VLSI Technology
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Lecture - 20
Ion-implantation systems and damages during implantation

So, in our discussion about ion implantation, so far you have seen that ion implantation is a more sophisticated, more controlled, more flexible way of doping a semiconductor and the profile that you get by ion implantation is given by a Gaussian distribution. This Gaussian distribution is strictly valid when the target is amorphous, but even for crystalline targets the Gaussian profile can be assumed, provided we follow certain precautions. Now, let us come to the actual ion implantation system. What are the different parts in that ion implantation system, how exactly does it function and how do we really control the dose by varying the parameters of the implantation system? So, first of all, in an implantation system the thing that is needed that is an ion source. We must have a source for the dopant and it must be ionized, right.

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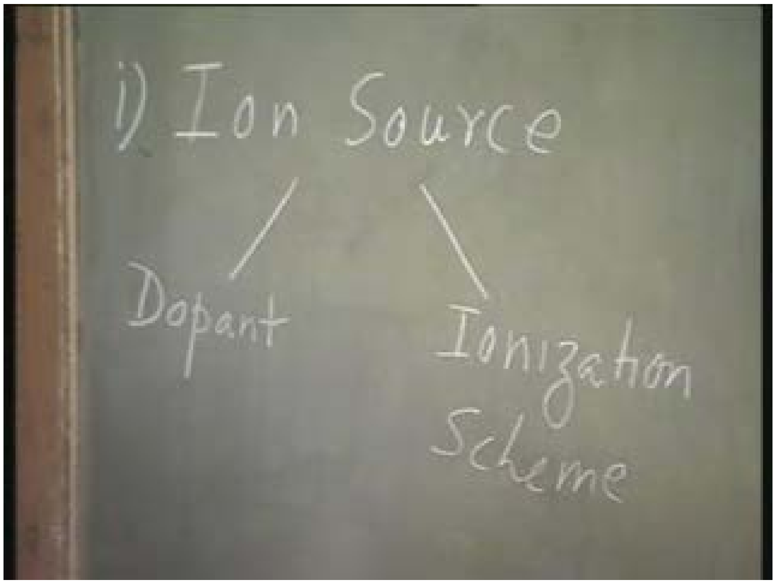

So, the first important aspect of an implantation system is an ion source. What do we have in this ion source? We have actually a dopant source and an ionization scheme. First of all, I must have a dopant source and then some means to ionize that. Dopant source that we use is obviously a compound of the dopant material and it is usually a gas, a gaseous compound of the dopant material and then, we have to have an ionization scheme. Normally an electronic discharge is used in order to ionize this gas, so that you get the ion beam of the dopant, ionized dopant species. Sometimes magnetic field is also used in addition to the electronic discharge to improve the ionizing efficiency. So, at the end of the ion source you have a small outlet, through which now the ionized dopant species can pass. They now go to the next stage in the implantation system which is the accelerator.

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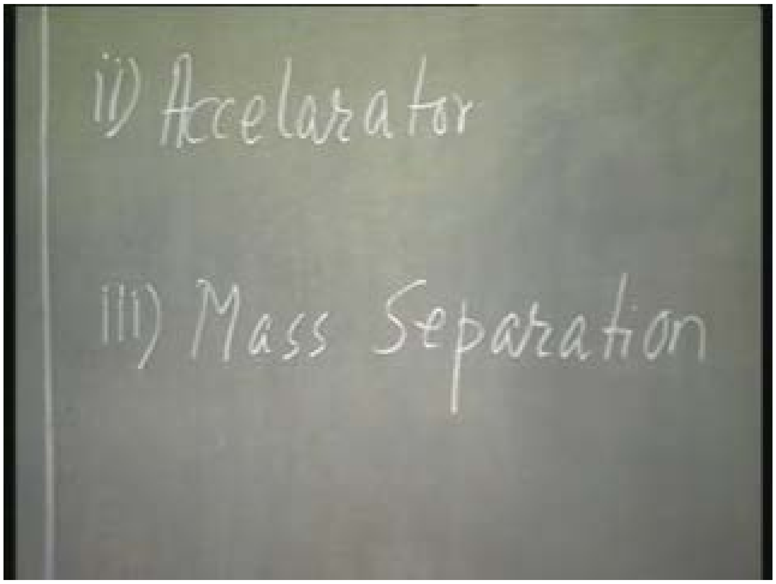

ii) Accelarator

iii) Mass Separation

As the name suggests, what is an accelerator going to do? It is going to accelerate the ion beam. It is going to impart energy to the ion beam and accelerate it down the line. Next comes a very important concept, the concept of mass separation. Now, before talking about what a mass separator really is, let me tell you once again, so far what has happened. I have created the ionized dopant species, I have accelerated them, so that now I have an ion beam of particular energy and this is going to impinge on the semiconductor. But remember, we said that ion implantation is a process much less prone to contamination. Now, you have used a compound of the dopant species and you have ionized this. So, there are various ions in this ion stream; possibility of having various types of ions in this ion stream. How then are you going to select a particular ion species to come and impinge on the semiconductor? This is done by doing the mass separation. In a mass separator, usually for ion implantation, what we use is a homogenous field magnetic analyzer, homogenous field magnetic analyser.

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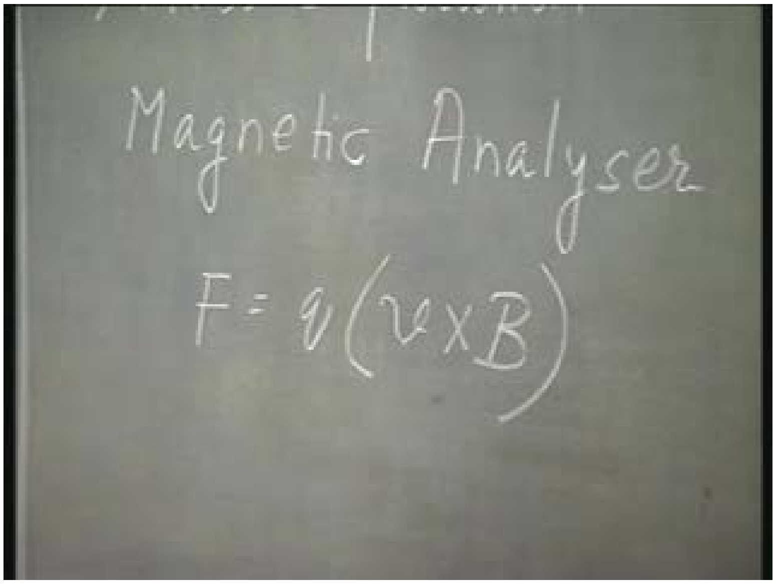

Magnetic Analyser

$F = q(v \times B)$

What are your ion beams, actually? This is a combination of a stream of charged particles with a particular mass. In general, I can say a charged particle of mass m moving with a velocity v. That small m and small v characterize the particular ion species; it is going to be different for different species of ions, agreed. Now, you are subjecting them to a uniform magnetic field B, perpendicular to its direction of motion, perpendicular to its velocity, right. So, under these circumstances, this particle is going to experience a force which is given by F. q is the electronic charge, small v is the velocity and B is the uniform magnetic field that is applied and because of this force, this will tend to move the particle in a circular direction, will try to move it like this and that circular path will have a radius say, small r and this particle will therefore experience a centrifugal force given by mv square by r, right. This centrifugal force is equal and opposite to the direction of this force, right.

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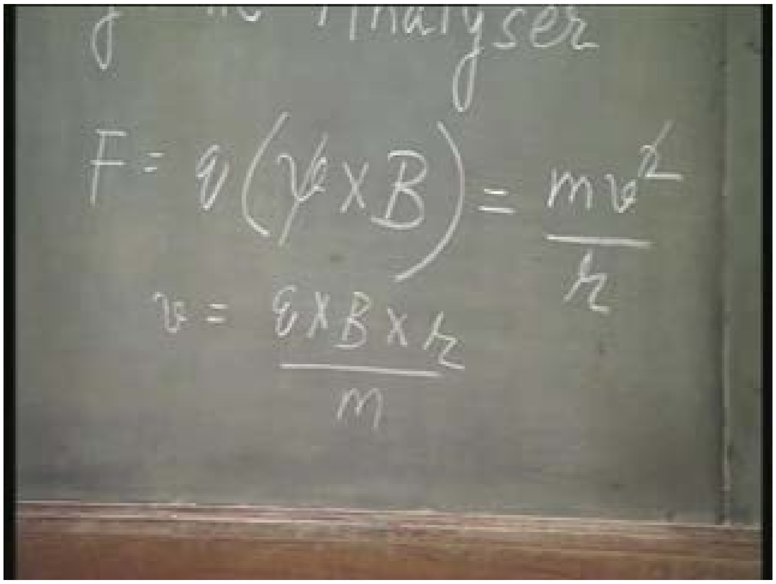

Analyser

$$F = q(v \times B) = \frac{mv^2}{r}$$

$$v = \frac{q \times B \times r}{m}$$

So, I can say that this is equal and opposite to the centrifugal force mv square by r; their magnitudes are the same, right. In this, I can therefore get that v is equal to ….., can I not? At the same time, remember how this velocity was imparted to this ion beam? This velocity was imparted in the accelerator section by using an electric field.

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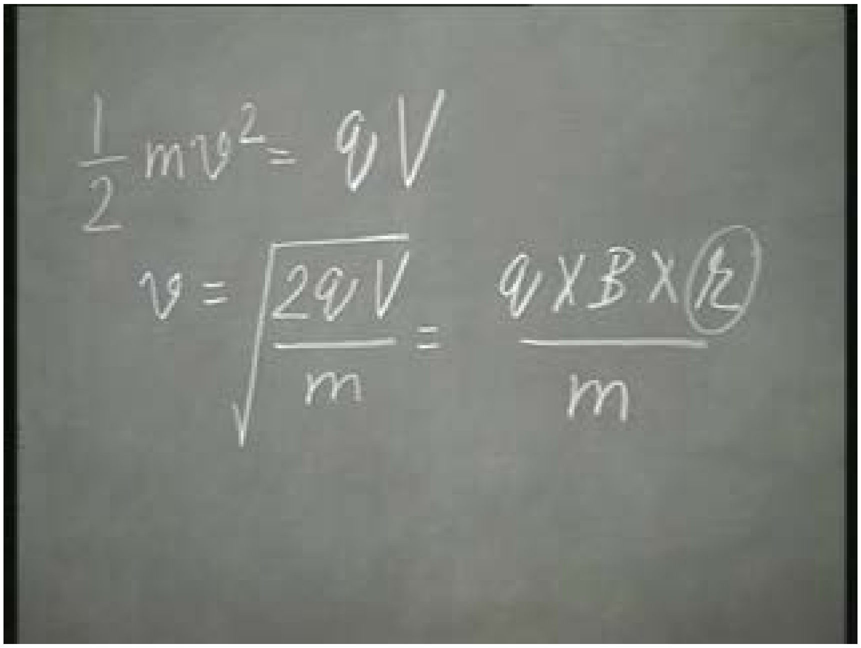

$$\frac{1}{2}mv^2 = qV$$

$$v = \sqrt{\frac{2qV}{m}} = \frac{q \times B \times \textcircled{r}}{m}$$

So, the kinetic energy of these particles is given by half mv square and that is imparted by the potential that is applied to it in the accelerator and if that potential is capital V, then this is the relationship; the potential energy gets converted into the kinetic energy. From this, therefore I can say that v is equal to square root of 2 q V; this V is the potential that is applied, divided by m. Now, if I substitute this value of v here, what do I get? I get this is equal to q into B into r divided by m.

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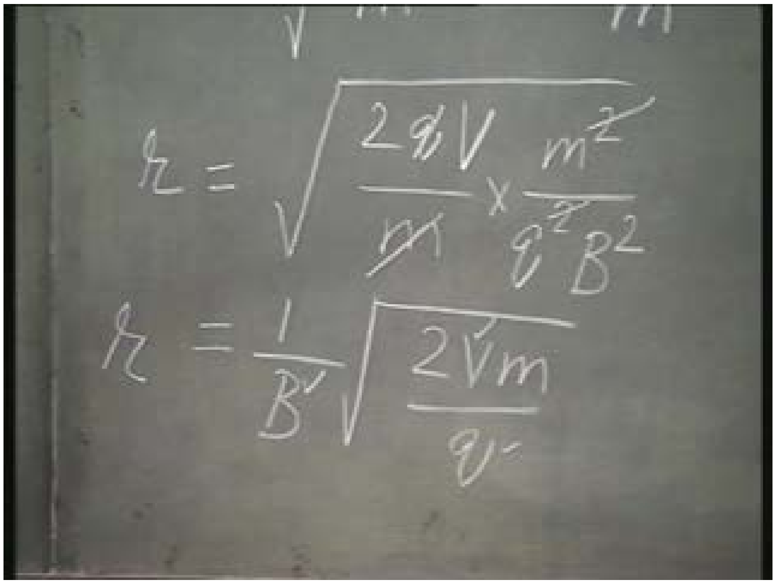

$$r = \sqrt{\frac{2\cancel{q}V}{\cancel{m}} \times \frac{m^{\cancel{2}}}{q^{\cancel{2}}B^2}}$$

$$r = \frac{1}{B}\sqrt{\frac{2Vm}{q}}$$

So, the radius of the circular motion of the particle that is r, r is therefore given by, r therefore can be given as 1 upon B square root of 2 capital V into small m divided by q, agreed. Now you see, in a particular system, I know what the value of B is, I know what the value of potential is and of course electronic charge that is the constant. Therefore, r is simply proportional to square root of m, where m is the mass of the particular ion species. What does it really mean? This is all mathematical equations. What does this really mean? In physical terms, what it means is this.

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If I have three different ion species with mass, masses m 1, m 2 and m 3, m 1 being the smallest, m 3 being the largest, m 2 being somewhat intermediate, then when they are passing through this magnetic analyzer, they will move with three different radius of curvature like this, agreed. So now, if I have a slit like this, if I place a screen here, you just oscillate, then this one gets stalled here, this one gets stalled here, but this one can pass through the slit. So, this is basically the mass separation scheme. Because you know that the radius of curvature is proportional to m, you can place a screen with a slit suitably, so that only that particular ion species with this particular mass will pass through this slit and therefore you have kept your semiconductor somewhere here, this is where your target is, it will go and hit the semiconductor, right. If you want even better control on this, then instead of using the simple homogenous field magnetic analyzer, you can use an electric and magnetic field together in mutually perpendicular directions, which is called the wind filter, you know the wind filter, the e cross h filter that can also be used and we have a fourth part of the implantation system.

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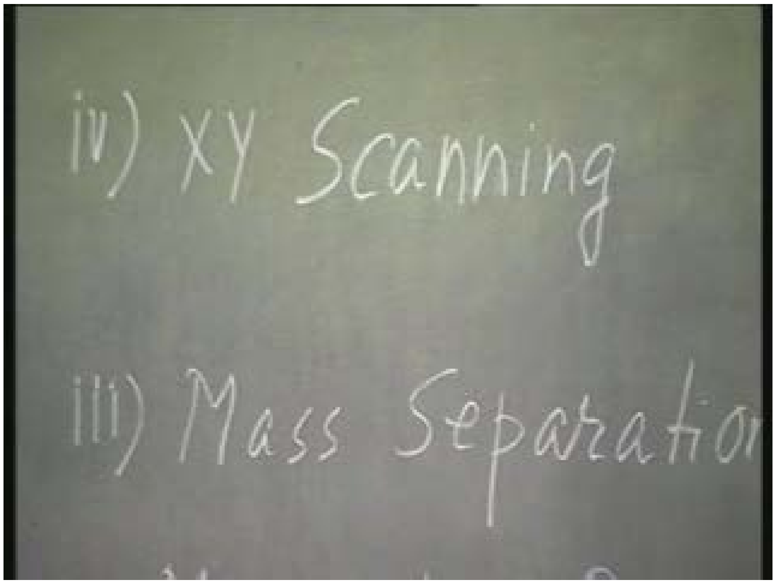

iv) XY Scanning

iii) Mass Separatio

If you have a small target, then this is good enough; you have the mass separation and this is coming and hitting on the surface. But, in actual practice you know you may want to scan over a larger area. So, this beam has to be scanned up and down, and to and fro. So, that is the final part of the implantation system, XY scanning. What you have now is an ion beam of a particular ion species after the mass separation stage. Now, this ion beam you can raster it all over the semiconductor wafer, right. So, you can use an XY scanning to move it up and down, to and fro, in order to implant all over the semiconductor, wherever necessary.

So, these are the four important parts of the implantation system. First of all, the ionization - the ion source, the dopant material as well as the ionization scheme, where you are creating the dopant species, the ionized species. Then, you have the accelerator where you are imparting velocity to this ion beam. Then, you have the mass separator, where you are selecting a particular ion species and finally the XY scanning in order to implant selectively over the semiconductor material.

Now, the question is how do we control the dose? What are the parameters we play with in order to control the dose? Controlling the dose is done in the first stage itself that is in the ion source itself. What we do is the parameter that the system operator has is the beam current. Now, what exactly is the beam current?

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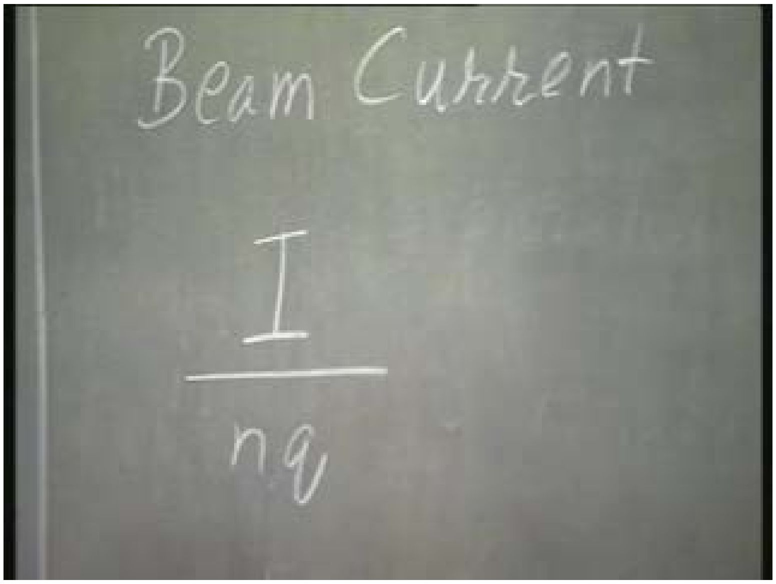

Beam Current

$$\frac{I}{nq}$$

The beam current is I; that is the parameter, the system operator has in hand. Now, if I have an ion species of mass, of charge q and say the charge state that is whether it is singly or doubly ionized, if I call that charge state say, n for example, then this I divided by small n times q is actually the number of ions hitting the semiconductor per unit time, right.

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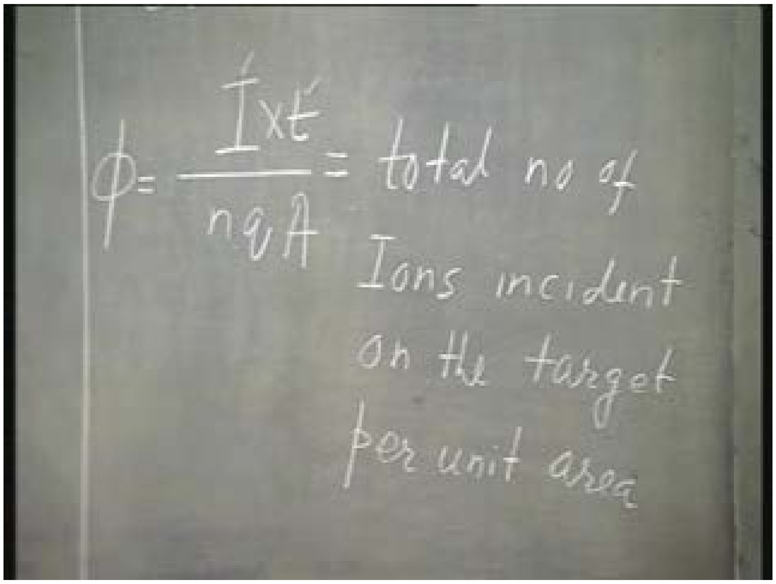

$\phi = \frac{I \times t}{nqA}$ = total no of Ions incident on the target per unit area

So, if I carry out implantation for a time small t, then I times t divided by n times q is the total number of ions that have hit the semiconductor surface, right and if the target area is capital A, then I times t divided by n times q times A is equal to the total number of ions incident on the target per unit area. What is this? Total number of ions incident on the target per unit area. That is equal to my total dose. So you see, you can control the dose either by controlling I or by controlling t or by controlling them together. So, for a practical system what would you want?

You would want a high beam current, right. If you have a high beam current, then you can impart a large dose within a relatively short time, agreed. t can be made small; if I is large, then t can be made small and still I can get a large enough dose. What is the advantage? Your throughput is faster, you can use the same implantation for various implantation run and the time for each implantation can be kept short. So, this is how the dose is controlled and of course, how deep the dopant is going to go that will depend on its energy and on its mass. If the dopant ion is light, then with a relatively less energy, it will go much deeper. If the dopant ion is heavy, then it will need comparatively greater energy, larger energy in order to penetrate through a comparable distance. So, you see these two things you can control separately. This is controlled at the ion source itself and the energy of course, you are going to impart in the accelerator. So, you have two parameters to play with: the beam current and the energy.

Now, so far you see, we have discussed only the positive aspects of implantation. That is we have discussed how good implantation is, how much better control, how much flexibility it offers, compared to diffusion for example. But, do not let us forget that implantation actually means, physically you are hitting the semiconductor surface with a stream of high energy particles and in the process it is going to create damage. You already know that once these ionized particles penetrate the semiconductor surface, it is brought to rest by two stopping mechanisms. One is nuclear stopping, the other is electronic stopping. Of these two, the nuclear stopping is the primary cause for damage, because it is colliding with the lattice atoms and in the process, imparting energy to the lattice atom. Sometimes this energy may be sufficient so as to cause displacement of the lattice atom.

Now, let us investigate this a bit more closely.

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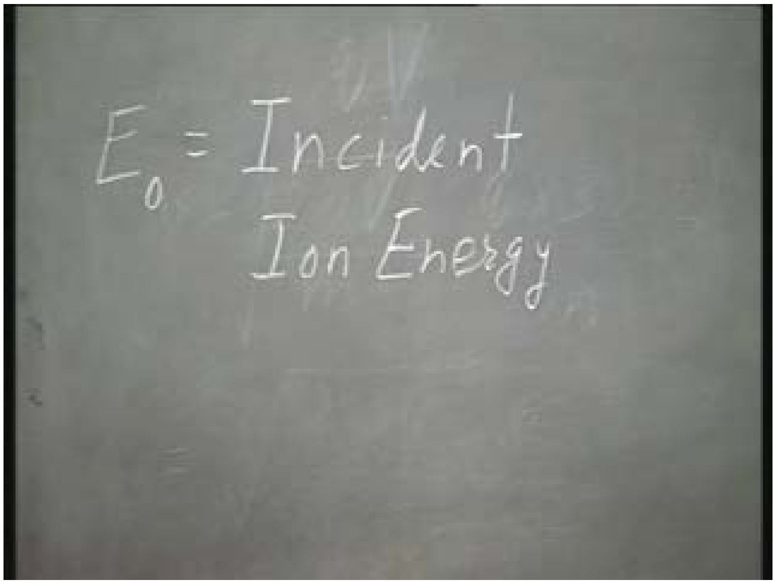

E_0 = Incident Ion Energy

Suppose the incident ion energy is E 0 and suppose E d is the energy required to cause displacement of a target atom.

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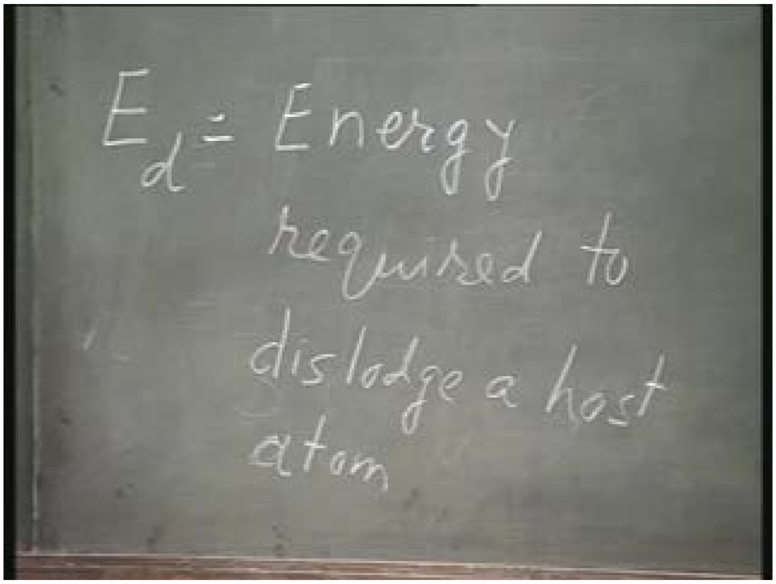

E_d = Energy required to dislodge a host atom

To dislodge a target atom from the lattice site we need an energy E d, energy required to dislodge a host atom. Then, if E 0 is less than E d, no problem, no displacement; the incident ion energy is not sufficient to cause any displacement. If however E 0 is greater than E d, but it is less than twice E d, then we will have a single displacement. It is greater than E d, it can cause a displacement, but it is less than 2 E d. So, we cannot have multiple displacement, right. But, suppose if it is greater than twice E d, then we can have multiple displacement or a cascade of displacements. So, the relationship between the incident ion energy and the energy required to dislodge a host atom will tell you how many, how much damage there is going to be.

So, on an average you can say that number of displaced atoms per incident ion will be given by E 0 by twice E d; on an average, you can say that it will be E 0 by twice E d. For silicon, this value of E d is 15 kilo electron volt and for implantation, we frequently use energies in excess of 100 kilo electron volts. So, you can understand how much damage there is going to be created, how many displaced lattice atoms there will be. So, obviously the atoms are, host atoms, are displaced from their original lattice site. There can be, they can create, they will create a vacancy as well an interstitial, so that means a Frenkel pair. So, a lot of Frenkel pairs can be generated, lots of damages will be there.

How to estimate and rectify this damage caused by implantation that is the major challenge. How to estimate the extent of damage and then how to rectify it? So, damages caused by implantation is the major flip side or the major negative aspect of implantation - damages caused by it. Unless and until we can rectify these damages, the semiconductor will be of no use. So, first of all how do you, how do you make out whether there is damage or not? A very crude way of making out whether there are damages is by visually inspecting. You know that a normal silicon surface is going to be mirror polished, right; the top surface on which you are going to fabricate, you are going to dope, you are going to create your devices close to the top surface, that top surface is going to be mirror polished. If there are damages, then the mirror polish will be the first causality. The mirror polish will be lost; you will have a sort of cloudy or milky surface.

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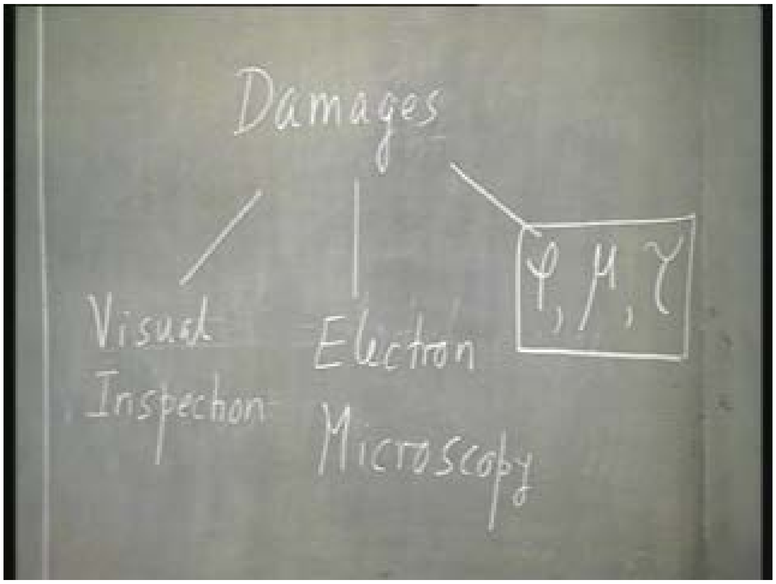

So, damages can be inspected first visually. This is of course a very crude way of looking at things. Immediately after implantation, we will find that the surface has become cloudy or milky. So, you will know that the surface is damaged; that is all. You cannot estimate any better than that, it is very crude way of looking at it. If you really want to estimate the extent of damage directly, then you can try electron microscopy or you can try rather …. back scattering, which will tell you about the exact crystalline imperfections present in the damaged surface. So, you can try electron microscopy. But we, the technologists, the VLSI engineers, do not forget we are primarily electrical engineers, so we are concerned about the electronic activity of the surface, right. We are not interested in the crude visual inspection or in the crystal imperfections, the direct investigation of the crystal imperfections. We are interested in figuring out how the device performance is going to be affected; what are the parameters, what are the factors which have got affected, that is of concern to us. What are these factors?

First of all for an electronic engineer, the most important idea is the conductivity, right. In a damaged surface, the conductivity is going to be extremely low. You are going to have a highly resistive surface, because of the damages; the electronic activity will be extremely low. So, change in conductivity and then, in a damaged surface, the mobility is also going to be extremely low. So, mobility is the second causality and finally the life time that is the third causality. So, we are most interested about these three factors. How rho has changed - how the conductivity has changed, how mu has changed - how the mobility has changed and what has happened to the life time?

Obviously, as a result of the implantation damage, all these three factors are going to get degraded and how much they have got degraded will give me an estimation of the damage. This is the only estimation I am interested in, because it is going to reflect directly on the device performance and I will say that I have rectified the damage only when I can restore these three factors to their expected value, right; because these are directly concerned with the device performance. I have to get back the electronic activity that is I have to get the active carrier concentration. You see, I may have put so many dopants inside the system, inside the semiconductor by ion implantation. But, they are not electronically active. That is why the resistivity is very high, rho is very high. I must get the active carrier concentration. Secondly, the mobility of that damaged region will be extremely low. I must get back the expected high mobility and then I must get back the expected carrier life time.

Before we try to get back these three factors to their expected value, let us look at the nature of the damage as …… when the implantation is due to a, I mean, when we have doped the semiconductor with a heavy ion such as phosphorus, compared to when we have doped the material with a light ion such as boron. Will there be any basic difference in the nature of the damage? Let us try and investigate that first. You know what happens when the ion beam is incident on the semiconductor. It is going to lose its energy and primarily, nuclear stopping is the mechanism that is responsible for the damages.

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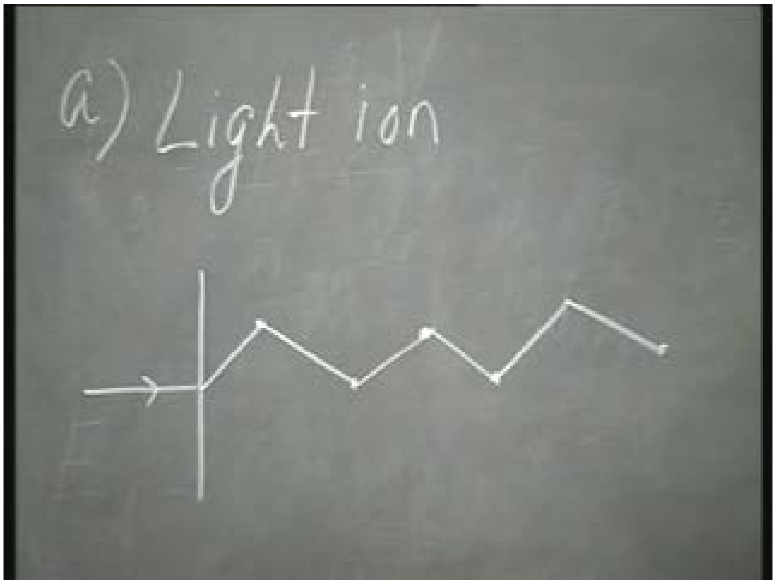

So, when a light ion is incident on the semiconductor, let us talk about light ion; it has got a small mass, it hits the substrate, under goes collision with the lattice atom. So, during each collision, it is transferring a relatively small amount of energy and because this incident ion in itself is a light ion, at each collision it is getting displaced through a large scattering angle, right. The lattice atom is much heavier compared to the incident ion. So, incident ion is getting deflected by a large scattering angle, but it is transferring only relatively less amount of energy. So, if this is the semiconductor surface and if this is the ion beam coming, then you see its path is like this. It hits here, in the process it gets deflected by a large angle; it is absolutely random, it can be this way or this way. Then again, it hits a lattice atom. Again it gets deflected by a large angle and the process continues and at each collision, since it is transferring a relatively smaller amount of energy, it is moving through a considerable distance before coming to rest. So, what you see is actually a long narrow branch of damage.

The damage will be relatively less in this case, because you see at each collision it is transferring relatively small amount of energy to the lattice atom. So remember, that I need minimum of E d 15 kilo electron volt for silicon; E d is 15 kilo electron volt in order to dislodge the host atom. Because the light ion is transferring a smaller amount of energy, it may not be sufficient to cause multiple dislocations. So, at every point you see, I have just a small damage. But, the incident ion is moving much deeper. So, I have relatively less damage, but a long narrow branch. This is what is going to happen in case of a light ion incident; an extended region with small branching dislocation, …. here and here, may be a small this thing; if any multiple dislocation is taking place, it is very small at these points.

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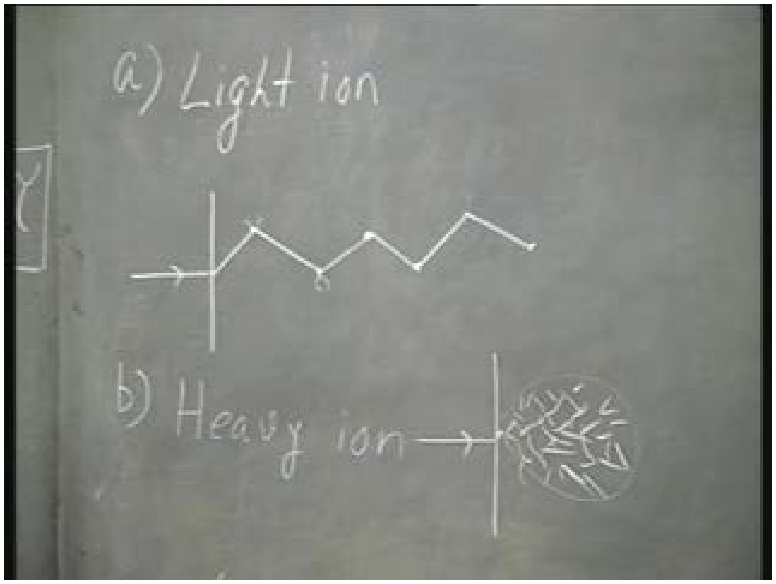

Now, let us take the case of a heavy ion. As before, this is the surface. Now, what is going to happen? This is a heavy ion. At every collision, it transfers a large amount of energy to the lattice atom and it gets deflected only by a small scattering angle, right. So, because it transfers a larger amount of energy to the lattice atoms, those lattice atoms in their turn will again cause dislocations and I will have multiple dislocations. At the same time since the incident ion is suffering, it is getting deflected only by a small scattering angle, I will have the maximum damage within a small region, agreed. So, what I will have is actually a horribly damaged region, but within a small volume. At every point, there is a collision and that collision is sufficient; there lattice atom has obtained sufficient energy, so as to cause further damage. So, it is full of damages, that region is full of damages, but within a smaller volume. So, you see essentially, the nature of the damages for a light ion and a heavy ion is basically they are very different. For the light ion I have an extended region with relatively less damage, for a heavy ion I have a lot of damage confined within a small volume. So, before I try to rectify the damage I must know whether the incident ion was light or heavy, then accordingly we can plan our actions.

Now, the other factor that is going to contribute to the damage is the dose. That is very easy to understand. If I have a large enough dose that means here I have shown you just for one single incident ion, if I have large enough dose, so many such ions, the whole thing is getting multiplied. So, if I have a large enough dose the damage is more; if I have a small enough dose, the damage is less. If now I have a large dose of a heavy ion, phosphorus for example, a large dose of phosphorus, then the damage will be so heavy, so that there is a possibility of an amorphous layer formation in silicon. So much damage that its crystalline structure is completely lost and the material has become amorphous in nature.

Obviously, for the light ions, for example boron, the dose required to amorphize the silicon will be much larger compared to phosphorous, because I have to create the same amount of damage in order to amorphize the region. Since boron is a much lighter ion, the creation of damage is much less. Therefore, in order to amorphize silicon, the dose of boron must be much, much heavier, right. But do not think, do not go away with the impression that this is something very bad; that amorphization of silicon is something very bad. It is not bad; in fact sometimes it can be used to our advantage. What are these advantages? First major advantage is of course in the control of the doping profile.

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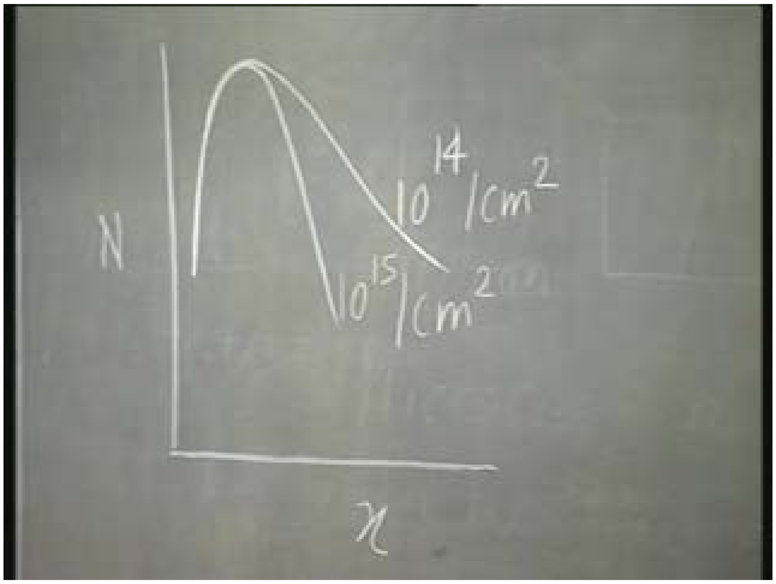

If you have an amorphous surface, then of course all the channeling and all that will be much less and I will have a primarily Gaussian profile. If the dose is more, you will have a more Gaussian profile than if the dose was less. That is why, sometimes prior to implantation, silicon is pre-amorphized by self-implantation or by an inert implantation. You can either implant Argon or neon or you can self-implant. That is you can implant silicon on silicon in order simply to amorphize the region, so that in that amorphous region when you next carry out the implantation, the profile will resemble a Gaussian more closely. So, now you have a damaged region depending on whether the incident ion is light or heavy, the dose is small or big, you have extent of damages and you know how to estimate the extent of damage also. For us the most important factors to estimate this damage are the changes in conductivity, mobility and the life time.

Now, we have to rectify this problem which is called the annealing of damages. Damages must be annealed out. Annealing essentially means a high temperature treatment; subject the material, the damaged material to a thermal treatment, when the damages will get annealed out. Now ideally speaking, ideally what should we have? We should have complete recovery, complete recovery of the life time, complete recovery of mobility and 100% carrier activation; that is on one hand, this is what we want. But in practice, we may have to fall short of this ideal requirement. What are the reasons? Why do we have to, may have to fall short of these things? One is in the material itself. Silicon can be subjected to 1200 degree centigrade with no problem. But, if silicon already has a metal pattern on that, if it already has an aluminum pattern on that, then you cannot subject it to a temperature higher than 500 degree centigrade. So, the material tolerance may be a problem and the second problem is of course, the longer and the longer is the duration and the higher is the temperature of annealing, remember there is going to be considerable change in the doping profile. It may not resemble the doping profile that was dictated by the ion implantation, because in this case, ion implantation is going to be followed by drive-in.

Effectively what you are doing is after ion implantation, you are subjecting it to a drive-in. So, the doping profile may get considerably changed, if D t is considerably large. D t may even become larger than your projected range and in which case, the ion implantation profile may get completely changed. So, these are the two major factors which will dictate your annealing time and temperature. On one hand, you would like to have the maximum carrier activation - 100% carrier activation, full 100% mobility, recovery and recovery of life time. On the other hand, you may be constricted to use a less than perfect temperature and time for the annealing.

Now, in this case, let me just tell you some general guide lines. First of all, the lower the implantation dose is, the easier it is to anneal it out; lower dose lesser damage, lesser damage, the easier to anneal it out. That is one factor. Second factor is even here you see, the crystal orientation matters. It is found that 1 0 0 anneals faster than 1 1 1and now when we discuss about annealing, there are essentially two cases. One case is where the silicon was amorphized prior to or during implantation and the other is where the silicon retains its crystalline nature. You will be surprised that the silicon which was pre-amorphized or amorphized during implantation is relatively easy to anneal than silicon which was not amorphized. That is why I said amorphizing may not always be a bad idea. In fact, it does offer certain advantages. This we will discuss in the next class.