a range which is at an angle with the incident angle.

So that, in the same direction which ion is reaching, that range is called projected range or it is $r \cos \theta$. θ we have calculated where it goes, okay. So we roughly know where will be the actual projected range. Using the analysis it has been found that typical range due to electronic stopping or any range is divided by $1 + \frac{M_2}{3M_1}$. And this is the range normally will be given to you in the graph sheets.

If you have those graph sheets, you will find there will be graph for range against energy. Range against energy. And this range is essentially R_p , projected range. Also there we discussed last

time that there will be some Gaussian distribution. And since Gaussian distribution is the probability function which is the normal distribution, we will be able to calculate what is the reliance or the standard deviations.

Just for the sake of this data we have given to you, just I have given idea that phosphorous, this is atomic number, this is atomic weight. Please remember these numbers are actually in atomic mass units. We will have to convert it to gram, okay, or gram per mole by using the real number as well as the 9.1, if the per gram you have to calculate. Okay, so maybe I gave that data exactly if you wish. But that is the number you should remember.

So one can see from here that arsenic is very heavy, so is phosphorous is okay. But boron is the lightest element, okay, boron is the lightest element. So when I am implanting boron and if I am implanting arsenic, the ranges will be different. And that is the fun part in that. In most cases boron will be stopped by electronic stopping and in the most cases of arsenic it will be nuclear stopping.

So we will show this, this is what I thought the numbers when I wrote. That the mass decides where they will go and rest. The probability function which all of you should know but I will just, I will hurriedly go through this.

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Probability: i $f(x)$ is Gaussian with mean m is $= \int_{-\infty}^{+\infty} x f(x) dx$

ii Standard deviation $\sqrt{\sigma^2}$ is given

$$\sigma^2 = \text{expt. value} [(x-m)^2]$$

$$= \int_{-\infty}^{+\infty} (x-m)^2 f(x) dx$$

$$= E(x^2) - 2m^2 + m^2$$

$$= E(x^2) - m^2$$

Peak value of $f(x)$ is $\frac{1}{\sqrt{2\pi}\sigma^2}$ at $x=m$

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma^2} \exp\left[-\frac{(x-m)^2}{2\sigma^2}\right]$$

$f(\sigma) = 0.606 P$
 $f(2\sigma) = 0.135 P$
 $f(4\sigma) = 1.81 P$

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There I am expecting you to know this. If $f(x)$ is the Gaussian function with a mean value m , then m is equal to minus infinity to plus infinity, $x f(x) dx$. And the standard deviation σ which is we calculate σ^2 , essentially is the expectation value of $(x-m)^2$. And if I write expectation value which is essentially $\int (x-m)^2 f(x) dx$, that I can expand this $(x-m)^2$ as $x^2 - 2xm + m^2$.

Expectation value of $x f(x) dx$ is m , so it will come minus $2m^2$ plus m^2 . So it is $E(x^2) - 2m^2 + m^2$. Now we have probability theory once again, little bit of signal processing first time in our course. So essentially σ^2 is expectation value of $(x-m)^2$ minus expectation value of $(-2xm + m^2)$. m^2 means expectation value of x^2 , so it is $E(x^2) - 2m^2 + m^2$.

So that is the number which is called standard deviation. Essentially what we are seeing, in a profile up to where the width we will have to calculate of what σ value to. This is 2σ . From the mean value each deviation is σ . So we want to know that x is equal to σ , how much is the concentration has gone down. That is the standard deviation and some values if you wish, if this is your pick value, then $f(\sigma)$ is $0.606 P$ essentially.

$f(2\sigma)$ is $0.135 P$, $f(4\sigma)$ is $1.81 P$. And where peak is the peak value of this function which is essentially if I substitute here, then it is $\frac{1}{\sqrt{2\pi}\sigma^2}$ at x is equal to m . Where $f(x)$ is Gaussian, $f(x)$ is Gaussian which is $\frac{1}{\sqrt{2\pi}\sigma^2} \exp\left[-\frac{(x-m)^2}{2\sigma^2}\right]$.

minus m^2 upon $2\sigma^2$. This is the Gaussian profile. σ is the standard deviation and m is the mean value. And this essentially gives you the Gaussian profile.

So one can see when I put x is equal to m , this becomes 1. So it is only 1 upon 2π , under root $2\pi\sigma^2$ is the value of f at the mean value, that is the peak value. What is the peak value? 1 upon root $2\pi\sigma^2$ is the peak value. Why I am interested? Because whenever I actually push ions inside the material, I will like to know, how many things I will like to know? What is the peak value, what is the deviation and where is the mean value. Okay. If I know then, I know everything about the numbers which I want to calculate.

So this is maths which I hope most of you should know or must be knowing. I hope almost every one of you know it. But in case there is a good probability theory in communications, even in maths book, one can go and verify again. This is what I remember. So I wrote down but just check, if I may not have made any mistake because this is all trivial. The height will increase, actually 1.81 I do not mean, I think I made a mistake. What I essentially means it will start increasing σ because as you go down for σ , then this value.....

“Professor-student conversation starts.”

Student: (())(6:50).

Professor: No, no, you did not get the point. If I calculate somewhere here, this value will be higher than this value. Its width will be higher. As you go down and down, so at infinity it is infinite, very large width. σ is infinite.

“Professor-student conversation ends.”

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The implantation process puts ions (atoms) below the surface and these ions come to rest at points which leads to Gaussian distribution. The Gaussian Profile is given by

$$N(x) = \frac{N_s}{\sqrt{2\pi} \Delta R_p} \exp \left[-\frac{1}{2} \left(\frac{x - R_p}{\Delta R_p} \right)^2 \right]$$

Here i ΔR_p is standard deviation called Straggle.
& ii R_p is mean range and is called Projected Range.
iii Peak concentration $N_p = N(R_p)$

The total ions/atoms implanted per unit area is called DOSE $N_s = \int_{-\infty}^{+\infty} N(x) dx$ & $N_p = \frac{0.4 N_s}{\Delta R_p}$

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Now let us come to our process. This maths you can verify again. Now let us think what we were doing. Since the implantation process puts ions and essentially when the charge goes away, its atoms below the surface and these ions come to rest at points which leads to Gaussian distribution. That is what still got. This is the random numbers. Some ions are hitting their target or the silicon surface and they can get inside and lose their energy by number of interactions.

It can be either nuclear stopping or it could be either electronic stopping depended on the energy of ion you start with. So the profile which is given for Gaussian profile for the implanted system is N_s upon root 2 pi delta R_p . Delta R_p is that sigma, is called straggle. The word used for sigma here is straggle. Straggle of an implant. So it is delta R_p , exponential minus half x minus R_p square. R_p is the mean value. Delta R_p square, so we have now this Gaussian profile.

I normally will be knowing how much dose I was putting which I can calculate otherwise. So I know or I will measure actually. So I know my N_s . For given energy I also note R_p and delta R_p , which data I will have. Which means I will be able to find N_x function as x. What is N_x against x, the profile. So I should be able to know the profile of impurities inside silicon by knowing the dose of impurities I pushed in and what is the R_p and delta R_p or energy at which they were implanted.

So that is how I actually get my impurity profile inside the semiconductor. Please remember the total ions per atom square which is the dose, is essentially whatever is the area under the cover

for N_x , is the total amount as impurity per unit area. Is that correct? N_x , dx , minus infinity to plus infinity is the dose. If I substitute this here, I can calculate the peak value of concentration, is related to dose by this formulation, $0.4 N_s$ by ΔR_p .

So I will be able, if know N_s , I also know peak value. What is peak value? At x is equal R_p , whatever is the value, this value. $1/\sqrt{2\pi}$ is 0.4, so $0.4 N_s$ by ΔR_p essentially is the peak concentration. So whatever I know for, I need to know for a profile. I roughly know everything of it. And once I know the profile, what is the advantage of knowing a profile? I will be able to then find out for a given Poisson's equation how many charges are there.

And therefore I can calculate the current densities. At the end of day I am interested in continuity equation and Poisson's equation solving. And to do this, I need to know the number of possible ions or atoms per C_c , per square, C_c as well everywhere profile as such. And only then my simulator can do. Normally what we assume, uniform doping. But it may not be actually uniform, it may be a profile there and must evaluate using every, so you must have to put a grade, see how much is the variation you can give. Finer grade or if you are doing finer difference.

If you are looking up final element, then you have to create triangles which you are very close so that the field does not change very much. So anyone who is looking into simulation can, you need to know N_x value anyway in your simulator. And therefore this is an essential part to know what is the N_x function I am going to get. Is that correct? R_p will be larger or smaller with E depending on what? The mass. Not just the energy but for the mass.

Heavier items maybe having smaller R_p because they will actually interact right there at the surface and may stop. Whereas lighter ions will have small knockout like Ping-Pong ball it just goes through and can go longer. So it is very funny system. The range of a lighter ion is longer than heavier ions, is that clear to you? Because the stopping is different in both cases. So this is something you have to understand.

Heavier atoms actually come, rest very close to the surface whereas lighter atoms go deeper. So which will go deeper in case of normal impurities? Boron, arsenic? Boron, so boron is the larger profile. So what you, if I want smaller range, what should I do? Energy I must reduce for boron. Whereas if I want deeper implant on arsenic, I must increase the energy for that. Is that correct?

But that energy should not be large enough compared to the, you see that it does go to electronics catering then.

So one has to keep worrying how much energy for which kind of specie I should use to get a profile of my choice. Is that clear? Profile of my choice. So in implant what are the parameters I will control? The energy of implant, okay and I will also, amount of dose. How much atoms per Cc I want to push into and what kind of profile then I get for. This is the what I will look for an implant.

Now can you see it is similar like diffusion? Even diffusion we got the profile. What was the difference between this and diffusion? In the case of diffusion what was surface concentration? Solid solubility when error function but if the source is removed, then it is as per the, how much time you do, correspondingly surface concentration will decrease. It flattens. Same thing is happening. But the surface here has smaller concentration.

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The implantation process puts ions (atoms) below the surface and these ions come to rest at points which leads to Gaussian distribution. The Gaussian Profile is given by

$$N(x) = \frac{N_s}{\sqrt{2\pi} \Delta R_p} \exp\left[-\frac{1}{2} \frac{(x - R_p)^2}{\Delta R_p^2}\right]$$

Here i ΔR_p is standard deviation called Straggle.
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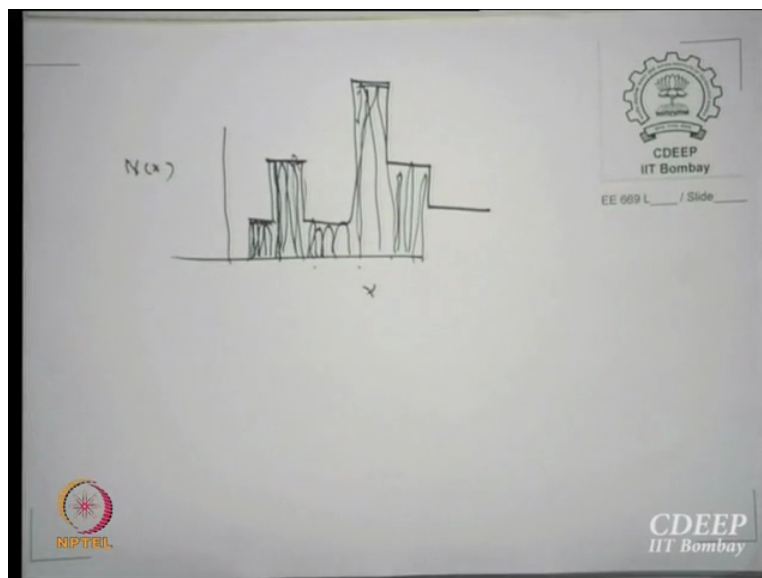
The Gaussian profile, this is say silicon. You are implanting from here. The profile will be something like this. This is my x direction. So this surface is away from the peak, is that clear? The difference between diffusion and implant. So what do I do if I want to make this peak coming to the surface? Okay, so what I will do is I will somehow manage. Of course I will not show how and which, I will put some other material which has roughly similar sigma for both.

And most of it goes into the other part which is oxide or anything insulating and the peak comes closer to the silicon surface. So I can tailor my profile by adjusting the thickness of the insulator between implant and silicon. Is that clear? So this is how profiles are actually monitored where do I want peaks actually. Where do you think peak should be normally, at the surface or away? So there are two kinds if it is reduced.

One is called buried channels, the others are called surface channels. I think professor Vasi will explain you much better. And in buried channel it is better to have implant profile down. So the surface concentration is very low. The most of the concentration is much below. So BT is adjusted below side and not on the surface. Wherein surface channels I want BT to be adjusted from surface itself. So there is an issue there because if the control from the gate has to be done, surface is easiest to control.

So if you are not looking for purity actions, buried channel may be very good. So depletion transistors are normally buried-channel devices. Whereas normal MOSFETs are always surface channel devices. Is that point clear to you? So this has to be understood. We need such kind of profiles. Also the other day someone was saying and I think he did it right.

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If I want arbitrary profile, let us say N_x versus x , I want this very random profile I want which is upside but maybe I need it. Some reason you are very good simulated people, you decide, I will just feed this profile and see what happens. Maybe something great may happen. So if that

happens, I will say okay, do not worry. What I will do is I will do multiple Gaussian profile with energy such that it is a very sharp peaks and their depth is decided by energy.

As I reach this point, I will increase the dose overlapping Gaussian profiles. So the envelope of all this similarly are here, similarly here. If I keep doing energy and dose, I will be able to create any arbitrary profile. Is that clear? By adjusting energy and dose, and do multiple implants, overlapping implants so that I get another profile which is what you were, actually arbitrarily I want this profile. Okay. So what is the biggest advantage implant provided? That it can create a profile of your choice.

You decide from a device side. Suddenly I want some impurity the low here like LDD we wanted do. So here is the possibility I can reduce concentration selectively at a distance. So this is something what you should know that why people look for implants. But everything is never good, so we will say why implant is not as good as everyone said. So 99 percent, all VLSI technology uses only implants.

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The Implantation process puts ions (atoms) below the surface and these ions come to rest at points which leads to Gaussian distribution. The Gaussian Profile is given by

$$N(x) = \frac{N_s}{\sqrt{2\pi} \Delta R_p} \exp \left[-\frac{1}{2} \frac{(x - R_p)^2}{\Delta R_p^2} \right]$$

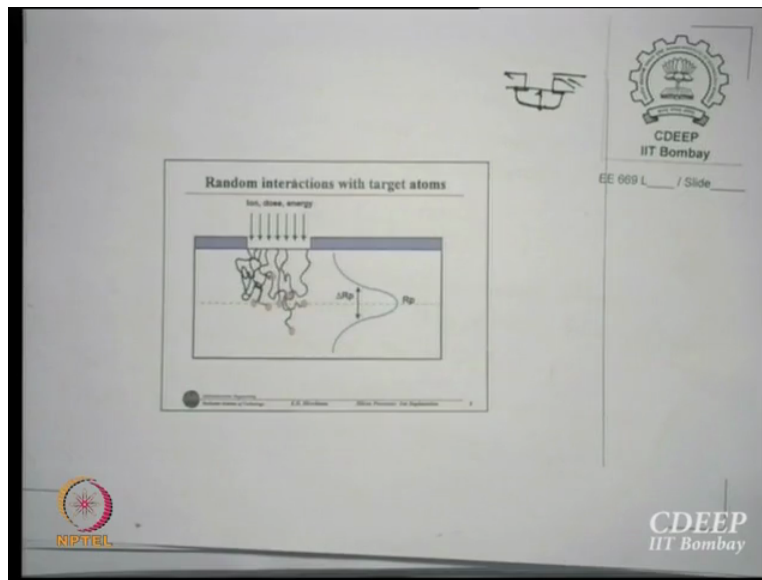
Here i ΔR_p is standard deviation called Straggle.
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So this profile, do you see what is the way it was? Last time I did show you or maybe I just, okay, there is a figure which I want to show you.

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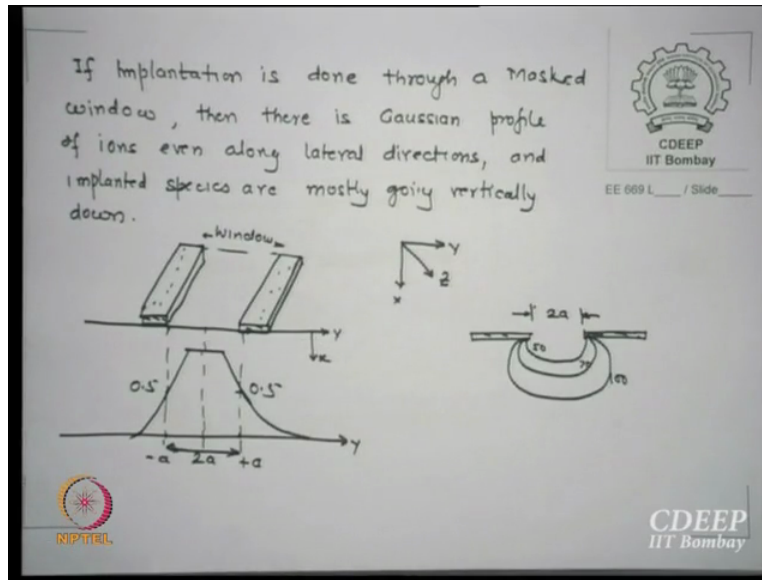
This was the figure which I last time showed you that this is the kind of profile you will get, is not it? This is the implant, this is silicon and this. Now you see at the figure very carefully. There is a mask material here. Okay and we expect no implant be possible through that. So there is a window in which I am doing implantation. And my assumption is all ions are only getting vertically down or x axis as I said.

And therefore I get a profile along x axis or vertically down. But in real life whenever you do a mass kind of implants using a mask, there is a lateral profile also is possible. Is that clear? Like in diffusion the impurities not only go down but also laterally. There I probably forgot the lateral junctions are $0.8 x_j$. Whatever happens in the window this in case of diffusion, so actually you see this, if this is your x_j , this additional diffusion is $0.8 x_j$ both sides.

So $1.6 x_j$ is actually getting inside. Is that clear to you? So it is sometimes good because if it is the channel length, it reduces. The lateral diffusion actually reduces the channel length, good for you but there is punch through problem. So there another issue may appear. So this essentially is what we keep saying to you that in diffusion is isotropic. What is isotropic word? All directions. It does not see which direction.

Though since the ion energy is downward, the maximum will travel on the downward side. But they still can interact on the sideways. Because they will hit, some may go. Now if they go through this window, this is an important thing because this is real life what will happen.

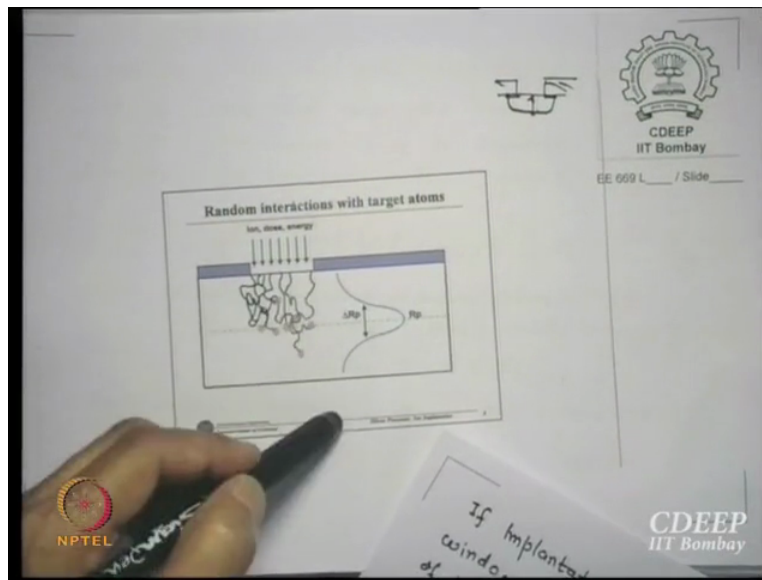
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You will actually do implantation through a profile or a window, mask window. Let us say this direction is x, this direction is y, and direction along the lawn is z. Now we see, let us say the window has a distance between the two lines. These are mask areas. You could do here fully also. This is $2A$ and this center point is A , so we say 0 to minus A , 0 to plus A and it is symmetric on the right hand and left side. Is that point clear?

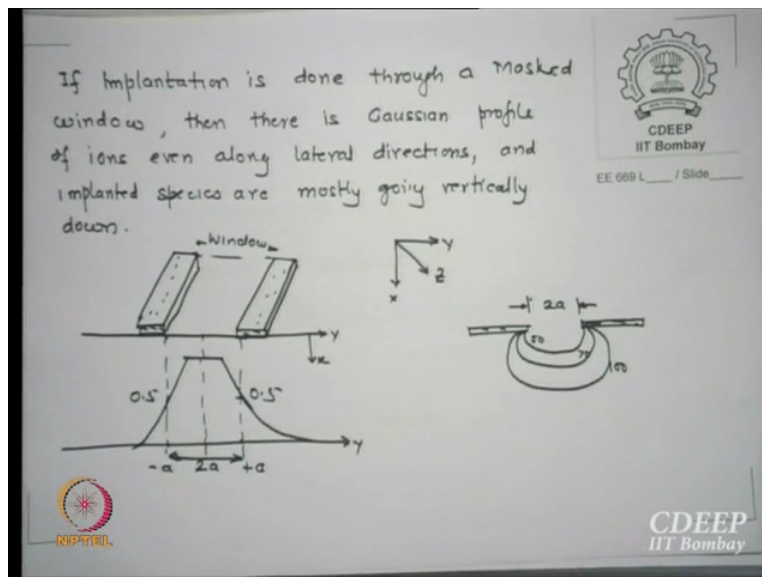
If I take 0 in the center, the profile is symmetric to plus A side and minus A side. And the way I look at it, somewhere here I again see Gaussian, error function profile. And I do not see Gaussian profile because during this source was available. And source is available for a certain distance only, that only. So during this, this profile will also appear on the y side, is that correct? The earlier version where it was? Only on the x side.

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This is x, so profile was like this.

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Now I am showing the profile which is along the y directions as well. This is called transverse impurity getting in, transverse. Ion is coming vertically, transverse way they also go. Why I, what is, why did they happen? It is isotropic process. Major ions will go vertically but some may interact and go laterally, transverse way and they will also give you equivalent what we call straggle, the equivalent change there, deviation on left and right side.

Without going into full maths which is available in the paper which if you wish I will give it tomorrow. I forgot to write down. This figure is given in every book, just that you see what, A it is 50 percent, okay. At the edge and then it goes down.

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Then

$$f(x,y,z) = \frac{1}{(2\pi)^{3/2} \Delta R_p \Delta x \Delta y} \times \exp \left[-\frac{1}{2} \left\{ \frac{(x-R_p)^2}{\Delta R_p^2} + \frac{y^2}{\Delta y^2} + \frac{z^2}{\Delta z^2} \right\} \right]$$

We assume $\Delta y = \Delta z = \Delta R_t$ - Transverse Straggle

$$N(x,y,z) = \frac{N_s}{\sqrt{2\pi}} \exp \left\{ -\frac{1}{2} \frac{(x-R_p)^2}{\Delta R_p^2} \right\} \left\{ \frac{1}{\sqrt{\pi}} \operatorname{erfc} \frac{(y-a)}{\sqrt{2} \Delta R_t} \right\}$$

For $y \gg a$ $\operatorname{erfc}(\infty) = \sqrt{\pi}$

Okay, just look at it. The profile now is 2 pi to the power 3 by 2 and now assumption is delta y and delta z are identical. Whatever is here is also happening on the z plane. Is that clear? This side and this side also. Main is x but it goes like this and it also goes z direction. And my assumption is since the window is same and only the lengths are too different which may happen some case, the lateral as well, I mean transverse as well as orthogonal to that will be same values assumptions.

So we assume delta y is delta z and the profile now is half x minus Rp by delta Rp square, y square upon delta y square, z square upon delta z square. If I write delta y by delta z is equal and that number I call transverse straggle. What I call that? Transverse straggle. So assumption is this side and this side it is same. So if I now do this analysis, this profile, now I get is Ns by root 2 pi, exponential this is my normal Gaussian profile along the x direction.

And y and z, I equated them now. So 1 upon root pi, compliment error function y minus a, root 2 times delta Rt. X upon 2 root Dt, we recall that error function profile x upon 2 root Dt, same function. Now this is one can see from here. If y is very very larger than a, far away from a, what

does that mean? Error function infinity is root pi. Error function, compliment error function of infinity is root pi. Root pi, root pi cancel, so that what is that I am trying to say?

Away from the edge of the window very close to it, it has effect as long as y is less than a , there is a straggle going on. But far away there are no impurity transversing. Is that clear to you? So y is A plus minus here there, they really have transverse R_t s. Whereas away from it, we do not look for it because this function says that y is larger than, much larger than a . They are based for terminal become 1. 1 means? Normal Gaussian profile will start taking only on the x direction. So initially you may find impurity like this but as you go down it is normal Gaussian profile.

Is that clear? So only at the edges there is additional R_t comes, at near the window edge. Below that it does not. That is what we are saying, is that clear? So this delta R_t graph also will be given to you. Energy against transverse straggle, energy against projected range and energy against straggle has been evaluated both experimentally and by PSN formulas. And those values, graphs have been already, will be (availa) are already available on the our webpage. So you can download whenever you need.

And one has to use them always to calculate R_p , delta R_p and delta R_t in case I actually specify you the window size. Then you must do that, that means I am already asking you to take care of delta R_t . If I then specify which essentially I mean neglected. Okay, then I assume as if this is always one for you.

Otherwise net profile should be something, this normal profile into this complimentary fraction and which is only at the edge it will be effective. Other places it will not be effective. So this is how actually implanted profiles are modified whenever I do mask implants. I have area and I implant through, top through a window. Then this may occur. Many times these values are not so crucial because delta R_t s are much smaller. But if delta R_p itself is small, smaller energies, then probably you should look for delta R_t also.

So it is, most cases I do not use R_t s. But if the profile is shallow, then I think they will actually effective. The other thing which modifies the profile is another thing. After all when you do implant, you push some impurities per centimeter square giving a profile N_x . You push some dose or impurities and they distribute and they found Gaussian profile, fair enough. But once I had a profile, no other impurity implant is stopped now, there is no additional ions coming.

Now the vapor may still see large amount of thermal cycles because this implant may be that third stage in the processing and you may have to go another 30-40 step in which at least 8 may be thermal steps. So what will happen? These impurities, the Gaussian profile, you keep driving it. What will happen? The profile will start flattening and flattening. Equivalently saying in Rp what is changing? Delta Rp will keep on increasing. So I say okay, I will add Dt product to delta Rp for any additional Dt effective I use. So here is what I do.

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Drive-In of Implanted Impurities.

Thermal Cycle after implant, just flattens the Gaussian profile, which essentially means that one will have lower peak conc. and larger standard deviation σ or extra ΔR_p

We know that Diffusion distances $\propto \sqrt{Dt}$

Hence the new Profile is

$$N(x,t) = \frac{N_s}{\sqrt{2\pi} (\Delta R_p^2 + 2Dt)^{1/2}} \exp \left\{ -\frac{1}{2} \left[\frac{(x - R_p)^2}{\Delta R_p^2 + 2Dt} \right] \right\}$$

where Drive-In is performed at temp T , where $D = D(T)$ and time of Drive-In is t .

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I say I had a Gaussian profile. I know peak and peak concentration will not change. Why it will not change? Because once the implant has reached, atoms have reached there, they cannot change. But as you increase thermal cycles, they will start spreading. They will start going deeper and deeper by diffusion. That number can be taken care through this formula which is delta Rp square plus 2Dt. Dt is effective, it can be D2T2 plus D3T3 plus D4, any number of time, temperature, cycles you go through, total Dt product will appear here.

And why I made it Rp square? Because Dt is centimeter square. So delta Rp square plus 2Dt to the power half, because I want actually range in 1 upon root Rp. So those similarly I substitute here, delta Rp square plus 2Dt. Do you recollect same thing we did in the case of Gaussian profile with driving going again and again. Same, there is no difference between this. So whenever I will go through thermal cycle of an implanted profile, I will actually reduce what?

What are things will change? The peak concentration will keep on reducing because the impurities are fixed, they cannot be changed now. Area under the curve is dose which is fixed. So if you flatten this profile, peak will go down. However delta, straggle will change or standard deviation because flatness, sigma will change. Sigma here is delta Rp was initially plus whatever thermal cycles you go through, that much value will get added to this. Is that point clear to you? So Gaussian profile with a diffusion going through is the actual profile which you get. Is that okay?

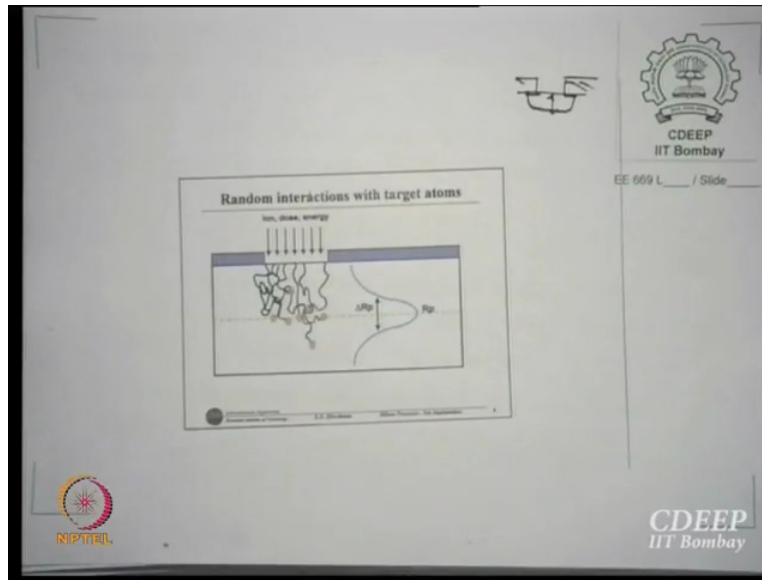
So this is very important that in real life as I say the first implant will come from channel stoppers, we will show next time. And after this channel stopper implant has been done, maybe second mask, I will go through at least 6 implants and 12 at least hitting cycles. So every time I do this, the earlier profile also will keep on changing. Whether it is very effective change I need or whether it will do lot of harm which I can see from my requirement, otherwise that profile will keep on modifying as I go through thermal cycles. Is that point clear to you?

So this is very very important in the case of actual, that is the difference between diffusion and implant is this. A surface concentration is not at the surface. Sorry, its peak concentration is not at the surface. That can be made and I showed you how. By putting something elsewhere, rest of the profile on this side and surface appears. So I can modify position of P by my choice. Is that clear? That is also doable.

This is particularly I am giving them. Those who are doing device simulation can think of actually arbitrary profile. I want slight differ, I want peak here. I want 10 percent down. Make any profile, implant can actually generate for you that profile. Anyway, what you do? You do not do anything. You only give the variation and one by one it will solve for you. It may take some time you to solve but it solves the final difference most cases and then it takes time. But that does not matter. So is that point clear?

Any implanted profile going through a thermal cycles will produce additional Dts to that and that should be added to the initial straggle. This is how the profile will get modified. Now one, just now I said you something and that now I want to show. If I am implanting something, have you noted down this?

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There is something, this violet colored mask has been shown here, maybe oxide, maybe photo, there is maybe anything through which no ions are going through, is that clear? But ions are very high energy particles, ions. So why are they not going through this? They will go everywhere. They had no such choice, this material, that material. Or that what we are saying that this material will have a range which is much smaller than the thickness I provide. So nothing goes below that. Or even if it goes, its just tail goes. Some small amount may go but that tail goes.

But this itself I can use for my advantage, tail. So I can have mask of photoresist. Photoresist is very good mask, why? Anyone? General photoresist is made of what? Resins, those carbon chains. Huge carbon links are there. So when the ions come, they actually will find many sides to interact. Is that correct? So they will actually go, they will not go deeper. They will be actually stopped by resist in much thinner thickness because they will go randomly inside left and right before going deeper because they lose energy.

Now this lose energy is what we are looking for. So I can have a mask of photoresist, I can have a mask of silicon dioxide, I can also a mask of silicon nitride and I can also have a mask of metals. It can be gold, tungsten, platinum, vanadium. Gold, vanadium is used.

“Professor-student conversation starts.”

Professor: Where do you think vanadiums are used?

Student: As a catalyst.

Professor: No, not as a catalyst. Vanadium is a metal sheet. Now it is used, I am not denying. Vanadium sheets are used in all space application ICs. All package of ICs are actually on the top there is a thin vanadium sheet is (bla), why did they put that? Stop the ion implants. Ions which are, the space is having a huge high energy radiations. To stop that getting in, they put vanadium. So vanadium is excellent mask. Vanadium is excellent mask for ions, much heavier ions, protons. It can stop most of them.

“Professor-student conversation ends.”

Of course if the energy is too high, you require much thicker vanadium sheets. Typically in a mass mission, 27 kilograms of vanadium sheets are used. You can now think what is the issue. If I had geostationary satellite for TV transmissions or other wireless applications, if my satellite takes 27 kilograms, 1 transponder, I do know whether you know exactly between transmitter and transponder, think of it. One transponder weighs roughly around 6 kgs to 8 kgs.

Now if I say this 27 kilograms of sheet which I put, I make it thinner than half. But my circuit below is such that it does not change its characteristic even with the dose it receives now. That is called red hard circuits. For the remainder 13 kilograms I will have another transponder, 400 million dollars annual fees hai ek transponder hire karneki. So red hard circuits are made because I want to remove the vanadium sheets as much as I can, of course fully I will never because I do not trust my technology will stand. So at least 50 percent chance I will take. That is why we call red-hard circuits.

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Masks for Implantation:

1. Photoresist
2. Silicon dioxide
3. Silicon Nitride
4. Heavy Metals like Gold, Tungsten, Platinum & Vanadium.

We take 'd' as thickness of the Mask-layer (In Fig. it is SiO_2) ions can be stopped in SiO_2 if d is large. However some 'tail' of Profile will allow a few impurity dose will enter Si.

Hence we can find 'd' for a given Stopping dose.

The diagram shows a cross-section of a mask layer (SiO₂) of thickness 'd' on top of a silicon substrate. Three arrows representing ion dose enter from the left. The dose profile is shown as a curve that starts at zero at the surface, rises to a peak within the SiO₂ layer, and then decays exponentially as it penetrates into the silicon substrate. The area under the curve in the SiO₂ layer is shaded with diagonal lines and labeled 'Dose in SiO₂'. The area under the curve in the silicon substrate is shaded with horizontal lines and labeled 'Dose in Silicon'. The total thickness of the mask layer is labeled 'd'.

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Let us say how do I know how much is the thickness for a resist I should have so that the below that whatever goes into silicon is smaller. I decide how much I want. This is called blocking capability. So how the blocking numbers are given. If the total dose is N_s and 6 nines blocking I want. What does that 6 nines means? 99.9999 percentage. That is the amount of impurity which has gone in, divided by the total impurities per centimeter square I pushed in. That ratio is the percentage how much I can block. Is that clear?

Smaller gone in, the total out of how much gone, that is the percentage I have declared. So I may block 1 nine, 6 nines, I may block 4 nines. I may decide how much I can tolerate. If you want 8 nines, it will be even more problem because then you allot it, this has to be adjusted. Thickness should be proportional. So why we needed it? We want to know how much blocking I have. How do I calculate? I will calculate those which goes into silicon.

I know how many impurities, integral I can always be. I will tell you how to get that. Once I get this, N_s I anyway know because that I started with. I say I want so many percentage of blocking, so I know q . If the q is the dose gone in, and N_s is the total dose, q by N_s percentage I know. Is that correct? If I know this, by implant profiles I will be able to tell you how much d I should I have so that this much blocking is possible. Is that clear to you what I am saying?

So many ions per centimeter square pushed in, I put thickness at some material where most of it stay and very small amount goes into silicon. The ratio which I allow decided by my blocking

capability I want, I want this mask should have 6 nines blocking. Or it has 89 blocking. So if I adjust my blocking, then I know how much is the thickness of that material I should have in terms of energy, in terms of blocking capability and specie which you are implanting.

For each specie, it will be different because their ranges are different. So we will have to figure out for each material. For silicon you may have another material and you may have another ions. So they you will have to figure out how much for that. So essentially I am now saying I can decide the thickness of the mask layer by deciding the blocking percentage I want. Is that clear? So here is the maths I do. Is that clear what I am doing?

I am pushing ions, I put some layer in. I right now showed SiO2 but can be any other material which any among them. And then the rest which is goes into, because it is Gaussian profiles. So part is called tail and so tail is going into silicon.

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If Q is the residual dose of ions in Silicon after being mostly in Mask material of thickness d , then

$$Q = \int_d^{\infty} \frac{N_s}{\sqrt{2\pi} \Delta R_p} \left[-\frac{1}{2} \frac{(x-R_p)^2}{\Delta R_p^2} \right] dx$$

We define $y = \frac{x-R_p}{\sqrt{2}\Delta R_p}$, then $dy = \frac{1}{\sqrt{2}\Delta R_p} dx$

Also $x=d$ $y(y_0) = \frac{(d-R_p)}{\sqrt{2}\Delta R_p} = y_0$ $x=\infty$ $y=\infty$

$$\therefore Q = \int_{y_0}^{\infty} \frac{N_s}{\sqrt{2\pi} \Delta R_p} (\sqrt{2}\Delta R_p) \exp[-y^2] dy$$

$$= \frac{N_s}{\sqrt{\pi}} \int_{y_0}^{\infty} e^{-y^2} dy = \frac{N_s}{\sqrt{\pi}} \left[\int_0^{\infty} e^{-y^2} dy - \int_0^{y_0} e^{-y^2} dy \right]$$

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Let us say Q is the residual dose. Residual means whatever has gone in the silicon out of total is the residual. Then I know the profile of Gaussian profile. How do I calculate Q ? x now it does not start with 0, x starts with d . So d to infinity, this is in silicon. d to infinity, this is in silicon. Q is the dose available in silicon. Silicon start from x is equal to d and not x is equal to minus infinity. It starts from x is equal to d .

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Masks for Implantation:

1. Photoresist
2. Silicon dioxide
3. Silicon Nitride
4. Heavy Metals like Gold, Tungsten, Platinum & Vanadium.

We take 'd' as thickness of the Mask-layer (In Fig. it is SiO₂)

ions can be stopped in SiO₂ if some

tail impur

Hence we can 'd' for a

If Q is the residual dose of ions after being mostly in thickness d, then

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Just check this figure. From d to it goes in.

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If Q is the residual dose of ions in Silicon after being mostly in Mask material of thickness d, then

$$Q = \int_d^{\infty} \frac{N_s}{\sqrt{2\pi} \Delta R_p} \left[-\frac{1}{2} \frac{(x-R_p)^2}{\Delta R_p^2} \right] dx$$

We define $y = \frac{x-R_p}{\sqrt{2}\Delta R_p}$, then $dy = \frac{1}{\sqrt{2}\Delta R_p} dx$

Also $x=d \Rightarrow y(d) = \frac{d-R_p}{\sqrt{2}\Delta R_p} = y_0$ & $x=\infty \Rightarrow y=\infty$

$$\therefore Q = \int_{y_0}^{\infty} \frac{N_s}{\sqrt{2\pi} \Delta R_p} \cdot (\sqrt{2}\Delta R_p) \exp[-y^2] dy$$

$$= \frac{N_s}{\sqrt{\pi}} \int_{y_0}^{\infty} e^{-y^2} dy = \frac{N_s}{\sqrt{\pi}} \left[\int_0^{\infty} e^{-y^2} dy - \int_0^{y_0} e^{-y^2} dy \right]$$

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So I say d to infinity, $N_s \sqrt{2\pi} \Delta R_p$, ΔR_p . $x - R_p$ square upon ΔR_p square dx. I integrate that. This is the profile. $N_x dx$ is the dose, is that clear? Integral $N_x dx$ is the dose. But dose where? From d to infinity. Not minus infinity to plus infinity but from d to infinity. For people who want to know much, as far as the (40:52) you do like this. This is how I do it. I substitute y is equal to $x - R_p$ upon $\sqrt{2} \Delta R_p$. Then I differentiate it. So Δy is 1 upon $\sqrt{2} \Delta R_p dx$.

At x is equal to d , y is d minus R_p upon $\sqrt{2 \Delta R_p}$ which is I call y_0 . And at x is equal to infinity y is infinity. Is that okay? I want to know this in terms of new parameters. You all change x to y naa? So when x is equal to how much is y , and x is infinity how much is y ? Okay, so we calculate at the limits. y_0 to infinity, $N_s \sqrt{2 \pi} \Delta R_p$, now this $2 \sqrt{2 \Delta R_p}$ exponential minus y square dy . Is that correct?

So I just changed from x minus R_p square into y terms. So if I do this, N_s is constant, $\sqrt{2}$ will cancel. So ΔR_p will cancel. So N_s upon $\sqrt{\pi}$, y_0 to infinity e to the power minus y square dy or essentially this. But any finite value to infinity can be written as what? 0 to infinity minus 0 to d . The rest, is that clear? So I now break this y_0 to infinity as 0 to infinity e to the power minus y square minus this, minus 0 to y_0 e minus y square dy . Is that okay? I could have directly written from here but I thought maybe I will show how it is done.

(Refer Slide Time: 42:55)

$$\text{or } Q = \frac{N_s}{\sqrt{\pi}} \left[\frac{\sqrt{\pi}}{2} - \frac{\sqrt{\pi}}{2} \text{erf}(y_0) \right]$$

$$= \frac{N_s}{2} [1 - \text{erf}(y_0)] = \frac{N_s}{2} \text{erfc}(y_0)$$


$$= \frac{N_s}{2} \text{erfc}\left(\frac{d - R_p}{\sqrt{2 \Delta R_p}}\right)$$

$$\text{or } \frac{2Q}{N_s} = \text{erfc}\left(\frac{d - R_p}{\sqrt{2 \Delta R_p}}\right)$$



$$\text{or } d = R_p + \sqrt{2 \Delta R_p} \text{erfc}^{-1}\left(\frac{2Q}{N_s}\right)$$

If we say, we need 6 nines Blocky (99.9999%) in Mask,
 then Dose in Silicon = $\frac{Q}{N_s} = 0.000001$

$\frac{2Q}{N_s} = 0.000002$



 EE 669 L / Slide

So Q , is that okay? Everyone has noted down. So Q is equal to N_s upon $\sqrt{\pi}$ but 0 to infinity e to the power minus y square dy has integral which is $\sqrt{\pi}$ by 2 . The other ones, 0 to y_0 e to the power minus y square dy , is an integral which is $\sqrt{\pi}$ by 2 error function y_0 . It is error function y . That is how error functions are defined. So I write $\sqrt{2}$ I will take it N_s by 2 , 1 minus error function y_0 which is N_s by 2 complementary error function y_0 .

Maybe we should put like this not to get confused. But what is y_0 ? d minus R_p upon $\sqrt{2 \Delta R_p}$. So substitute by y_0 , so $2Q$, Q is equal to N_s by 2 complement error function d minus R_p

upon $\sqrt{2} \Delta R_p$. Then I do little maths. I take 2 in this side, N_s back, so $2Q$ by N_s is complimentary error d minus R_p upon $\sqrt{2} \Delta R_p$. Is that clear? Just there. Or to say d , why we are doing all this?

I want to know the d . For what values? Q by N_s value I will decide which is blocking. So for that how much d I should have for given energy which will decide R_p and ΔR_p . So I write, readjust the terms, so I get d plus $\sqrt{2} \Delta R_p$, complimentary error function inverse $2Q$ by N_s is d . Complimentary error function inverse are $2Q$ by d minus R_p upon this which is essentially R_p plus $\sqrt{2} \Delta R_p$, compliment error function of this.

Now this is, so what should we do now? If I say I want 6 nines blocking, what does 6 nines means? 99.9999. This is the blocking I want. So Q by N_s is how much? 10 to the power minus 6. But I want $2Q$ by N_s and this is the catch, the error function term has to be evaluated for $2Q$ by N_s and not Q by N_s . This is the only catch in all that analysis. So $2Q$ by N_s is 0.000002. This is complimentary error function inverse. So how do I calculate the this value?

1 minus error function inverse of that is this. So what do I do? I subtract this from 1. So I get 0.999998. And for which I go on the error function table and find the value of x there which will be inverse of complimentary of $2Q$ by N_s . Is that clear? This is $2Q$ by N_s . This is complimentary word going on, so 1 minus this will be error functions. So you subtract 1 out of, 1 from, this from 1, so you get 0.999998.

Look for error function table. The error function values against x and see for this value how much is x . So this value I can obtain. I obtain this value for a given energy R_p on ΔR_p are known to me. So I know how much is thickness of the material I wish. The only catch I did something. Can you tell me what is the catch word in this? Maybe I will show you this later. So is that point clear to you? How to calculate d .

So I will give a blocking. I say 4 nines, then how much it will be? 99.99. So 10 to the power minus 4 but into 2. Subtract from 1 and 0.9998 only will come. Go on error function table, for this error function value how much is x , that will be this value. Then for given energy from the graph, I know R_p and ΔR_p , so I know the thickness. Whatever I said, I did it again just to show you. As I keep saying I keep writing myself. So that is the value, so I did not go on the table to check this but you can see what is the value. This will be around 3 point something.

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Then $d = R_p + \sqrt{2} \Delta R_p \operatorname{erfc}^{-1}(2 \times 10^{-6})$
 $= R_p + \sqrt{2} \Delta R_p \operatorname{erfc}^{-1}(0.999998)$

$d \Rightarrow$ will be thus different for different energy of implantation (R_p & ΔR_p) as also Blocking needed.

We made an assumption here that $R_{p_{SiO_2}} = R_{p_{Si}}$ & so are straight. But in reality, this is not true.

Then actual = $\frac{R_p \text{ in Mask layer}}{R_p \text{ in Silicon}} \cdot d \text{ obtained (as above)}$

Typically, assumption of $R_p \text{ in Mask layer} = R_p \text{ in Si}$ is good for SiO_2 .

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598 is roughly 3 or 3 point something. So this will be root 2, 4 into, so this will be roughly 4. This into root 2 will be roughly 4 for something of that kind. So R_p plus 4 times ΔR_p is roughly the, rough I am not saying, because that exact value you can take from the table. I can just tell you from 598 the error function is roughly 4. Error function 4 is roughly this value, sorry 3. So 3 into 1.41 is roughly 4.2 or 4 roughly you can say now.

So 4 into ΔR_p plus R_p is the d thickness, for what values blocking? 6 nines blocking if I want to do, I will be able to find the d . The problem assumption, the problem which is created and gauged, that I am assuming R_p and ΔR_p in the material F, mask material, same as that of silicon which is not true. So what we do is some rough estimate we did and which is not accurate but sufficiently (48:58).

If you find out R_p of the mask layer and this I may give R_p of the mask layer whichever is the material. R_p is the silicon, then the ratio will be also ratio of their thicknesses. So d actual is R_p in the mask layer upon R_p in silicon into d obtained from here. Is that word correct? Assumption, if both are same R_p s, then you get d and this d should be multiplied by ratio of R_p to the mask layer divided by R_p to the silicon. This is rough estimate which gives reasonably good results.

If these are equal, then what was happening? If I assume both are equal, then? It is 1. d obtained is same as d actual. But in real life it will be different. Will be smaller or larger? Normally mask R_p will be smaller, so this is the ratio smaller than 1. So actual obtained will be bud into, fraction

will be actual thickness will be even smaller to actually mask. Typically 6,000 Armstrong of photoresist can block 300 kgs of implants.

0.6000 Armstrong means 0.6 microns of resist, can block 300 KV of any ions. So it is a very powerful mask. Is that clear? So in the implant what mask I should use normally? Resist. Why should I go put another layer? I am anyway doing lithography. Resist sitting there, I use that itself as a mask, resist sitting, is not it? So instead of removing and doing implant later, I will do implant right there. Is that correct? Keeping resist there.

So what will happen then? I do not need additional state also to go through. Is that okay? So this resist is one of the major mask which is used in all implantations. Is that clear to you? So please take it. Normally R_p in silicon is same as SiO_2 nitride. So normally whatever you obtain is true but for metals or for resist R_p s are different. And therefore this number must be specified. If not specified, do not do all this, you just write d whatever it is.

But if specified, you will have to take a ratio and figure out how much the ratio and then multiply it with this value to get the actual values. Is that okay? So this somehow we have now figured out. What are the things we have done? We implanted, we said how are they coming, how much dose I can put, so much. I know the profile now. I also know if I want to profile moving, I can adjust profile moving. I can do any arbitrary profile through multiple implants of different doses and different energies. So I can create any arbitrary profiles.

We also see where the actual R_p s and ΔR_p can come because of the scattering whether it is nuclear or it is electronic. So this much we are done so far. Some question was last time rose after the class that how is this impurities which are ions actually get activated. Means unless they sit where, substitutional sites, how are they going to actually contribute to conductivities. So obviously there must be some process must be happening either directly or indirectly that they will actually get into the substitutional side.

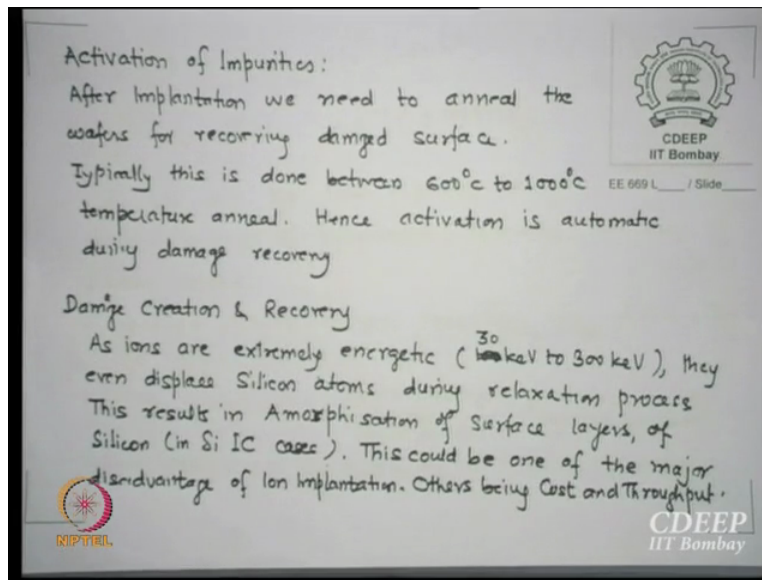
The impurities are coming inside in ion forms and they are resting randomly. They are not going to necessarily substitutional sites. Is that clear? So if they are not reaching substitutional side, they will not contribute to conductivities. Is that clear? Only when they replace silicon, only then they are activated. So I must do some process now in which these so called ions which are coming inside and due to this scattering rest somewhere, they actually occupy the surface there.

Further I say if they are heavier ions, then I also figure out the damage is very high. I will show how, okay. So now that means the surface of silicon is not silicon then, crystalline silicon. It is actually amorphous. So now these two are two different things but they can be taken together in one go. Amorphous has substitutions, that is the purpose. Typically what we do is to recover the damage which is caused, we anneal the sample after implants at temperature from 600 to 1000.

Nowadays we do RTP, Rapid Thermal RTPs, but even if old time furnace we used to do that 600 to 1000. And the way we used to do it, some for a while we will do 600, then we will go to 800, then we will go to 1000. Time-wise we will adjust because some impurities may be activated at 1000, some may get activated at 600 depending on the dose I have or initial impurities where they were. So there is the catch going on that you have to learn anneal cycles, this is called annealing.

Now this recovery of silicon from amorphous to this itself helps you to create substitution sites, that is the fun. Is that clear? Recovering of the damage which is amorphous, when you start recovering to crystalize, the crystal these which is called epi-growths, they are substitutional sites automatically easily available to them. And here is some maths which you can do. Please remember ion energies could be as low as 10k, maybe 100 I wrote but maybe as low as 10kv or 30kv at least.

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Maybe I should write. Lowest energy normally will be 30kv. So 30kv to 300kv implants are done. Larger energy means what? Deeper implant. Smaller energy means shallow implants. But if you are doing a nuclear stopping in particular case, what will happen? They will push, they have enough energy, okay. They will push silicon atom from their original sites. Then they actually know, so silicon crystallinity is broken because silicon is not in periodic structure at the surface. So at least some 100 planes. Now that happens that the please remember that is the area where you are, in F80 that is the channel area. Is that point clear to you?

This, the worst case will be where the silicon, this inversion channel is going to come. You are actually implanting something to adjust BT there and you are creating all damage there. So its recovery should be extremely good because I am adjusting threshold there actually. So this recovery is a very tricky game. So that the BT is exactly adjusted by you. I will show you this when I go through full process.

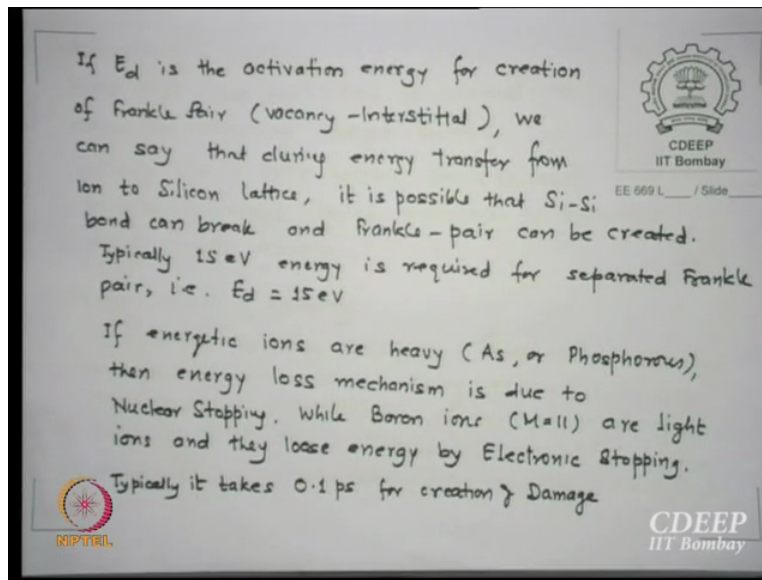
Now the surface layers of silicon, this could be of the major disadvantage of ion implantation. Then every time I must recover it because there is damage going on. So what we now say, we have done some crystal, about crystals thinking about we did something. It requires certain energy to create a Frenkel pair. If the silicon atoms moves, what it will do, leave behind a vacancy. So it is called Frenkel pair.

So if Frenkel pair has to be created and it moves away from the surface where now impurity can come and rest, it needs certain amount of activation energy. Is that point clear? After hitting ions, the energy absorbed by silicon atom should be sufficient enough that it displaces itself, moves down along with a vacancy pair with it and that is called Frenkel pairs. So basically what we are doing is trying to create Frenkel pair movement from surface to the away.

And as impurities will come, they will occupy vacancy sites and this silicon will keep moving. This is called first silicon because it is a single atom, it moves. It is called first silicon blocks and that it moves itself. So silicon diffusion is very important in the case of recoveries. Some other day more details, isme infinite chije hai. Material mein subkuch mane jasakti hai aur sahibhi bataya ja sakta hai.

Okay. Please remember the three major problems in implantation is, the disadvantage of implantation is damage, the other is very cost, very large amount of cost per wafer is created if I do implants. And not hundreds of wafers can be implanted simultaneously, so there is a lower throughput rate or lower throughput because I may put 24, 40, 80 but in way furnace how many I can push? 250 equivalent (58:54) in one run. So that is something which implants, implanters do not allow. You can put 200 wafers implanter also is there but then the cost of implanting itself is exorbitant.

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So whatever I was saying, if E_d is the activation energy for creation of Frenkel pair, and not just creation but moving away, the silicon during the energy transfer from ion to silicon, it is possible that Si-Si bond may break and Frenkel pair can be created and it can move away from the amorphous area. And that typical energy one observes by calculation and by equivalent measurements, is 15 electron volt.

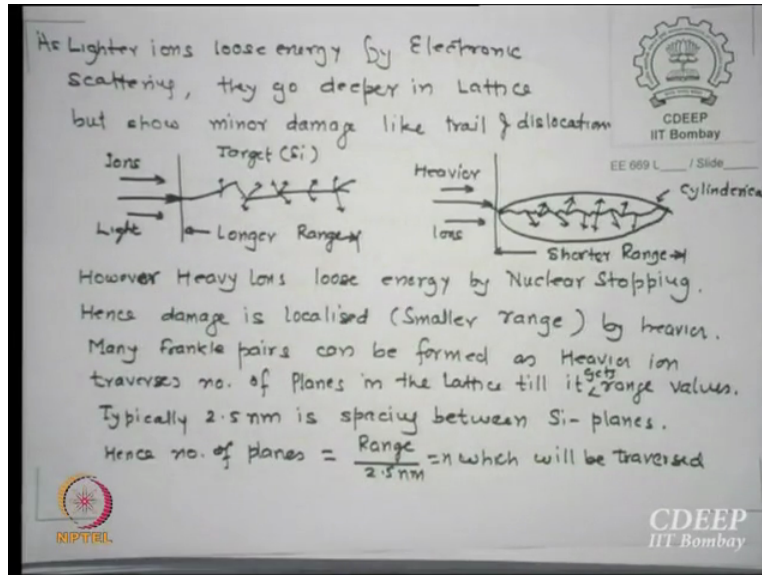
Separated Frenkel pair means moving away, it requires roughly 15 eV of energies. If energetic ions are heavier, like arsenic or phosphorus, their atomic mass is 78 and 30 odd something. Of course phosphorus is in between, boron is 11, 10.8. Boron is very light, it is just 11, 10.8. So how the boron will lose its energy most likely? Electron and the heavier will always lose with nuclear. So most likely arsenic, phosphorus stopping will be nuclear and boron stopping will be by electron stopping.

So if you see the damage, you have not, you wanted that? Lighter will always be mostly electronic because they will not be able to transfer the energy to silicon to move it out because they are lighter ions, they do not have, half mv square enough. Is that correct? What is, kinetic energy is very small with them. So they cannot push too much. So there mostly the energies they will lose through scattering of, with electron they will exchange energy.

But heavier ions, half mv square is high, m is high. So it actually move the silicon, is that clear? Is it okay? I repeat energetic ions are normally heavy and they normally are, lose their energy

through nuclear stopping and lighter ions do not able to move silicon. So they lose most of their energy through electronic scattering.

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So if you have lighter ions or heavier ions, the kind of damage shown here is the following. For lighter ions, you know there is small displacement, maybe very small. I have shown you larger just for this but the range is very high, long. The lighter ions can keep going because it is not losing too much energy with the lattice. Lattice is not moving, so lattice does not get enough energy out of it but electrons do. So they keep moving in and that creates something called dislocation chain which is small displacements.

They do not move too much. So this is called small dislocation chain is created but the range is sufficiently long, lighter ions. So which is funny, is not it? Lighter is actually creating damage deeper but it is smaller damage. Whereas if you have heavier ions, of course this looks to be same but this is much smaller. This is the shorter range but the damage this is where silicon atoms actually move away because of energy transferred to them. And they create Frenkel pair which are moving away from the original sides.

So only in the case of heavier atoms, we should really look for what is the kind of damage it is creating. Lighter, since it is a dislocation, even normal 600 degree anneal, they will come back. So lighter ions anneals, implants are annealed at lower temperatures, why? Because damage is

much lower. Higher ions, heavier ions damage will be larger this, so you must anneal it at higher temperature. Is that clear why range of temperatures?

So you have to do this differently. There is one interesting theme which book has given and which I thought is interesting. Many Frenkel pairs can be formed as heavier ion traverses number of planes in the lattice. Now in a lattice we have already seen, I hope you have not forgotten your Miller indices. There are number of planes, identical planes. 100 may have n such planes parallel to each other. That is why it is shown in triangle 100 or bigger this.

So if you have number of planes, ions are hitting. So it is trying to go deeper by actually going through number of planes where atoms are actually situated, silicon atoms. So what we say, typical distance between the two planes of silicon is around 2.5 Armstrongs or 25 maximum, 2.5 nanometers or 25 mm, maximum distance in this case is. So let us say the range, whatever is the range of ions gone in, divided by number of distance between the plane is the number of planes through which ions are going through.

So divide range, range divided by the distance between the planes. This is the arbitrary number, this can be even 0.25, 2.5 Armstrong and then the number will be even larger planes, 1000 planes will be involved. So as I start actually putting the ion in, it interacts with number of planes and then come to rest. So in a given range and distance between plane is known, so I know how many planes it has actually crossed. Is that okay?

If this is my range and these are my planes, so I know in this range if the spacing is known, I know how many planes it is actually interacting. I want to know for every plane interaction how much energy it loses, ion loses. If I know 1 per plane is so much and I know so many planes, then I look at total energy should be same as which I started with. So let us see what it is. Is it okay? I have number of planes, ions are entering and interacting, losing energy and going through and through because all energy cannot be given to one single plane atoms. So it keeps moving.

This is particularly true for heavier ions, lighter ions are very small amount of damage and recover at 600 degree itself, so we do not care too much. Though it may be deeper but we do not care very much. Is that okay?

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Energy lost per plane then is

$$= \frac{\text{Initial Implantation Energy}}{\text{no. of planes.}}$$

No. of atoms involved N

$$= \text{no. of planes} \cdot \frac{\text{Energy lost per Plane}}{2 \times E_d}$$

$$= \text{no. of Planes} \times \frac{1}{2E_d} \times \frac{\text{Initial Implantation Energy}}{\text{no. of Planes}}$$

$$= \frac{\text{Initial Implantation Energy}}{2 \times \text{Energy of displacement - for FP.}}$$

An 50 keV, Implant of heavy atoms, will displace Si-Frenkel

$$= \frac{50 \times 10^3}{2 \times 15} = \frac{10}{6} \times 10^3 \approx 1700 \text{ FP. (Si atoms displaced)}$$

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Now energy loss per plane is the implanted energy divided by number of planes. Let us say I have 30kv implant or 300kv implant, divided by number of planes is the actual energy loss per plane. 300kv has to go, range means what? The energy rest to 0. So if 100 planes required to this, this much range, that means per plane is divided by 100 energy. The assumption is every plane actually loses only that much energy which is not very valid assumption but greatly okay.

So initial implantation energy divided by number of planes is the energy lost per plane. Let us say number of atoms involved in interaction is n, then actually number of planes into energy loss per plane, what do you mean by atoms involved? In creation of Frenkel pair. They have now Frenkel pairs, so it is number of planes multiplied by energy lost per plane into twice E_d . E_d is the displacement energy required.

And twice because one on this side, probability by both side it can move. So it is called degenerative factor, so 2, so $2E_d$. If I say number of planes 1 upon $2E_d$ initial implant, any number of planes, so this, this cancels. So essentially I cross it directly but I just showed you how game goes. The number of atoms involved to create Frenkel pairs is initial implant energy divided by $2E_d$ or $2E$ for creation of Frenkel pairs.

An example is a 50kv implant of heavier item, arsenic or anyone could displace silicon Frenkel pairs, 50 into 10 to power 3 divided by 2 into 15. So roughly 1700 atoms will be displaced, Frenkel pairs. Is that correct? Frenkel pair means one silicon moving is creating a vacancy. Is

that clear? So Frenkel pairs, 1700 atoms will be required to lose 15kv of heavy ions in silicon. Is that clear?

So this number is not very small, but in the 10 to power something, this number is very small. So the damage is always localized. So I can now find that whenever I will do this anneal, 600-800-1000 for each of these Eds will correspondingly Frenkel pairs will be varying and as the Frenkel pair is moved, impurity ion which was hitting, that may actually occupy the vacancy and releasing the silicon.

So it substitutional itself during the Frenkel pair motion, so how the ions activate? During anneal the pairs are moving and number of pairs, I just now 1700 for example I showed you. So their impurity ions will keep on, these are apart from what? This is at the surface only, the rest is in silicon available. At the surface what, wherever is the damage, recovery of damage also allows me to ionize that part. So I get substitutional impurity actually getting into sides.

So damage and activation is together, so it is both, we do not have to twice anything. We do anneal once and all that recovery as well as substitutional thing is done in one go. Only thing is if it is 10 to the power 12 dose, I may have to do different temperature, 10 to the power 15 dose which is very heavy dose. I may have to do much higher temperatures. Is that clear? However the dose, the number of atoms which are impinging are heavy high, so the damage will be also will be high. So you will have to anneal at much higher temperature.

Although I have not given, but book has given. Typically it requires 0.1 picosecond to generate one Frenkel pair. You know the kinetic energy, if you know velocity by that, you can evaluate. Typically 0.1 picosecond is required to create a pair. You can see how fast this process takes place. Okay, so we only are left with now the machines which we will start next time, that is Friday which is not big one. And after that we will start with the actual, please do come on Friday and Saturday. We are actually going to show you how silicon IC is going through 16 mask process and chip is actually fabricated.

There are two processes I need which is itching as well as metal ion depositions. Right now I assume we can, we say we can do that and we will continue doing the full because I want to first show how IC is made. That is given in Lamar's book, so I will actually follow it. But I have already shown you diode, I can show you a transistor. So now I will show how normal MOSFET

is created, CMOS. So is that okay, implants now? Only thing left is implant machine which is very interesting.