Processing of Semiconducting Materials

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Lecture - 9
Diffusion and Ion Implantation – III

In my last lecture we have discussed about the diffusion. As I mentioned earlier that there are two techniques which are usually used for the doping in semi conductor; one is diffusion, another is ion implantation. But remember that these type of diffusions or ion implantation is used to form junction. Generally not to diffuse the whole material not to dope the whole material during crystal growth, I shall show you that during crystal growth the doping is made.

Suppose you want to make silicon n type or p type. So, it is made during the crystal growth itself by adding required amount of arsenic or phosphorous or boron etcetera, but you if you have a p type material or an n type material and you want to dope it by n type or p type for the formation of a p n junction or some for device fabrication like say CMOS etcetera, then you need this kind of either diffusion or ion implantation.

So, since we have covered the diffusion earlier. So, now we shall start implantation ion implantation. So, as the name implies, you will find that ion implantation is nothing but the implantation of ion, inside the material. So, the process involved will be first you have to take a material, suppose you would like to dope by boron. So, you have to take boron, then that boron has to convert into ion then its mass and energy must be increasing, yes. And finally, it will fall on the surface of the substrate or the wafer on which you want to dope. So, this is a process and you know that the ion implantation process is done by some ion implanter, using some cyclotron or that type of a machine.

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Ion Implantation

Introduction of energetic, charged particles into a substrate

Implantation energy: 1 keV to 1 MeV

Average depth: 10 nm to 10 μm

Ion dose: 10^{12} to 10^{18} ions/cm^2

(no. of ions implanted into 1 cm^2 surface area)

So, in this view graph, I have given some introduction on ion implantation, you will find that ion implantation is nothing but the introduction of energetic charged particles into a substrate. And the energy I have written that it is a introduction of energetic. So, what is the energy? The energy of the beam must be 1 KeV to 1 MeV, 1 KeV to 1 MeV. Now, what is KeV and MeV? KeV is kilo electron volt and what is MeV? Mega electron volt; mega electron volt 10 to the power 6, so the energy is very, very high. You find that normal electron volt is very is less amount of energy, the band gap of silicon is 1.12 electron volt, but if u consider the implantation, then it is very, very high. The order of 1 MeV and another thing is that what is the average depth that can the ion beam penetrate it is from 10 nano meter to 10 micron.

So, deep inside the material it can reach minimum can be 10 nano meter and inside it can be 10 micron also. The ion dose; the dose is defined as the number of ions implanted into 1 centimeter square surface area. So, number of ions implanted into 1 centimeter square of surface area. If this is the definition of the dose, then the ion dose is basically 10 to the power 12 to 10 to the power 18 ions percent centimeter square. Remember per centimeter square. So, if you have a wafer of say 2 inch or 4 inch or 8 inch diameter, then you convert the area using the formula pi r square because it is almost circular in shape. So, you use the pi r square formula and then you convert the total number of ions etcetera.

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Ion Implantation: advantages over diffusion process

More precise control of the amount of dopant

More reproducible doping profile

Lower processing temperature

Now, this ion implantation has some distinct advantages over diffusion process distinct advantages over diffusion process. One thing is that the advantage is that ion implantation is done at very lower temperature lower processing temperature in diffusion, we have seen that how much temperature. It needs of the order of 1000 degree centigrade, 1200 degree centigrade. So, very high amount of energy is associated for diffusion, but you know that for diffusion the energy is dissipated for the formation of the vacancy as well as the movement of the impurity atom inside the crystal lattice.

So, for that reason you must enhance the temperature and we have seen that for silicon the temperature is almost 1000 degree centigrade, right? But for ion implantation you see that the processing temperature is low. Low means it is almost to room temperature almost to room temperature another thing is that more precise control of the amount of dopant control is very precise.

In this case because you can measure the beam current this dose or the amount of dopant can be controlled by the beam current one parameter is there it is known as the beam current. Using the beam current, you can control very precisely and using a mathematical problem. I shall show you that how the beam current is measured and how the beam current is related to the dose and more reproducible doping profile in case of diffusion? Sometimes we find that during diffusion the doping profile can change depending on the temperature depending on the dose depending on the surface concentration. So, profile

can change profile means the trajectory inside the material from the surface to the maximum depth it has covered. So, these are the advantages of ion implantation, remember that the most important advantage is the low temperature.

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Doping layers can be implanted without disturbing previously diffused regions (due to low temperature)

Ion beam current can be measured accurately during implantation so precise control of doping concentration is possible

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Another thing is that advantage is that the doping layers can be implanted without disturbing previously diffused regions previously diffused regions. Means suppose you have a material already n type doped you want to make a p n junction. So, you have to dope the material with p type. Now, if the temperature is increased. So, what will happen already there is doping inside the material because it was already n type.

So, those dopant atoms cannot change their position inside the material as you go on increasing the temperature during diffusion. So, what will happen to the already diffused atom they can also move. So, that means, the crystal structure can change. So, that is the thing that in ion implantation you can dope without disturbing previously diffused region. Suppose already there is a small region say you want to make a shallow junction.

So, already there is a say 1 micron or 0.1 micron p layer is there, but if you further increase the temperature by say 100 degree, 1000 degree centigrade, then what will happen that p region which was earlier say 0.1 micron, it will move deep inside the material. So, you cannot control the depth. So, this is the advantage that in implantation without disturbing the previously diffused region because of the low temperature associated during implantation. As I have already introduced the term ion beam current

and we discussed that the ion beam current can be measured accurately during implantation. So, precise control of doping concentration is possible. So, these are the advantage of ion implantation over diffusion.

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Ion Implantor

Ion Source: heated filament to break up source gas (BF_3 or AsH_3 into charged ions (B^+ or As^+)

Extraction voltage (40 kV): causes charged ions to move out of the ion source chamber into a mass analyzer.

Magnetic field: to choose only ions with the desired mass-to-charge ratio

Acceleration tube : accelerated to the implantation energy

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Now, ion implantation is made using an ion implanter. There is a machine which is known as the ion implanter it is basically a cyclotron type of machine using which the material ion is first produced it is accelerated. Then it is scanned through some electrostatic deflection and then it is implanted on the surface of the material say this is the surface of the material. So, the beam will come and it will be accelerated. Then you can scan the beam you can scan the beam means where it will fall here or here or there. So, you can scan or the whole surface are you can scan and then it will penetrate inside the material through the surface and then it will come to rest after struggling certain distance here. The ion source is one of the important important component of an ion implanter.

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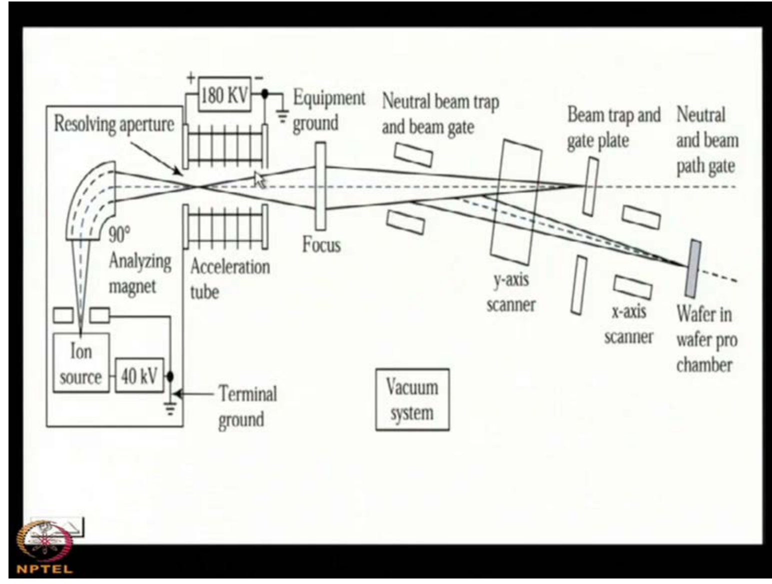

Let me show you the ion implanter. This is the ion implanter machine, this is the huge machine and very costly machine. You see that there is an ion source here is there is an ion source. So, first you have to make the ion from the source material. So, that means, for ion source heated filament is used to break up source gas into charged ions. So, you have to take a gas say it is a BF 3 or AsH 3, right? That gas you have to break into charged ions by using some heated filament and the ion will be produced either B plus. As plus depending on the nature of the ion you will find the ions then there is an extraction voltage 40 kV, very high voltage. You see that this is the 40 kV voltage which is connected with the ion source.

So, this 40 kV extraction voltage causes charged ions to move out of the ion source chamber into a mass analyzer, that means, that voltage is used to move it outside from the ion source to the mass analyzer. Then there is a magnetic field to choose only ions with the desired mass to charge ratio, because for ion it is very important you have to choose the mass to charge ratio. Then it is sent to the acceleration tube it is accelerated to the implantation energy. So, this is the process that first there is a ion source, then you make the ion you analyze the ion. Then this is the acceleration tube through which it will pass it will it you can accelerate the ion to proper energy.

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Apertures: ensures well collimated ion beam

Pressure: < 10^{-4} Pa to minimize ion scattering by gas molecules

Ion beam is scanned over the wafer surface using electrostatic deflection plates

Energetic ions lose energy by collision with (i) Electrons, and (ii) nuclei in the substrate and finally come to rest at some depth within the lattice.

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Then that is apertures which ensures well collimated ion beam. So, that it does not get deflected. It is get deflected, then the control will be very difficult. So, that is why that is a collimated ion beam and you see that this is the, this collimation is there. So, that then aperture this aperture you can control the diameter of the aperture as per your requirement, it depends on the diameter of the ion beam. You can increase the diameter, you can decrease the diameter. Suppose, you want to fall the ion beam into say 1 centimeter square or it can be say 10 centimeter square depending on your requirement. So, you can change the aperture as well.

And another important consideration is the pressure that pressure inside the chamber inside the accelerator is must be it must be 10 to the power of minus 4 Pascal. It is very, very small pressure to minimize ion scattering by gas molecules because if it the, if it is not evacuated, then what will happen? There will be gas molecules inside, the tube inside the tube there will be gas molecules. So, when the ion beam will travel through the gas molecules it will be scattered. So, it will be scattered. So, it can lose its energy that direction can be changed by scattering. So, that is why care must be taken. So, that the acceleration tube or the tube through which the ion beam is passing is almost evacuated that is why 10 to the power of minus 4 Pascal less than this is required. Then the ion beam is scanned over the wafer surface using electrostatic deflection plates.

And finally, the energetic ions lose energy by collision with either electrons, and nuclei in the substrate. Finally, come to rest at some depth within lattice. So, most important thing of the ion implantation is this part; that means, the how the energetic ion will lose their energy there must be collision inside the material. So, inside the material what type of collision can be done what kind of collision can be made; one is that the in a atom there is a cloud of electron. So, there can be scattering with the electrons it will collide with the electrons or it can collide with the nucleus. So, there are two possibilities and we shall show that it depends on the energy whether it will collide with the nucleus or with the electron cloud.

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Average Depth: controlled by acceleration energy

Dopant Dose: controlled by monitoring the ion current during implantation

Side Effect: Disruption/Damage of the semiconductor lattice due to ion collision

To remove the damage: annealing

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Now, you want to make a junction. So, what should be the junction depth from the surface? How it can be controlled? It can be control by the acceleration energy, it can be 10 KeV, it can be 100 KeV, it can be 1 MeV. So, depending on the acceleration energy it will travel the distance inside the material and the dose will be controlled by monitoring the ion current during implantation, but there is side effect for diffusion. We do not have any side effect here there is a side effect and the side effect is the damage of the crystal lattice. The damage of the crystal lattice suppose we are working with silicon, you are you would like to implant something inside silicon.

So, silicon crystals had some has some atomic arrangements and it has some precise energy. If you give that energy the atoms can be displaced or replaced like the creation of

vacancy etcetera. We have shown that how much energy is required during the vacancy type of diffusion.

So, now here the energy is very very high severely high. So, what will happen? It will collide and during collision all thing will be damaged inside the material, it will be damaged and because of this damage sometimes the crystalline material because all semiconductor device is processed using crystalline material barring a few I shall give those examples also. Almost all electronic device you need crystalline where is single crystal material high purity, very high purity single crystal material.

Now, if you use an ion implanter and it damages your crystal structure inside the material. So, what will happen basically the crystalline structure can be converted into amorphous even can be converted into amorphous, amorphous even. So, if it is converted to amorphous, then what will happen your ultimate goal cannot be achieved because the ultimate goal is to use some device to use that material for fabrication of some device. So, for that crystalline is required. Why amorphous is not used, can you tell me? Why we are scared about amorphous state for semi conducting materials? What is the difference between crystalline and amorphous?

Student: (( ))

Basically for an amorphous material, it is completely random arrangements of atoms in the crystal lattice. There is no periodicity it is completely random and due to that randomness the scattering will be very, very high. So, if the electrons scattering is very very high, then the mobility will fall mobility will decrease. So, that is the reason amorphous material is not used for normal electronic device. It has some other applications amorphous is also used I shall show you in some particular applications in say solar cell in xerox machine. Those materials are also useful, but not for electronic device application.

So, you will that the side effect is disruption or damage of the semiconductor lattice due to ion collision and to remove the damage annealing is done. So, what is the annealing annealing is nothing but what is annealing heating?

Annealing is heating at a particular temperature for a particular time period, if you heat the material under certain ambiance. So, it will restructure inside the material the atoms

will restructure it is themselves, the material will restructure itself to its original situation original face. That means, if the crystallinity changes, then using annealing crystallinity will regain. So, that is the side effect and the side effect can be treated as well.

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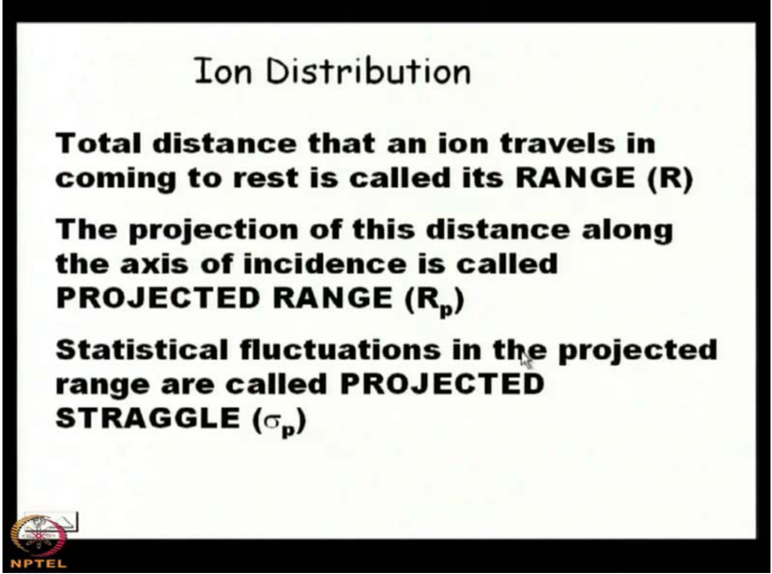

Now, some definition total distance that an ion travels in coming to rest is called its range. Total distance that an ion travels in coming to rest is called its range total distance is range.

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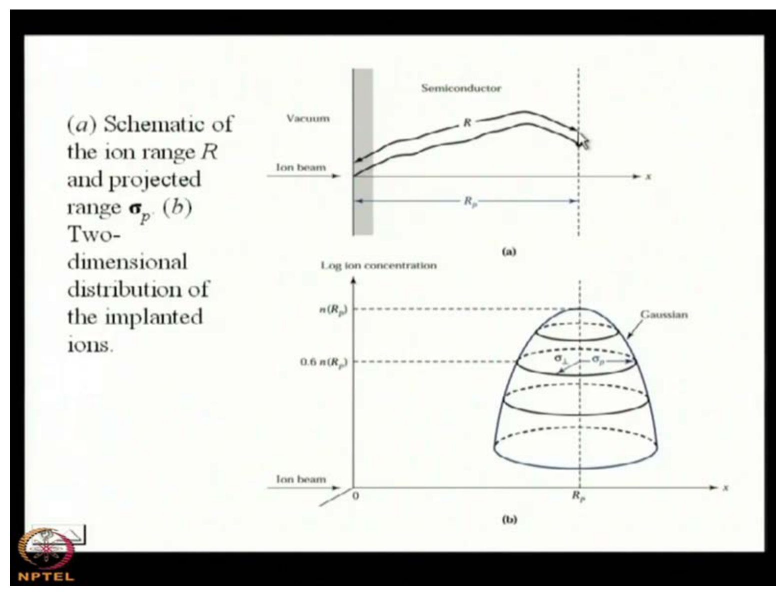

So, that means, this is the range this is the range you see that this is surface this is surface and from surface to deep inside the material it is that is it trajectory inside the material remember? So, that is the range this is the ion range and the projection of this distance along the axis of incidence is called projected range. So, one is range another is projected range the projected range is nothing but the projection of this distance along the axis of incidence. So, this is range and this is projected range R P is the projected range; that means, it is the along the axis.

So, that means, R P is the minimum distance R P is the minimum distance from the point of incidence to the point of final penetration or termination of the ion beam. Suppose, the ion beam is penetrated at this point the incident point is here and it has moved through this trajectory. Finally, come to rest here, so along the axis the distance is known as the projected range, right? Another thing is that statistical fluctuations in the projected range are called projected straggle. So, we shall use projected range and projected straggle straggle means statistical fluctuations because you know that the mass and charge is different the energy you can control.

So, different ion will reach at different time different position. So, there will be a statistical distribution of the ion inside the material that is why that statistical fluctuations in the projected range are called projected straggle, s t r a g g l e yes. So, this is the range and this is the straggle, this thing is straggle; that means, this sigma P is the straggle sigma P is the straggle.

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Implanted impurity profile

$$n(x) = \frac{S}{\sqrt{2\pi}\sigma_P} \exp\left[-\frac{(x - R_P)^2}{2\sigma_P^2}\right]$$

S: ion dose per unit area, R_p: projected range, σ_p: projected straggle

Compare with Diffusion Profile

Now, the implanted impurity profile using an ion implanter will take the shape of Gaussian distribution people have calculated and the concentration or the ion dose is given by S by root 2 pi sigma P sigma, P is the straggle; that means, this is the statistical fluctuation exponential minus x minus R P whole square by twice sigma P square. What is S S is the ion dose per unit area? Ion dose per unit area sigma P is the straggle R P is the projected range R P is the projected range. So, if you write down this expression for the profile this is remember this is for the ion implantation. Now, if you can compare with the diffusion profile. So, what you will find if you can compare with the diffusion profile.

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$$n(x) = \frac{S}{\sqrt{2\pi}\sigma_P} \exp\left[-\frac{(x - R_P)^2}{2\sigma_P^2}\right]$$

Constant-total-dopant diffusion

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

S: total amount of dopant per unit area

4Dt is replaced by $2\sigma_p^2$.

Distribution is shifted along x-axis by R_p

So, this is the implantation this profile is due to the implantation just now. We have write down the value this expression and the and that for diffusion this is the expression that we have deduced in the last class C S by root pi Dt exponential minus x square by 4 Dt. So, this is for diffusion and that is for ion implantation. Now, what is the difference or is there any similarity between them? Obviously, there is some similarity between them if you find that this expression you just replace 4 Dt by 2 sigma P square this 4 Dt and this 2 sigma P square if you can replace this 4 Dt by 2 sigma P square, then it will assume the same shape like the upper one except that there is a shift in the distribution. Earlier it was at x now it will be x minus R P. So, there are two important approximation that you can make, if you can understand the doping profile of the implantation with the diffusion.

Student: Excuse me sir

Yes.

Student: Sir, in that formula…

Yes?

Student: In (( )) profile if sigma P is under root or outer root.

Which one?

Student: S sir. S by n x.

Root Dt.

Student: No sir (( )) that side sir.

Sigma P is outside.

Student: Yes sir.

Yes sigma P is always outside. So, if you compare these two relations, so you will find that if 4 Dt is replaced by 2 sigma P square and x is shifted along and the distribution shifted along x axis by R P. Then these two thing will be similar, now one thing we have discussed in our earlier lecture is that for diffusion the peak concentration will be at the surface, but for ion implantation it will be inside. The material for some distance there will be a peak. So, now, you can explain that observation using these two relation why for diffusion this expression is maximum when x equals to 0 when x equals to 0? Then C is maximum, so that means the maximum concentration will be at the surface and it is maximum when x equals to R P for this expression. This expression is maximum when x equals to?

Student: R p

R P. So, R P is not x equals to 0 R P is not obviously, x equals to 0.

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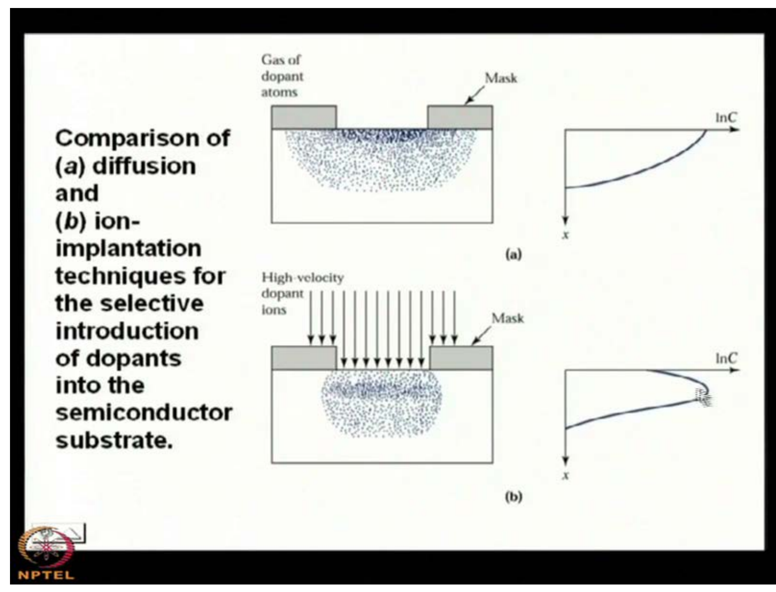

So, now, if you can move to our earlier slides, you can see that the changes you see in these in this view graph, you see that here it was maximum at x equals to 0, here the maximum was not at x equals to 0, but for some position R P. So, this is R P this peak is that R P. Now, it is clear? Why the maximum concentration was at the surface for diffusion and at R P for ion implantation it is because of the expression we have used for the doping profile.

Student: Sir.

Yes?

Student: When a relation of n x and C.

Yes.

Student: C x t the coefficient have been matched 2 sigma square is equal to 4 Dt.

If 2 sigma square is equal to 4 Dt, then it is matching why it is not matching.

Student: Coefficient sir, coefficient term (( )).

Which one?

Student: S by root over of 2 S by C.

It is matching; obviously, it is matching.

Student: There is 2 sigma P square is equal to Dt.

4 Dt.

Student: In coefficient sir, it is not matching.

It is it is completely matching.

Student: Yes sir.

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Ion Stopping

Two mechanisms: (by which an energetic ion, on entering a semiconductor (target) can be brought to rest

1. By transferring energy to target nuclei: causes deflection of incident ion beam, displaces many target nuclei from their lattice sites.
2. Interaction of ion with the cloud of electrons surrounding the target's atoms: Ion loses energy in collision with electrons, electrons can be excited to higher levels or can be ejected (ionization)

That is not the problem, you come to my office I shall show you then ion stopping. That is important consideration, that how the ion beam will be stopped inside the material. There are two mechanisms by which an energetic ion on entering a semi conductor target can be brought to rest. So, the semi conductor which the implantation is made is known as the target the semiconductor surface or the semi conductor wafer on which you want to implant the material is known as the target. So, when ion beam will incident on the target. So, it will come to rest by two mechanism one is by transferring energy to target nuclei it causes deflection of incident ion beam displaces many target nuclei from their lattice sites. It is like the collision of the two hard spheres it is the collision of the two hard spheres like this thing.

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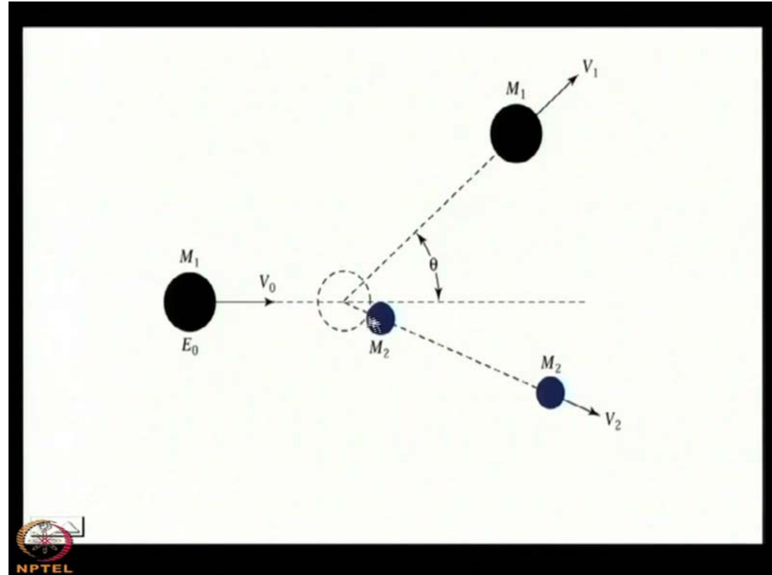

You see that this is your target with M M 2, it is at rest and this is your ion beam of mass M 1 energy 0 moving along with V 0 velocity. So, if they collide what will happen?

Student: Momentum deflection.

Yes.

Student: Scatter.

So, they will scatter here, the M 1 will move to that direction and the host atom will move through another direction it will with V 1 it is will V 2 etcetera, right? So, one thing is that by transferring energy to target nuclei and it will cause deflection to the incident beam you see that the beam was in this direction, but there was a deflection theta. So, now, the beam is going with a making an angle theta with its own original direction.

So, there is a deflection and it displaces many target nuclei from their lattice site like this. It was this nuclei was at this point it is displaced. Now, to this site obviously, because the energy is very, very high and so you can expect that type of a situation will happen during ion implantation another is the interaction of ion with the cloud of electrons surrounding, the targets atoms. So, ion loses energy in collision with electrons and electrons can be excited to higher levels or can be ejected.

That means either there will be a excitation of electrons from lower level to higher level or the ionization can be possible, that means the it can eject from its own position depending on the energy value. So, these two situation can happen, one is the collision with the nuclei for which both the nuclei and the atom will be both the nuclei and the ion will be displaced from their original direction.

Another is the collision with the electrons for which the electrons will gain energy, they will move from lower energy state to higher energy state or they can be ionized as well because you see that if you implant with say 10 KeV or 100 KeV of ion beam. Then it is a huge energy and that energy and if you stop that ion beam. So, where the energy will go? So, energy will be transferred to the nuclei or to the electron, and they will obviously energized and that energy gain you have some consequence one is the deflection another is the ionization.

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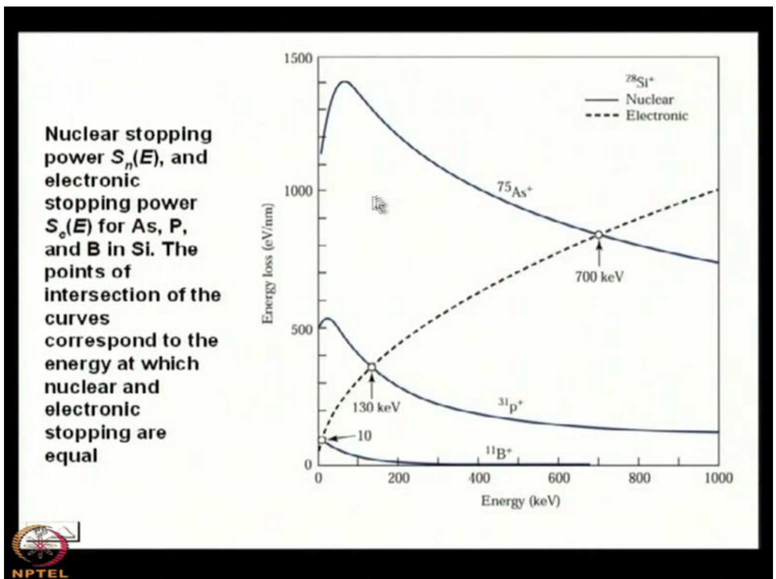

Here you see that there are three ion, we have used one is arsenic. This is arsenic, this is phosphorous and this is boron. Boron phosphorus and arsenic three ions, we have used in silicon. Obviously, it is silicon and this solid line is due to nuclear energy loss and dotted line is the electronic energy loss for silicon the electron energy loss is this dotted line, but for nuclear energy loss there are three different lines for three different nuclei. For, why electronic energy loss is not different, who can tell? Only one curve, we have shown for the electronic energy loss it is it is very simple because that.

Student: (( )).

Yes it is, it is for the silicon only. If the boron or the phosphorous or the arsenic or whatever be the ion is stopped by the electron whose electron are there it is silicon. So, for silicon the energy is same that is why that is the curve the dotted curve is there for electronic energy loss, but for nuclear there also the silicon nucleus is involved. But two bodies involved one is the ion of phosphorous with silicon or the ion of boron with silicon or the ion of arsenic with silicon.

So, three different curves are there. Now, what we find from this curve? Why we are interested about this curve? It is because you see that when the energy of implantation is low when the energy of implantation is low you see in the x axis, we have plotted the energy. So, when the energy is say this 10 10 KeV or even less what we find.

Student: Loss (( )).

That the energy loss will be due to electronic the energy loss will be here electronic. Then if you increase the energy for boron you see that for boron the curve is at the lowest position, so then if you increase the energy say 400 KeV, so this 400 KeV is basically this position. So, it will be electronic energy loss it will be electronic energy loss. So, far as the boron is concerned it will be electronic energy loss.

Now, if you take phosphorus as an example. So, beyond 130 KeV beyond 130 KeV the loss was due to nuclear, but if you cross 130 KeV the loss will be due to the electronic, but for arsenic till 700 KeV. The loss will be due to nuclear only and above 700 KeV the loss will be electronic. So, as you go on increasing the atomic mass boron phosphorous and arsenic. If you compare the atomic mass obviously, boron has the lowest and arsenic has the highest. So, as the atomic mass increases, you will find that that the loss will be more and more more and more nuclei for boron. It is almost above 10 KeV, it is fully electronic for phosphorus above 130 KeV. It is electronic and for 700 KeV arsenic, it is electronic above 700, right?

So, this is the implication that the stopping of the ion beam inside the material will entirely depend on the energy of the ion beam and the ion itself. If the ion is say arsenic and you are using say 400 KeV. So, what you will expect if the ion beam is arsenic and you are implanting at 400 KeV.

Student: Nuclear collision.

It will be nuclear. So, all the energy will be lost during the nuclear collision, right? Similarly, if you consider that say that you are using the 600 KeV ion beam of phosphorus.

Student: Electronic electronic.

It will be obviously electronic, right? So, people have calculated graph is available data is available and you can see whether it will be electronic or nuclear.

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Implant Damage

Electronic collisions: do not displace (semiconductor) atoms from their lattice positions

Nuclear collisions: host atoms are displaced causing “implant damage” or “lattice disorder”

Displaced atoms possessing sufficient energy may cause secondary displacement of nearby atoms (cascading) to form a “tree of disorder” along the ion path.

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Then the drawback of this implantation the drawback of this implantation is that it can cause damage it can cause damage. Electronic collisions do not displace semiconductor atoms from their lattice position; obviously, because atom is not involved for electronic collision only electrons.

Electrons are involved. So, there will be no displacement of atom in the crystal lattice for electronic collision, but for nuclear collision host atoms are displaced causing implant damage or lattice disorder displaced atoms possessing possessing sufficient energy may cause secondary displacement of nearby atoms, which is known as cascading to form a tree tree of disorder along the ion path, right? What is this now a ion beam is colliding with a nucleus the ion beam was say 1 mega electron volt or say 400 kilo electron.

So, it will transfer its energy to the nucleus, then that nuclear energy will be increased. So, it will collide with the neighboring nucleus some energy will be transferred to the neighboring nucleus. Then that neighboring nucleus is energized now. So, it will collide with a third nucleus. So, unless the whole energy is dissipated by this collision there will be cascading effect that is why I have written that secondary displacement of nearby atoms that is known as the cascading and because of this cascading a tree of disorder along the ion path will be observed tree of disorder. You see what is the tree of disorder, yes this is the tree of disorder.

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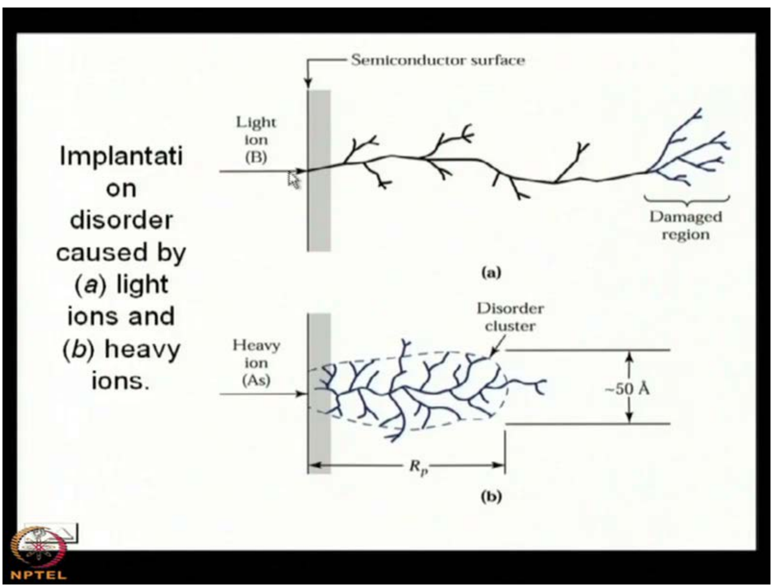

Here this is you see in the first figure, figure a there is a light ion beam and it has travelled through the region. Obviously, after certain distance there will be some damage or during its travel along this axis, there will be some displacement or some damage as well this is like a tree with branches and leaves and flowers etcetera. It looks like a tree that is why it is known as a tree of disorder, but if there is a heavy ion you will find that the damage will be from the one set of implantation.

You see that this is within this R P; that means, the projected range the whole material formed a disorder cluster and the thickness of that disorder cluster is not less. So, far as the semiconductor dimension is concerned it is 50 angstrom, it is 50 angstrom. So, it is not very less if you consider that quantum oil case for gallium arsenide aluminum. Gallium. Arsenide. quantum well we shall discuss those thing what should be the well

thickness. Well thickness will be 60 angstrom 50 angstrom 40 angstrom, so that means, this 50 angstrom dimension is not less in semiconductor so that means, a huge region though it is confined to 50 angstrom, but for semiconductor it is huge region there will be tree of disorder. Because of this disorder you find that in some cases the materials can even become amorphous. Yes.

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Annealing

On implantation, semiconductor may become "amorphous"

To restore mobility and other material parameters and to activate the implanted ions: annealing is done

Conventional annealing: Long time and high temperature is required to remove damages

Rapid Thermal Annealing (RTA): 100 sec down to nanosec

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So, how to cure those damage damage can be cured using annealing on implantation. semi conductor may become amorphous to restore mobility and other material parameters. To activate the implanted ions annealing is done another term. we have used activate the implanted ions. What is the meaning of this term to activate the implanted ion? Activation means you have to supply energy because ion atom is there ion is there, but for its activation some amount of energy is required. So, that it can give away its electron or form the bond etcetera. Otherwise you will not get the free electron your ultimate aim is to increase the free electron what is your aim for doping.

Student: (( )).

That means free electron the number of free electrons you have to increase. So, if you want that the donor will donate 1 free electron to then system. Then activation of the ion or the atom must be done and for that some amount of energy is required that energy is supplied by the annealing because annealing is the heating of the material.

Student: But sir one point is there, the purpose of annealing is must on (( )).

Yes, exactly. Exactly. It is exactly

Exactly because for activation the energy is very, very small, so it will get from the atmosphere as well from the material itself at higher temperature. For activation you need not to use some 600, 700, 1000 degree centigrade for activation it is 4 40, 50 degree 60 degree is sufficient.

So, there are two types of annealing; one is known as the conventional annealing, another it is known as the rapid thermal annealing. One is the conventional annealing another is the rapid thermal annealing, which is known as the RTA rapid thermal annealing. In conventional annealing basically you have to use a furnace and you have seen how a furnace looks like with a heavy mass.

The thermal mass of a conventional furnace is very, very large because you know that the furnace is the volume of furnace is very, very large. So, long time and high temperature is required to remove damages long time and high temperature. Why long time and high temperature? Why long time and high temperature is required? Because you cannot increase the temperature very quickly the that means, the thermal gradient say if you want to increase the temperature by 100 degree centigrade percent second.

It is not possible using your conventional furnace, 100 degree centigrade per second 300 degree centigrade per second very quickly. You want your temperature to raise by say raised to 1000 degree centigrade. So, within 2 second, 3 second, 4 second you have to increase the temperature of the furnace, then why the temperature must be very quickly raised. What is the rationale behind this statement?

Student: Thermal shock.

Yes, one thing is thermal shock another thing is that say for gallium arsenide. Now, arsenic will evaporate if for a long time you would like to increase the temperature from 30 degree room temperature to 1000 degree. Say if it takes 30 minutes or 40 minutes, then what will happen the arsenic will evaporate for 30 to 40 minutes. So, there will be vacancy.

So, that is why quickly, as quick as possible the temperature is raised to the processing temperature at which you would like to anneal and rapid thermal annealing. You see that the time is very, very less 100 second down to nanosecond 100 second down to nanosecond, very quickly. That is why it is known as rapid thermal annealing.

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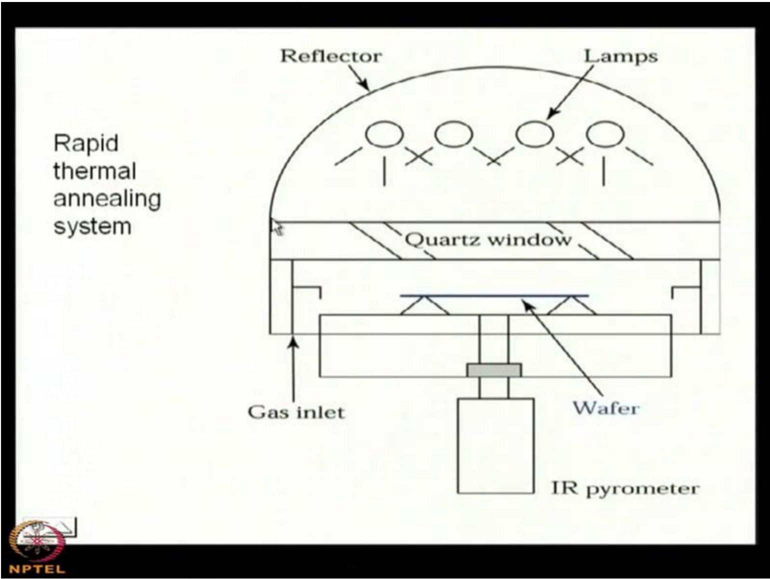

This is the diagram of a rapid thermal annealing, you see conventional annealing is done using furnace, but for rapid thermal annealing this is gas inlet. There is a tube quartz tube. Obviously, this through this quartz tube there is a place where the wafer can be placed and gas inlet means you can use many ambience. That means suppose you want to anneal using argon, so what you have to do first? We have to start sending the gas through the gas inlet. So, that the argon will replace the whole air inside the chamber and then you switch on your thermal annealing system. So, that the annealing will be using argon or in argon ambience or you can choose other ambience like nitrogen vacuum also. You can use vacuum you can use oxygen, but remember that if you use oxygen or if you anneal the material in front in presence of air, then what will happen?

Student: Oxidize.

Oxidize, the material will oxidize. So, that is also detrimental for our use that is also detrimental for our use. So, that is the reason that the gas inlet through this gas inlet you send the gas of your choice. Then when the stabilization is completed that means, when the stabilization of gas flow is done you switch on the heating arrangement here. The

heating arrangement is lamp heating, very powerful lamp is there and that lamp will glow there is a reflector.

That reflector will not allow the light to go out. So, within this small volume the temperature will increase very quickly you can put 10 lamp 5 lamp 6 lamp depending on the situation depending on the rate of heating you want. You can use the number of lamps and there is an infrared pyrometer or there may be thermocouple using with the temperature. You can measure then there may be temperature controller it will control the temperature.

If you use a temperature controller, then you can make a small programming that you would like to increase the temperature at the rate of 250 degree centigrade per second or 1000 degree centigrade. That means, 4 second will be required from room temperature to reach the process temperature at that position say 10 second. It will stay for annealing and then the temperature will be down to room temperature again; that means, then the system will cool itself, right?

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RTA: 100° – 300°C/s: can cause wafer defect due to thermal stress.

Conventional: contamination (from hot walls), large thermal mass, costly manufacturing floor space, limited ambient control

So, in rapid thermal annealing some 100 degree centigrade to 300 degree centigrade per second gradient is used, ramp is used and it can cause wafer defect due to thermal stress. Obviously, the time is very, very less even then since the rate is very high. So, the impact is very high, but for conventional annealing system here only thermal stress is involved no other thing is involved. No contamination is there, here. There may be contamination

from hot walls large thermal mass costly manufacturing floor space and limited ambient control because limited ambient control means, if you want to make argon ambience or nitrogen ambience using a conventional furnace. It is very difficult to make and the conventional furnace is large volumes furnace.

So, the large thermal mass is involved costly manufacturing floor space means floor space is also large compact to the rapid thermal annealing system because the rapid thermal annealing system is a very small system, which can be placed on the table top, but for furnace you cannot make that kind of arrangement.

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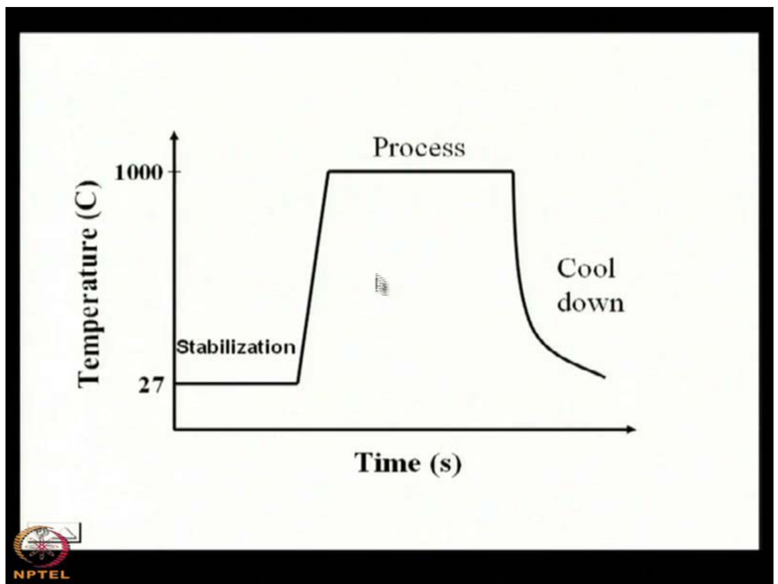

So, these are the advantage disadvantage of RTA and conventional system, yes. In RTA you see that this is the view graph you see that I have plotted temperature along y axis and time along x axis. So, say the room temperature is 27 degree centigrade. So, first some time is required for the stabilization gas flow stabilization, then you see very quickly it reaches to 1000 degree centigrade very quickly it is almost not exactly parallel to the y axis, but delta t is very, very less.

For normal furnace, it is the slope is very high and this is the process temperature. Say 1000 degree centigrade, you use to process and after processing for say 10 second 20 second 50 second it cools down this is the thermal profile of the temperature time profile for the rapid thermal annealing system.

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Assume 100 keV boron implants on a 200 nm silicon wafer at a dose of 5 x 10^{14} ions/cm^2. Calculate the peak concentration and the required ion beam current for 1.0 minute of implantation. Given: σ_P = 0.07 μm, R_P = 0.31 μm.

Then one example, I shall give and we shall conclude for today's lecture it is related to our ion beam current, which we have used time and again we have introduced the term ion beam current. It is because that ion beam current can be controlled and so the dose can be controlled.

Assume 100 KeV boron implants on a 200 nanometer silicon wafer at a dose of 5 into 10 to the power 14 ions per centimeter square, calculate the peak concentration and the required ion beam current for 1 minute of implementation? These are given straggle is given and projected range is given R P is the projected range and sigma P is the straggle. Let me solve this problem very quickly you see that one thing is the peak concentration peak concentration means, it will be at x equals to R P peak concentration means it will be…

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So, if it is say n x it is equals to S by sigma p rho 2 pi exponential minus x minus R P square by 2 sigma P square. So, this is the expression this part is 1 for x equals to R P. So, maximum will be when x equals to R P. So, that means, this part will be one or it is equals to n x max will be S by sigma P root 2 pi you know what is S S is given it is 5 into 10 to the power 14 it is given in the example S is 5 into 10 to the power 14 and sigma P is given it is 0.07 micron.

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So, using this expression, you can calculate the maximum concentration, but what about the ion current beam current will be I equals to q Q by t what is q Q is 1.6 into 10 to the power minus 19. What is t? It is 1 minute or 60 second, then what is capital Q? Capital Q is the total number of implanted ion q is total number of implanted ion how it is calculated it is equals to 5 into 10 to the power 14 per centimeter square multiplied by pi r square.

Now, what is r r equals to 220 nanometer 200 nanometer that means, you can change it into proper value. So, the total surface area you can calculate and so that beam current. So, that means, if the current is decreased ion concentration will decrease, if the beam current increases the implanted ion concentration will increase. So, it is directly proportional. So, you can just by changing the ion beam current you can say how much ion you have implanted, precise control of the ion can be possible.

Thank you.