VLSI Technology

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Lecture - 19

Ion-implantation process and stopping mechanisms

In the previous class, we have discussed about the relative merits and demerits of diffusion versus ion implantation and you know that ion implantation is a more sophisticated process, which obviously offers you much better control, more flexibility; you can tailor the doping profile in which way you choose, because you have two independent parameters to play with. You can play either with the dose and with the energy, so that you can decide where the peak concentration will be located, how much will be the peak, how deep the dopant should go in, with a lot of freedom which is not available there in case of diffusion. Because, in diffusion always the surface concentration is going to be the highest concentration and after that, it is going to follow either the complementary error function or the Gaussian profile and if you want to bring down the surface concentration, necessarily you have to go deeper. These two factors, the surface concentration and the depth they are inter related in case of diffusion, whereas you can, you have much greater degree of freedom when it comes to the case of ion implantation.

Now, what really happens during an ion implantation process? During the ion implantation process, an energetic ion beam of dopants is injected onto the semiconductor surfaces, directed towards the semiconductor surface and they have sufficient energy, so as to penetrate the semiconductor surface, go inside, right. Now what? When once these dopants have gone inside the surface, they start losing their energy, right. They have started with some initial high energy, high energy ion beam and then, once they have penetrated the semiconductor surface, they begin to lose their energy. This process of losing their energy can be either by colliding with the lattice atoms, elastic collision. They transfer their momentum to the lattice atom, in the process they lose some of the momentum; that is atoms gain some momentum and please understand that this is also

the mechanism responsible for the damages during ion implantation, because the energetic ion beam is imparting some of its energy to the lattice atom and if that energy is high enough, then the lattice atom can get displaced from its original site and that is how the defects are created, right. So, this is called the nuclear stopping; the nuclear stopping, when the energetic ion loses energy by colliding with the lattice atom, loosing energy to the lattice and in the process creating point defects, like vacancies and interstitials.

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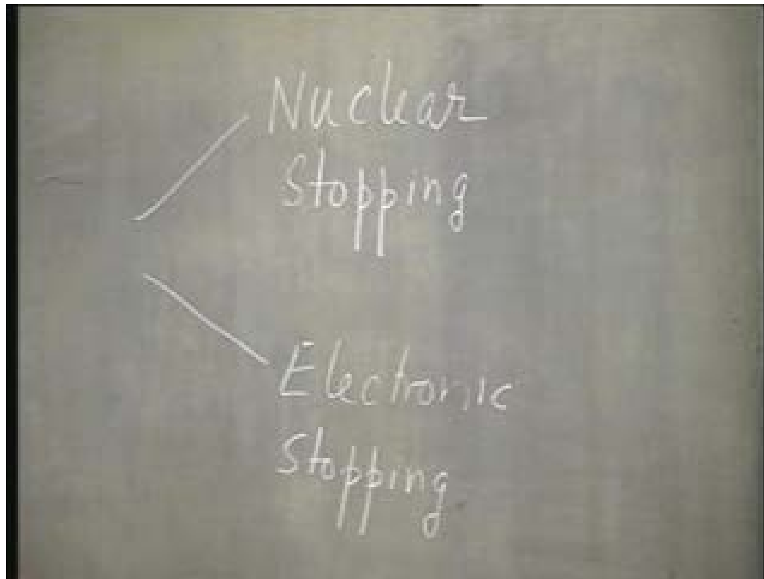

The other process is of course where the energetic ion beam supplies the energy to the bound electrons. In the process, the bound electrons become free electrons, because they gain the energy and that is called electronic stopping. Nuclear stopping, nuclear loss or nuclear stopping let us call it and the other is …. Electronic stopping process is not really responsible for defect generation. In this process only transient generation of electrons are taking place. Nuclear stopping is the process which is primarily responsible for defect creation, because in this process the lattice atoms get displaced. So, the ion is losing energy by these two processes.

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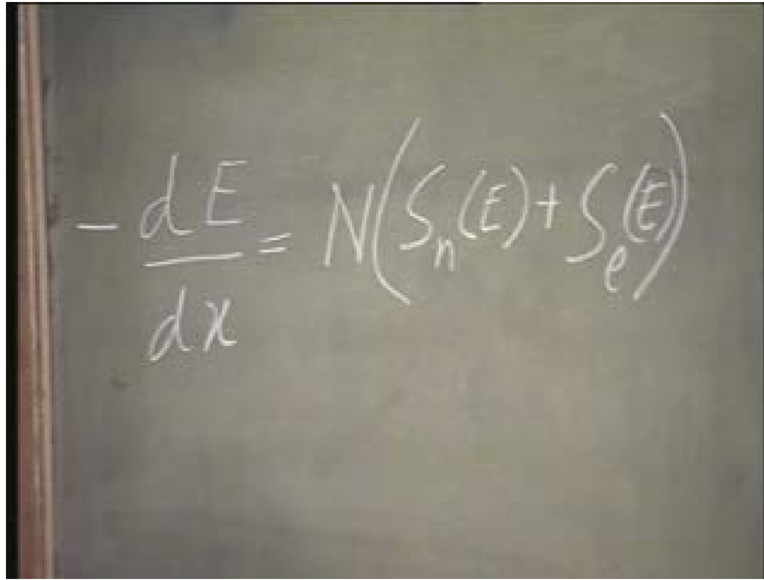

I can write an equation for the energy loss, the rate of energy loss as dE dx; E is the energy, x is the distance, negative sign is because it is an energy loss. That can be given as…….. Let us inspect these terms. This is the energy loss, N stands for the number of target atoms per unit volume per centimeter cube. See, whether the ion is losing energy by nuclear stopping or by electronic stopping, in both cases it is interacting with the target atom, right; the target being in our case, silicon. So obviously, the loss is going to be proportional to the number of target atoms available. That is why this term N is coming into picture, number of target atoms per centimeter cube and these two terms, S suffix n as a function of energy and S suffix e as a function of energy, they refer to these two stopping processes, respectively. S suffix n is for nuclear stopping, S suffix e is for electronic stopping.

In other words, what I am trying to say is that the rate of energy loss is proportional to both the number of target atoms per unit volume as well as to the sum of these two stopping mechanisms, nuclear stopping and electronic stopping. How exactly this nuclear stopping and electronic stopping are related to energy? Notice that both of them are functions of energy and this energy is the ion energy. How exactly they are related to the ion energy, we will discuss a little later, but for the time being, let me just say that both

are functions of the ion energy. Depending on whether the ion energy is high or low, one or the other process will dominate and so, this is what I get. The energy loss is given by this equation.

Now, when the energetic ion beam has entered the semiconductor surface, you know it is like this.

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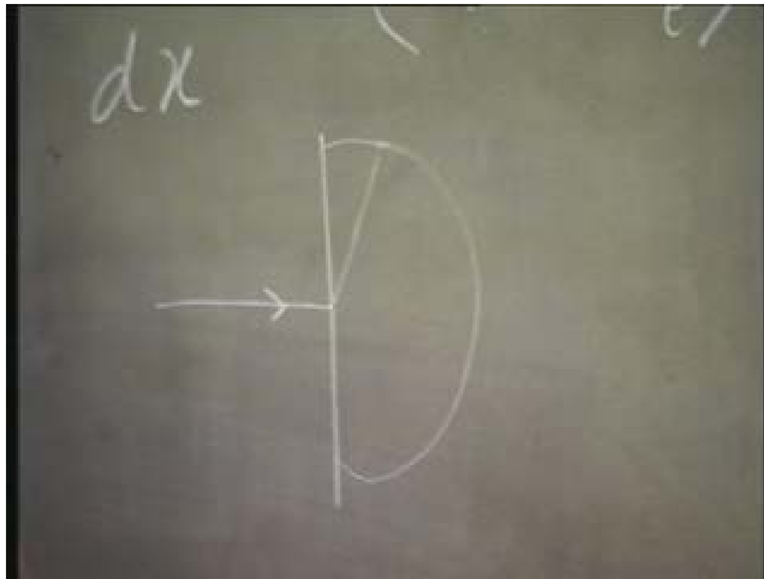

Let us say this is the semiconductor surface, this is the energetic ion beam and the ions can move like this, comes here and then, it starts getting deflected because of its collision with the lattice or because of losing energy to the electrons and it can actually move like this. So, what I am interested in knowing is where has the ion finally gone and stopped? Finally what is the resting place of the ion? When the ion energy becomes zero that is the point where it comes to rest, therefore that is the point up to which the dopants have penetrated the semiconductor. So, just as in case of diffusion, you see, I need to know how far the dopant has gone inside the semiconductor and in ion implantation jargon, this is called the range of ions.

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The range that is R and what is R? R is the distance traversed during which the ion energy has fallen from its initial energy to zero. Is it not? So, I could say R is actually nothing but ....., agreed and now if I look at this equation, I could express this as…...; we will call it E 0 for the initial energy. Do you all agree to this? See, all I have done is I have taken this dx, integrated it in the range 0 to R. R is the point where the energy is falling to 0 and 0 is the point where the ion beam is just entering the semiconductor that is where its energy is E 0 that is the initial value of the energy. The minus sign I have taken into account by changing the limit. It should have been from E 0 to 0, I have changed it from 0 to E 0.

So, this is the equation for the range of ions. This is something we need to discuss later when we find out how exactly this nuclear stopping and the electronic stopping depend on the energy. Then, we can find out how R is going to be a function of energy. Obviously, R is going to be a function of energy, right. How exactly R is going to be a function of energy? In other words, this is understood that the higher the energy of the ion beam is the deeper it is going to penetrate. So, how exactly the range is related to the energy will be obtained, simply by solving this equation, once we know how nuclear stopping and electronic stopping are related to energy. But, before we go into that I want

to tell you about two other parameters, which are of vital importance for ion implantation and these two parameters are called projected range and the straggle.

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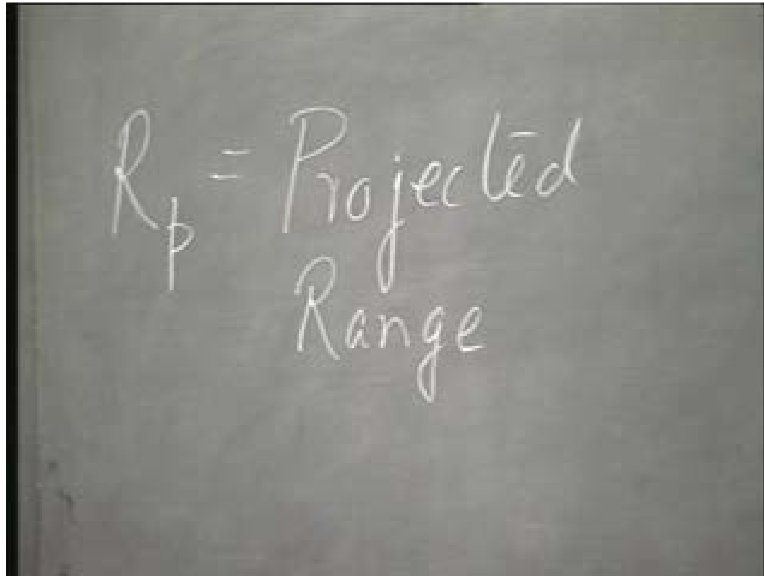

The concept of projected range is very important.

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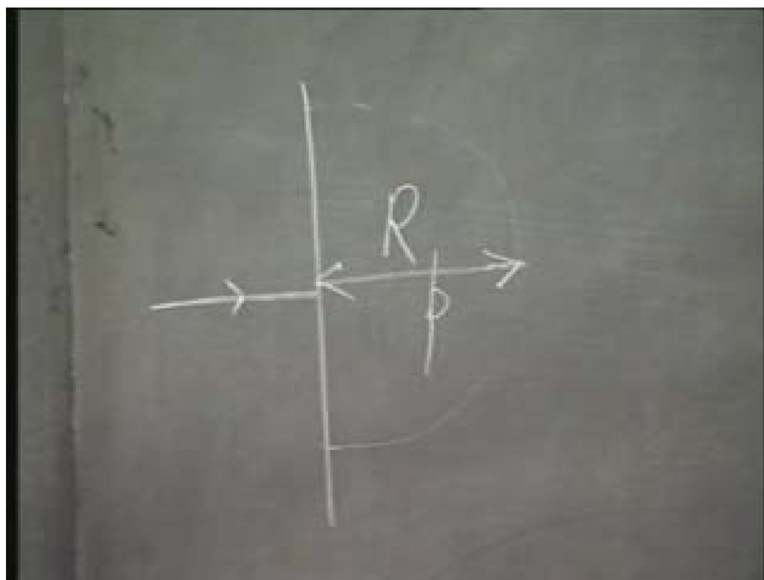

See, when we discussed about the range, what did we say? That this is how the ion beam is coming and ion can come to rest anywhere in this region. But, what are you really interested in? Suppose you are creating a pn junction. What are you really interested in? What is your junction depth? Is it not? In the direction of the ion beam, how is it coming to rest? So, this is actually the projected range. That is the distance traveled by the ion in the direction of the incident ion. So, this is R p and obviously R p is going to be related by, related to the range; R p is going to be related to the range. So, projected range is the distance traveled by the ion in the direction of the incident ion and the projected range is characterized by, see, it will not be exactly the same for all the ions, right. So, it will be characterized by the average value of R p, average value of the projected range which is usually written as R p.

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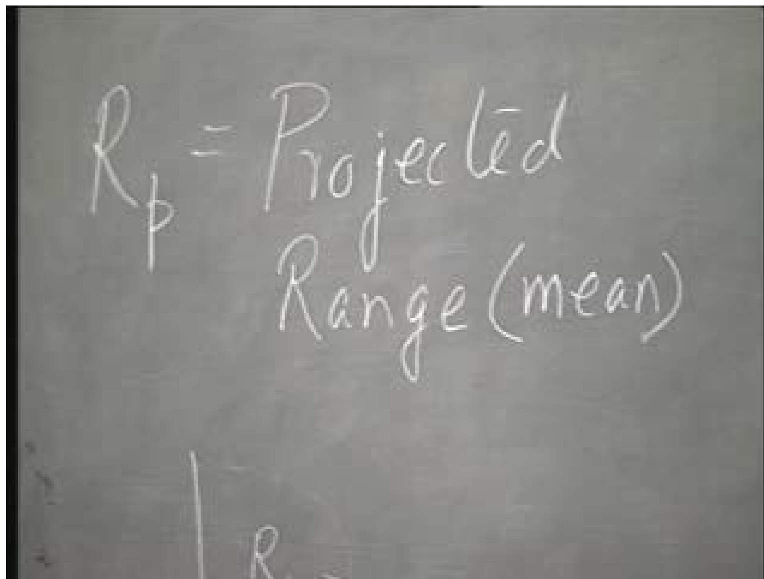

So, this is actually the projected range, mean value of that and the variation in the projected range will be taken into account by a factor delta R p, which is actually the standard deviation in statistical parlance and in ion implantation jargon, we call it the straggle.

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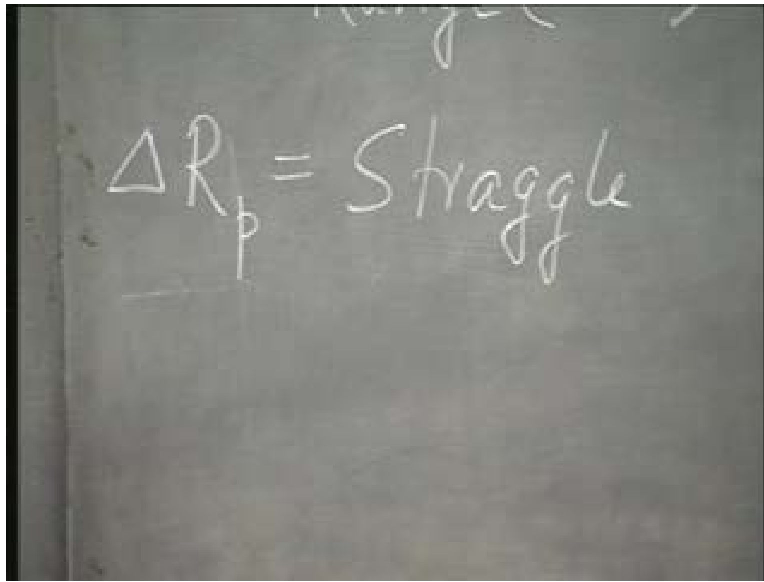

You know the meaning of the word straggle. It means a sort of, sort of deviation. I mean you know, I mean deviation from the mean, so to speak. That is the straggle, which actually in proper statistical term is the standard deviation. So, any ion implantation process is going to be characterized by these two factors - the mean value of the projected range or R p and the straggle that is delta R p. Now, how is, so we have defined or we have seen, looked at a few important parameters associated with ion implantation. These are: how deep the ions are going to penetrate which is characterized by these two terms.

The next of course what comes to mind is how is the doping profile going to look like.

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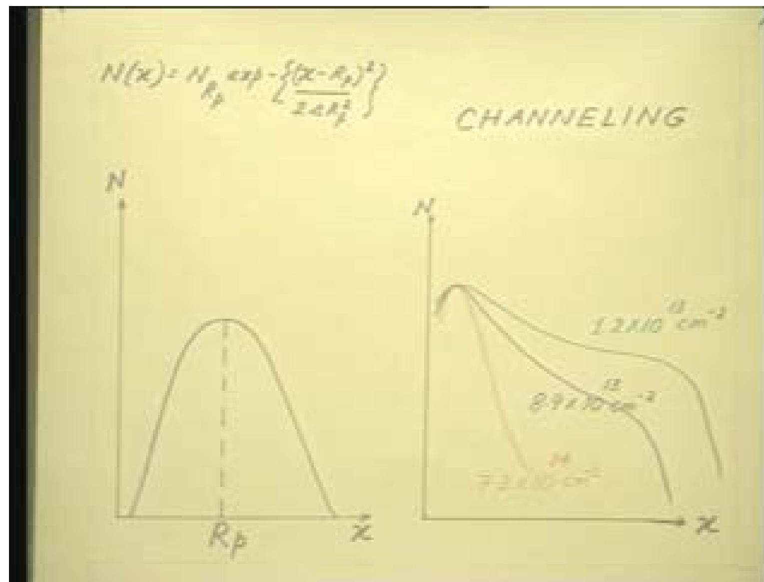

Now, in case of ion implantation, if we assume that the target is perfectly amorphous, perfectly amorphous that is there is no symmetry in the target then, the ion implantation profile will be given as a simple Gaussian function, simple Gaussion function, as you can see in the card here, which is simple Gaussian function N versus x. Look at the left side of chart. It is a simple Gaussian function and a Gaussian, you know, is characterized by the peak exponential x minus the peak position divided by the straggle. So, that is what is going to happen.

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N x is going to be given as N at R p, it is going to be given as N at R p, R p is the projected range where mean projected range, it is the mean value that is that is where the maximum number of ions are going to come to the rest, so that is where the peak concentration is located, exponential minus x minus R p by root 2 delta R p whole square. Another form of writing it is there on the card, where I have written it as x minus R p whole square divided by 2 delta R p square, the same thing basically. So, if your target is amorphous, then it makes the analysis very simple and can be given simply as a Gaussian function.

But, at this point, I expect you people to protest vehemently and say, but our target is not an amorphous target, it is a crystalline target. VLSI technology is done on single crystal silicon, where does this amorphous target come into picture? Well, my answer is very simple. My answer is I shall make the silicon single crystal resemble an amorphous target. I can do it by various ways and means. So, bear with me, I will tell you how we will make this target look like an amorphous; but please understand why I am harping on this amorphous thing. When we say amorphous, there is no preferential direction for the ions to go in. Whenever we talk about crystalline that means you have a regular array of atoms. In between there are empty spaces, therefore if the ion can go into one of these

empty spaces, it can travel a long distance without colliding. So, that makes the analysis much more difficult and we shall see, in real life what really happens. So, for the sake of analysis it is very simple to analyze, if you assume that the target is amorphous and as far as the ion beam is concerned, we will try various ways and means to ensure that the single crystal silicon resembles an amorphous target to the incident ion beam.

But before that, what I want to do is assuming that this is an amorphous target and assuming that this is a Gaussian function, what is the dose that is what the total impurity concentration is, what is the junction depth and so on and so on? So, if you want to calculate these things, then you already know that the dose or the total impurity put inside the semiconductor is given simply by the area under the N versus x curve. Even in case of diffusion, you have seen that it will be simply given as the area under the N versus x curve. In other words, I have to integrate the N x from minus infinity to plus infinity.

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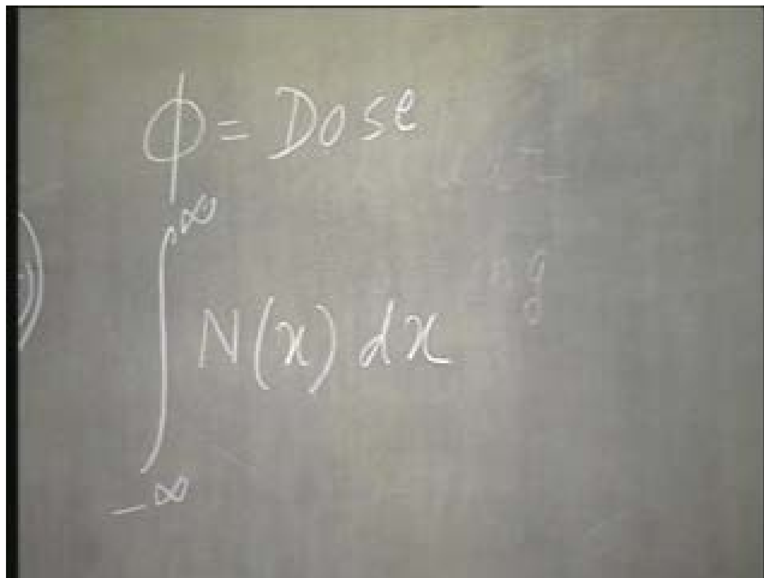

So, the dose which is called phi, in ion implantation this is the notation which is usually used, that is the dose that is given by ….., simply by integrating it between the limits minus infinity to plus infinity. Now, you already know what N(x) is. Let us try to integrate this. So, what do we get?

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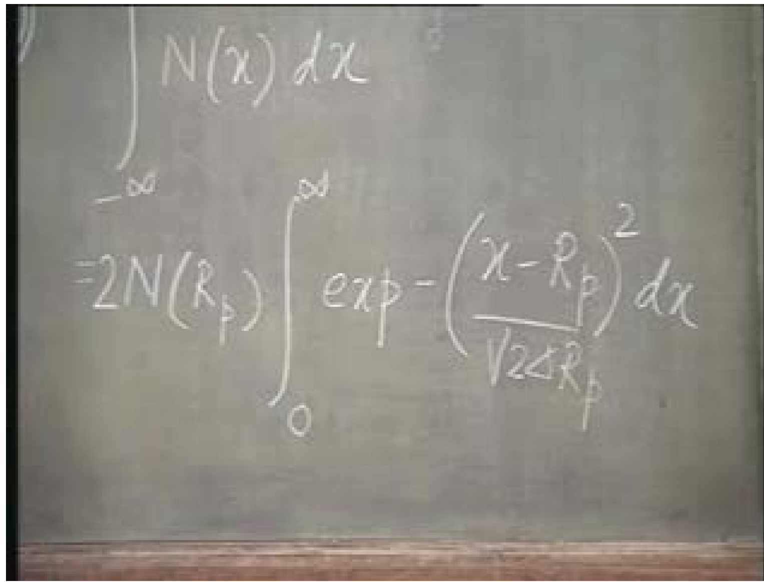

We get this is equal to say, the peak concentration is a constant. It does not depend on the distance anyway. This is where the maximum number of ions are coming to rest. So, this is not the function of distance. R p, you know is only dependent on the energy. So, this is something I can take out of the integral and then what I get is ....., agreed. I have not put the limits. Now, since this is a symmetric function, you know a Gaussian function is a symmetric function, I could write it as ......, right. Now I will do some elementary integral calculus.

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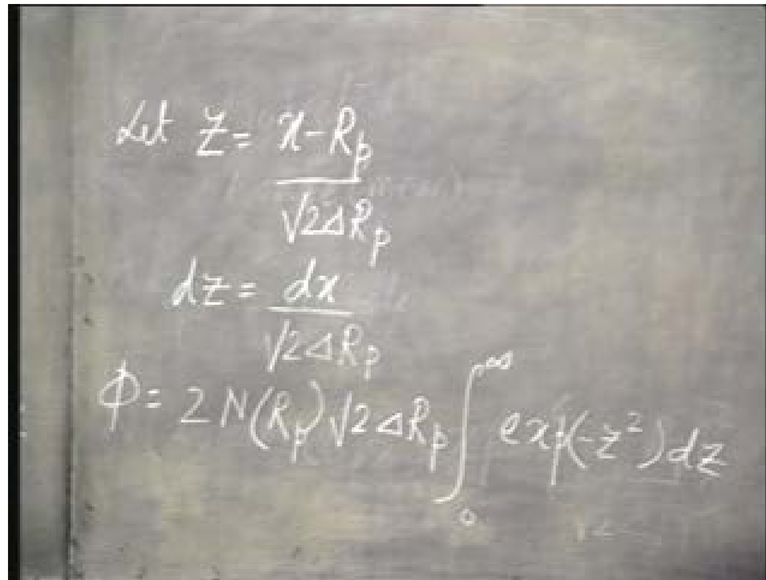

Let us say ……, so that and therefore the dose becomes equal to ......, right. Now, do you remember what the value of this definite integral is, exponential minus z square dz integrated over the limit 0 to 2 pi?

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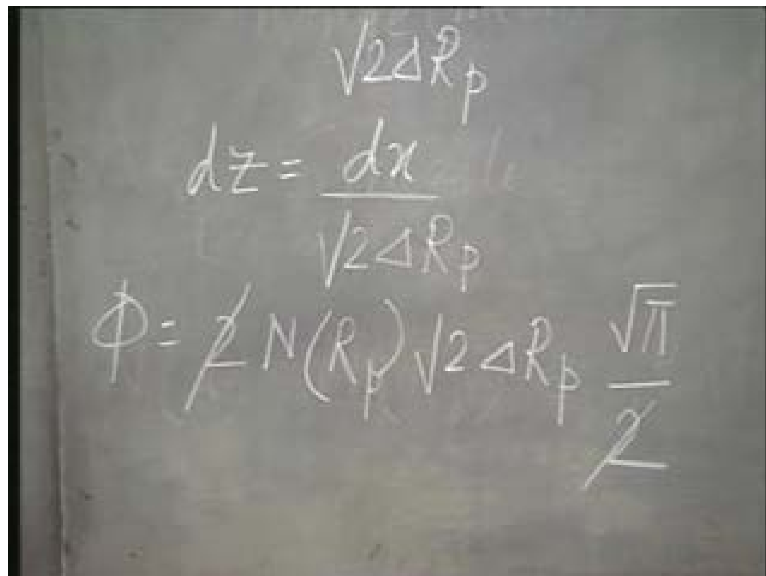

It is root pi by 2; value of this definite integral is root pi by 2.

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In other words, I can say, let phi is finally given as ...... Now you see, in other words, therefore I could write that the peak doping concentration is given by phi divided by root 2 pi times delta R p. Phi is the ion dose, so most often what we will do is when you are operating an implantation system, you will control the dose in order to control this peak concentration. The dose is actually dependent on the ion beam current. So, in the instrument you control the dose simply by controlling the ion beam current; we will see that a little later. So, the dose is a parameter which you can control. So, controlling the dose you can control this. Delta R p as well as R p will be a function of the particular target ion combination. It will be dependent on the particular target and ion combination. It is related to their respective atomic masses. So, provided the target is completely amorphized, it is a totally amorphous target, we can approximate the ion implantation profile by a Gaussian profile with a peak at x equal to R p, which is given as a function of total dose as phi by square root of 2 pi times delta R p.

Now of course, we come to the question as to what, how do we make the silicon target look like amorphous? One very common way of doing is to misalign the single crystal with respect to the ion beam by 7 to 10 degrees. What do I mean by that? That is the ion beam should not be directed along a major crystallographic axis; you know, x y z, I have

three major crystallographic axis. The ion beam should not come parallel to any of these crystallographic axis; it will be slightly misaligned. If it is slightly misaligned, then to the incident ion beam, the symmetry of the lattice structure is not visible. The symmetry of the lattice structure is only visible, when the mean is oriented along either of the crystallographic axis. So, it is a very common practice to misorient by 7 to 10%.

Now, if the beam is aligned along a major crystallographic axis, then of course we see a lot of variation from the expected Gaussian distribution and that is because, when the beam is directed along a crystallographic axis, it is possible for the incident ion beams to find the corridor in between the lattice atoms, the interstitial space, in fact. It is possible to find the empty passage way between the arrays of atoms through which the ions can move forward a considerable distance without any collision, therefore without any loss of energy. So, what will happen? The ions will move much deeper than that is normally expected. This process is called channeling. This is known as channeling.

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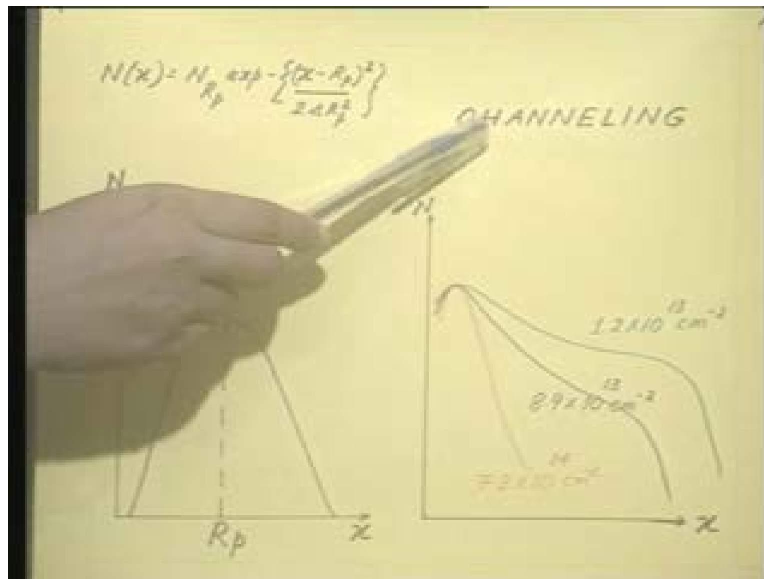

That is the ions have found the channel in between the regular lattice atoms and it has moved forward a considerable distance. Now, I have plotted the case of channeling as a function of distance and I have used a third parameter. This is the dose, the total dose.

The topmost curve, the green curve has the smallest dose. The dose is 1.2 into 10 power 13 per centimeter square. The middle curve has the middle dose that is 8.9 into 10 to the power 13 per centimeter square, slightly more than the first curve and the orange curve here, it has the highest dose of 7.2 into 10 power 14 per centimeter square. You see that the channeling is most evident when the dose is relatively small. These particular curves I have plotted for phosphorus ion implantation, phosphorus ion implantation, at 40 kilo electron volt and in this case, the beam is aligned in 1 1 0 direction.

Do you see a very interesting feature? That is as the dose increases, the amount of channeling becomes less, lesser and still lesser, right. Se, look at the orange curve. It resembles the Gaussian function more accurately than the green curve, which is going much deeper into the semiconductor. You know why? That is because, the higher the dose is the more is the disorder. You are forcing more number of energetic ions onto the semiconductor surface and in the process you are creating more disorder, more damages, so that the sample surface starts resembling an amorphous target and then the profile is going to be a Gaussian. On the other hand, when your dose is much smaller and the ion beam is directed along a major crystallographic axis that is 1 1 0, then the disorder is less. The target resembles not an amorphous target, but a crystalline target and it is possible for the ion beams to find the channel and move forward through a much greater distance.

So you see, indirectly I have told you another way of making silicon surface resemble the amorphous target. That is it is quite commonly done prior to the implantation itself; prior to the actual implantation itself, you do a self-implantation that is you direct an energetic silicon beam onto the silicon surface. You know why are you doing that? You are simply creating disorder on the surface, surface is getting amorphized, so that your profile is going to be more Gaussian; it is going to resemble a Gaussian function more.

There is another way of resembling an amorphous target and that is implant through an oxide, implant through a thin oxide. If you have a thin oxide layer on the semiconductor surface, thin oxide is truly an amorphous material, right; thin oxide, it is not going to stop the ions, it will allow the ions to go inside. But, to the ion beam it will resemble like an

amorphous target. These are quite commonly done; implantation through oxide, implantation while misorienting the silicon surface and prior to implantation a self-implantation to amorphize the substrate, so as to reduce the effect of channeling, not merely the effect of channeling, there are other advantages also which we will discuss later. But, before we go for those things, let us come back to our original point of discussion and that is the stopping mechanism. The ion is going to lose energy once it is inside the semiconductor and how exactly is it going to lose the energy?

You know, there are two processes - nuclear stopping and electronic stopping. How the energy loss is I told you that in both cases, the energy loss is going to be a function of the incident ion energy that is when the incident ion has certain range of energy one of the stopping mechanisms will dominate. Let us now look at that, first of all the nuclear stopping.

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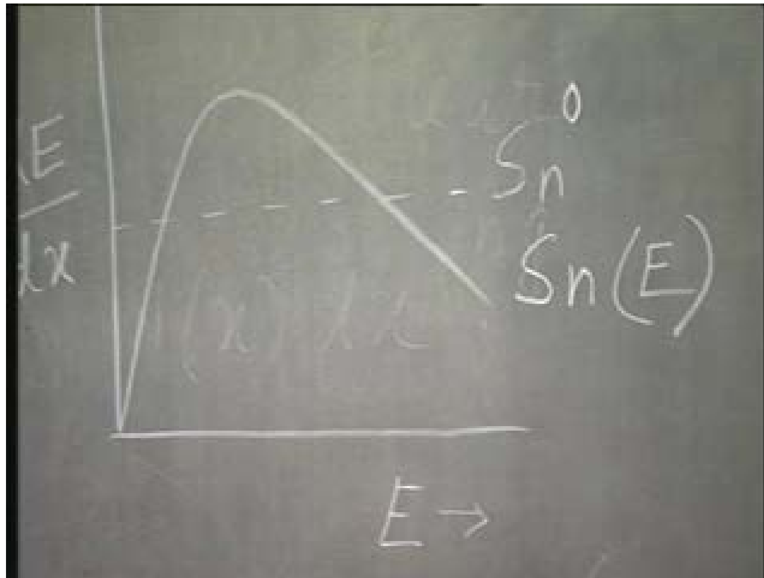

So, in case of the nuclear stopping, if I plot the loss of energy as a function of energy itself, it is going to be something like this. This is the loss due to nuclear stopping. What do you understand from this? When the ion is entering the semiconductor, at that point its energy is maximum; right. At that point, you see, the nuclear stopping is relatively less.

Remember this is E, so this is the point where E is high. When E is very large, the loss of energy, the transfer of energy to the lattice atom is relatively slow process.

The dominant mechanism there is going to be not the nuclear stopping. As the ions starts losing its energy that is as the ion slows down, the transfer of energy becomes a more efficient process, obviously. That is where we see it is peaking up and then again as the ion is losing more and more energy, finally the transfer also comes to zero, when the energy has fallen to zero. That is there the ion is coming to the rest, it does not have any energy, therefore it cannot transfer any energy to the lattice also. This is the actual pattern of energy loss by nuclear stopping mechanism. But, since this is difficult to model, an approximation is made which is taken to be a sort of constant with energy. It does not vary with energy, the line parallel to the E-axis. So, this is called S n 0.

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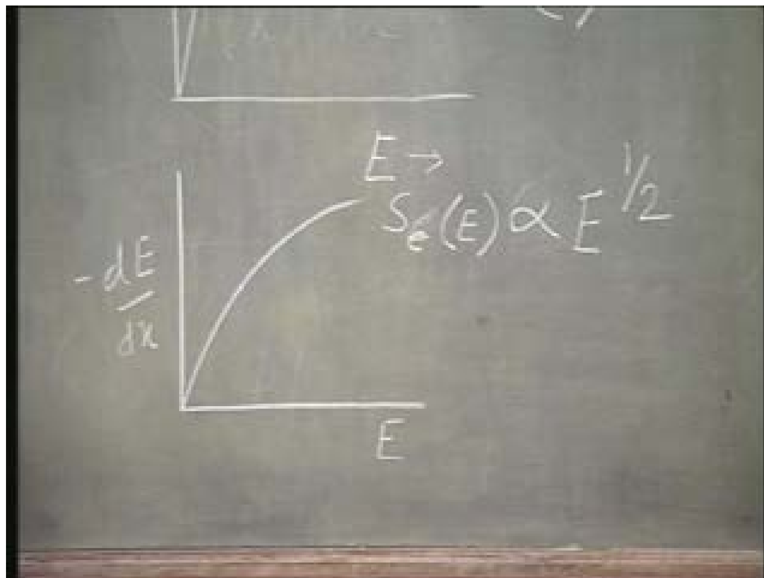

On the other hand, if you look at the electronic stopping, this increases like this. That is S e, it is proportional to the square root of energy. So, you see at the starting point where the ion is just penetrating the semiconductor, the electronic stopping is highest and then, as the ion starts losing its energy, the electronic stopping becomes less and less.

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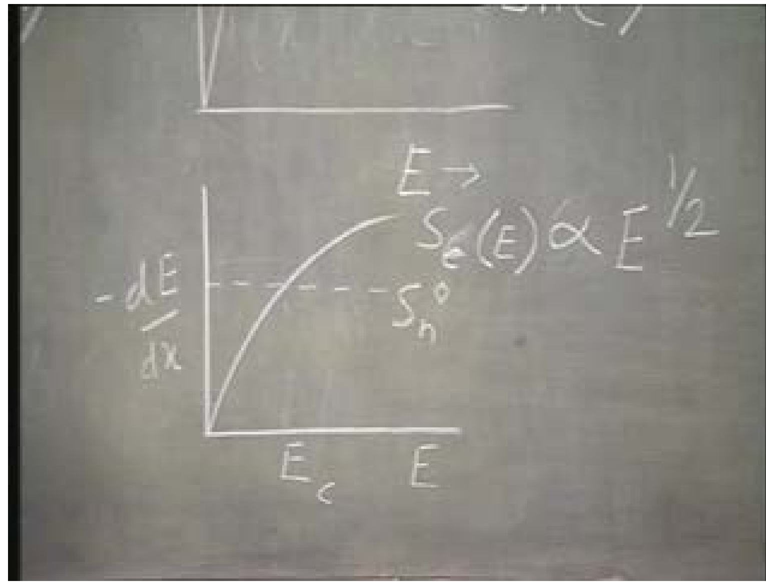

So, if I try to plot on the same this thing, both S e E and S n 0, I have taken this approximation for nuclear stopping, they are going to obviously intersect at a particular point. I call this point the critical energy E c. That is the significance of the critical energy is this that when the ion energy is higher than this critical energy, then electronic stopping is going to dominate and when the ion energy is much less than this critical energy, then the nuclear stopping is going to dominate. I am going to define two zones, two regions of ion energy. When the ion energy is very high, electronic stopping is going to dominate that is there the ion energy is greater than the critical energy, much greater than the critical energy and below critical energy, the nuclear stopping is going to dominate.

So, now accordingly let us come back to the range R and accordingly therefore I can take one term and neglect the other, so as to give me a relation for the range.

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So you see, if the ion energy is such that the electronic stopping mechanism is going to dominate, I will neglect the nuclear stopping; R will be simply given as ….. and S e E you know is ….., so that I can write it finally as some constant K 1, right. In the other case, in the other case, when the nuclear stopping is going to dominate, in that case I can say R is given by, remember if I take this approximation, then nuclear stopping is independent of energy, so this is simply a constant C and therefore it is going to be some other constant K 2 times E. This is where electronic stopping dominates and this is where nuclear stopping dominates. So, in both cases you see R is some function of energy. It is either proportional to the square root of energy or it is proportional to energy, showing that as the energy is increased, the ion moves deeper into the semiconductor, as of course intuitively we guessed.

Now that we have found R, for us in order to obtain the peak concentration and all that, the factor that we are most interested in is the mean projected range and the mean projected range is related to R and the particular target ion combination. See, R is simply a function of energy. R p however, is related both to the range as well to the particular target ion combination and various theories are there.

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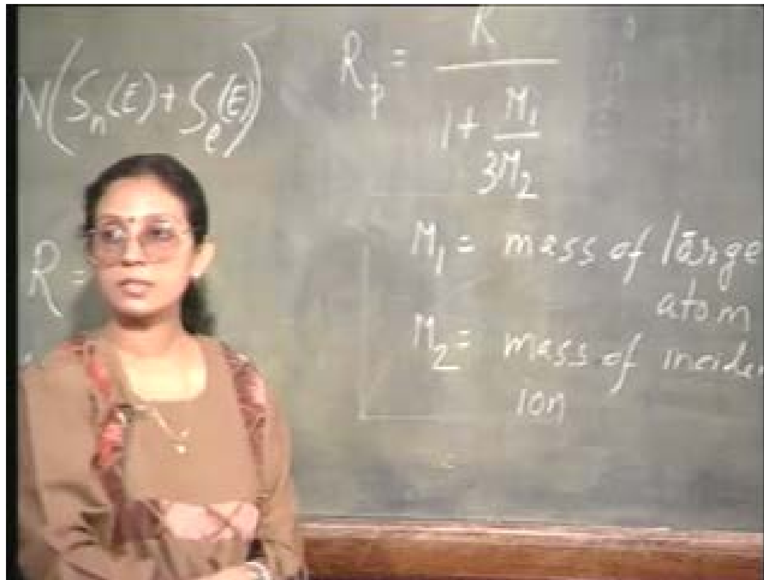

I will just give you one accepted version which simply says R divided by 1 plus M 1 by 3 M 2, where M 1 is the mass of target atom and M 2 is the mass of incident ion. So you see, if the mass of the incident ion is going to be larger, then this factor is going to be smaller. On the other hand, if the incident ion is a very light material, then this factor is going to be much smaller, this is going to be larger and R p is going to be reduced. Just to give you some example, the critical energies below which the nuclear stopping dominates and above which the electronic stopping dominates, these are also different for different incident ions. So, for silicon, this critical energy for boron it is 15 kilo electron volt, for phosphorus it is 150 kilo electron volt. See, boron is a much lighter material, so you need much lesser energy to push it inside. So, the critical energy for boron is 15 kilo electron volt, for phosphorus it is 10 times, 150 kilo electron volt. So, this is about ion implantation and how the incident beam is moving inside the semiconductor.

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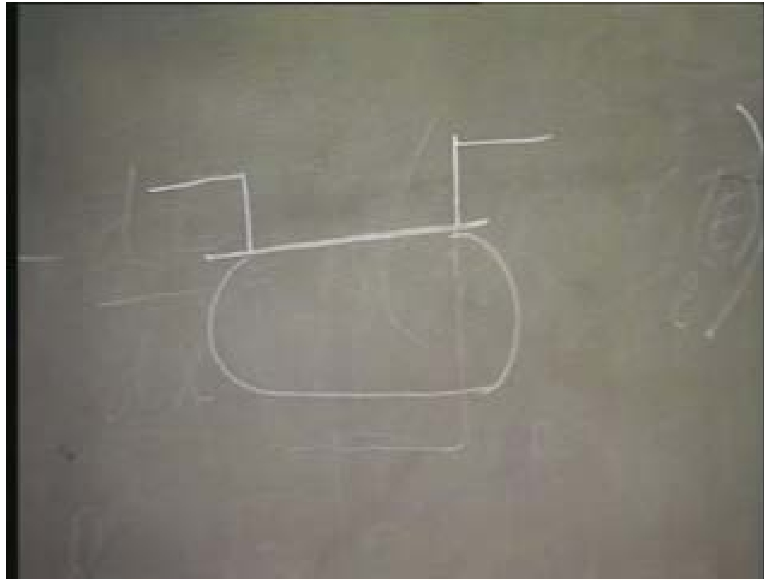

But again, just as in case of diffusion, you know that if I have a window, ideally speaking I would expect, if I have a window like this, ideally speaking I would expect the dopant only to move like this. But, as a matter of fact there will always be a lateral spread, a lateral diffusion you have seen. In case of ion implantation also there will be some lateral doping and that is extremely difficult to model. So, what is usually done is we simply give a relationship. That is whatever we have given so far, see, it is one dimensional, right. We have simply taken doping concentration to be a function of x.

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$$N(x,y) = \frac{N(x)}{2}\left[\operatorname{erfc}\frac{y-a}{\sqrt{2}\Delta R_t} + \operatorname{erfc}\frac{y+a}{\sqrt{2}\Delta R_t}\right]$$

Now, we want to bring the lateral dimension also into picture and is simply given by this, where we assume that this window has a dimension of 2a, so that if I take this point to be y equal to zero, this is minus a and this is plus a.

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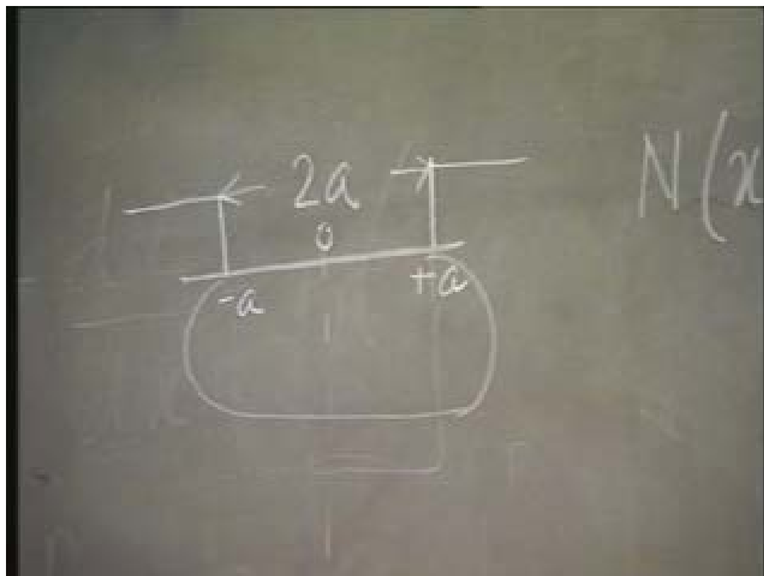

So, whatever was N x, I have simply multiplied it by the distribution in the y direction, in order to get this thing, the x and y direction.

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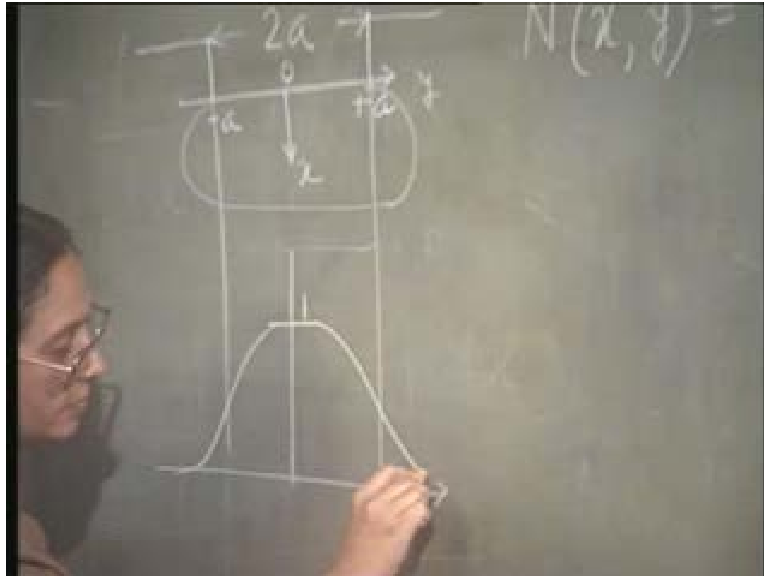

So, the fall out of this is going to be, remember, now this is my y direction and I take any point. x is here, x is in this direction. This is x and this is my y, understood. x is moving inside, y is lateral. So, this is going to be, if I say in the middle of the window, this is 1, at the edge of the window this value is going to be 0.5. This is the fall out of using this formula. You see, at x equal to zero, sum of this will be 2. So, it will become N x and at y is equal to zero, the sum of these will be 2 and it will be N x. When y is minus a or plus a, one of the functions will go to zero; the other function, the maximum value can be 1, therefore it is N x by 2. I leave it as an assignment for you to work it out and see that it is really so; really at y equal to zero, the function, the value of the function you get is N x and at y equal to plus or minus a, the value you get is 0.5 times N x. Let us stop here today.