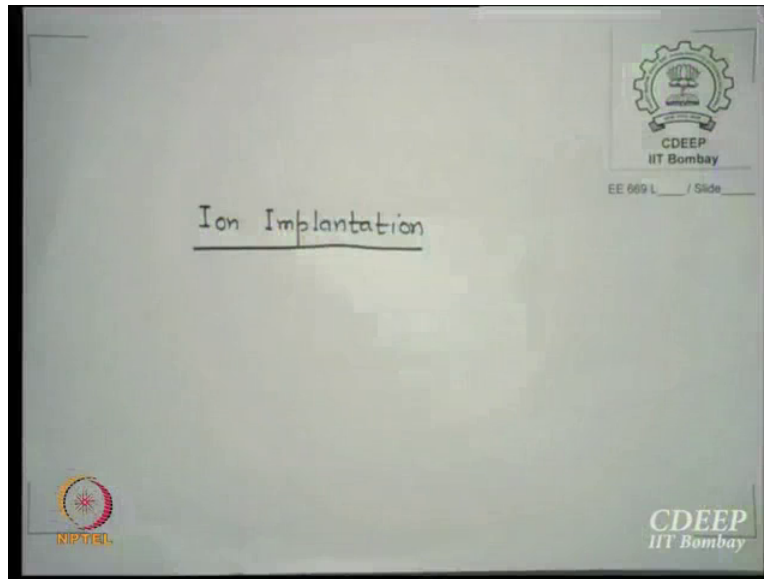


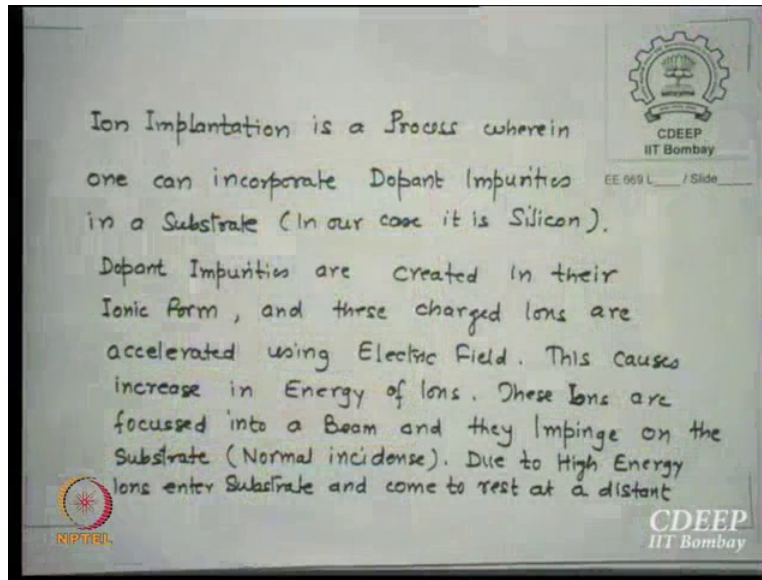
**Fabrication of Silicon VLSI Circuits**  
**Professor. A N Chandorkar**  
**Department of Electrical Engineering**  
**Indian Institute of Technology Bombay**  
**Lecture No. 19**  
**ION Implantation.**

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Let's start with the new topic today. We have so far done uhh the basic of crystal growth, we have done how a clean room is working and how do we actually go into the clean room and what are the requirements we have also seen the incorporation of impurities through the process called solid state diffusion. Then we looked into oxidation, then we have also looked into lithography how to print image okay or the patterns. Uhh one of the possibilities of incorporation of impurities or rather the one which is nowadays used is ion implantation the word itself suggest something has to be implanted and then (1:05.7) impurity ions okay. So we start with the little bit basic thinking on implantation. By the way implantation has nothing to do only with VLSI this process is known to us for almost 100 years it was very late very late in 80s that it was first time used used by VLSI people. Implants were known many many years ago okay. So don't think that this is very recent or something. So the machines then were different, machines now are different for semi-conductors but otherwise basic idea is same ages ago, this is for us only specific.

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Implantation is a process where we can incorporate open impurities in a substrate and in other case it is mostly silicon but it can be any substrate. The open impurities are created in the ionic form and these are charged ions and therefore can be accelerated by electric fields. This causes increase in energy of ions. The ions are then focussed into a beam and then they impinge on substrate. Normal incidents, due to high energy ions when they enter substrate, they interact with the atoms of the substrate and therefore after a while lose their energy and come to rest. At some distance inside the substrate or the distance up to which they can go and rest is called range okay, is called range up to which they can go in and rest or lose all their energy is called range. So we're trying to see since I know ions can go inside a substrate and due to the interaction of atoms they will lose their energy and once they lose their energy they will come to rest inside the lattice.

Now whether they will occupy the substitution sites will be decided by how much further thermal process we do to them but mostly if there are vacancies are available they will like to first somewhere there but otherwise we may have to do something to actually force them to sit into substitutional site so that they can contribute to conductivity. Now if you've noted down the energy loss mechanism is what we're really interested in, how far they can go inside is what we want to know and if you have noted down this I will give another sheet to write it down or another...okay so up to where they can go they are decided by energy loss mechanism is interaction of ions.

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called "Range". The energy loss mechanism is interaction of ions with nuclei of atoms of the substrate, as well as with free electrons available. Thus Energy-Range relation is created. Time for which ions impinge on the substrate, decides the total amount of impurities which resides in the substrate. Amount of impurities is measured as Dose which is no./area.

As impurities rest inside the substrate after random interactions, the impurity profiles are Gaussian or Normal Distribution of impurities is observed.

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With nuclei of atoms of the substrate they can also interact with the electrons in the lattice and therefore there are 2 ways of scattering, one is the interaction between ions and the nuclei the other between the available electrons in the lattice. The energy range relationship therefore can be created and larger the energy obviously it will take longer before they will come to rest. Smaller the energy they can be they stop at much earlier depths. Time for which these ions impinge on the substrate decide the total amount of...how long you do this much, this will decide how many impurities you are pushing inside okay. So this is something to do with the work number of atoms or number of ions per unit area or called dose. So how many atoms per centimeter square we can push in from the surface inside is the dose given for this doped atoms okay.

Now generally since there will be lot many number of ions and they will be impinging on substrate, the randomness in their coming and hitting the atom because atomic position and where they hit. The randomness in their coming and hitting the atoms because atomic positions and where they hit what angle they hit they normally will get randomize inside and this random nature of atoms coming inside a lattice essentially leads to a random distribution which is the most common distribution called Gaussian Distribution so most likely they will follow a Gaussian Distribution in a dust that means fewer at the surface fewer at the bottom and

maximum in the center okay so there will be some kind of a Gaussian profile from the dust side okay.

Now this is essentially because we don't know which atom going where so it's a random numbers, larger number per centimeter square are entering and therefore larger atom they will be able to and there will be not be one interaction. Ion hitting one atom then it moving away it may hit someone and then come down so there is a average effect going on and therefore it will be more randomized in nature okay. Now this is where the things are very simple because once you say it is random distribution uhh it's a Gaussian profile and what was the difference between solid state diffusion where the how the impurities where getting inside by compliment air functions. Now I don't need to have complimentary because the first time itself when will get in I will have a Gaussian profile and any thermal cycle ahead will actually will not change the distribution or the doors but will just flatten up okay so more impurities will go ahead and ahead. And we will see how many and where do they go.

So this is very important that the first time itself when I push impurities in I get a Gaussian inside and that's something very easy for me to then operate at. What is the advantage? If I put very short very small time as well as very small energy ions where will they rest? Very close to the surface, for a short time I know how many small number of impurities per cc per centimeter square I am pushing in so what is the equivalence of that in a solid state diffusion? A sheet charge approximation we were trying earlier is much easier to control now because I can decide my dose as well as my time and can create surface charges okay. And that's the beauty of implantation. Okay so let me say something more about possible processes.

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Dopant Incorporation in Semiconductors

- Solid State Diffusion
- Doping during Crystal Growth
- Doping during Epi-growth
- Doping using At. Pressure CVD for Doped Glasses.
- Ion Implantation

Advantages of Ion Implantation :

- Precise control on Impurity Dose and at Depth
- Impurities directly below surface - Buried Profile
- Relatively Low Temperature Process (w/o Diffusion)

choice of Mask-Material

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The dopant incorporation in semiconductors we have seen so far solid state diffusion is the most earliest version which we have discussed a lot we have also seen during crystal way I can add impurities and therefore incorporate impurities in a crystal. Process which we have not done is repeat action growth. So during repeat action growth also you can dope the wafers uhh dope the silicon or any other substrate. Uhh we can also do some part of what we call as during CVD using dope glass this possibly time permitting I will show you this is called poor man's implanter. Atmospheric pressure low temperatures CVD using dope glasses I can push impurities in. And this process was suggested by N D grove way back in 60s and we call it's poor man's implantry if you don't have implanter which is very costly to some extent you can play with this smaller CVD system not accurately but some way. And of course we can always put the impurities inside what is called process of ion implantations.

Now why are we looking for ion implantation compared to solid state or any other process? Of course the second and third that is crystal growth doping and this have the biggest advantage that they are during the grow of the lattice. And therefore they are uniformly distributed so if you're having a uniform doping only 2 process can do either during the crystal growth or during the EP growths, otherwise there will be always profiling okay. So advantages of ion implantation are, the precise control of impurities those in depth which I just now said I can decide my time I can

decide my energy and therefore I will be able to push exact number of impurities per centimeter square and also I can decide how deep they should go depending on the energy I choose okay. So this is one interesting thing compared to solid state please remember solid state diffusion cannot be very accurately controlled simply because the amount of source impurities which are coming from gaseous phase to solid phase and then they react.

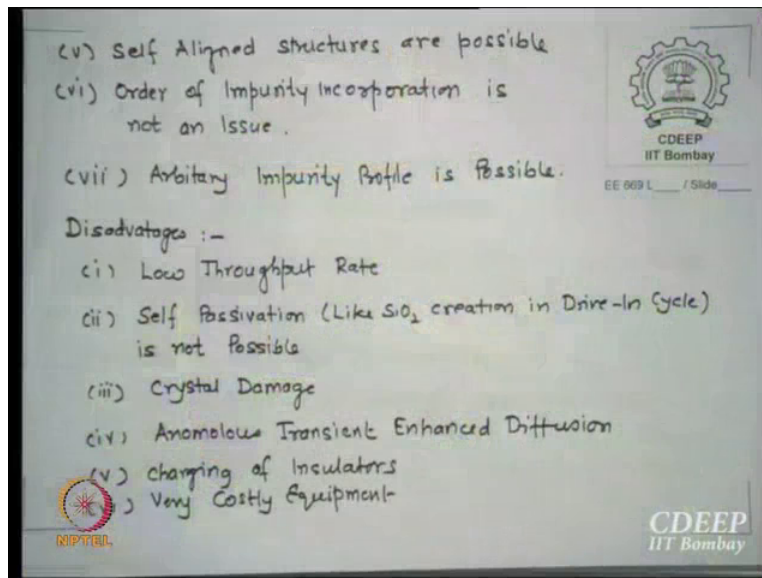
Here we're not reacting but pushing in okay. The impurities directly below the surface can be created we don't have to get into the silicon dioxide okay. They can go below the silicon dioxide itself. Almost everyone can go below the layer and therefore we it's called buried profile. I can do a profile which is in the silicon and not in any other material above okay. I can put energy which process that okay. Uhh normal to diffusion normally compared to diffusion the this process is low temperature process. This statement need to be qualified in the present context so you need to (( ))(10:43.8) the samples afterwards which is around 850 degree centigrade. Nowadays almost all VLSI ultra large scale integrated process can go below 400 or 300 so this is still not so low as we thought but since solid state diffusion is to take 900 to 1250 this look to be very low temperature process as of now. The variance of this implantation will be used and we will see that. You see that will be called plasma implants which will be low temperature implants okay.

The biggest advantage is allows is the choice of mask material. Since I am pushing the ions through any layer to a depth what is on the top is not so crucial for me okay. So I can have silicon dioxide I can have silicon nitride I can have even resist which can, resist is very good because since resist is raising large carbon hydrogen chains they are randomly distributed and therefore more likely to pass stop implants because they will actually they will interact right there with carbon chains and will not allow anything to really go actually. But if I push energy even they can cross that ions, is that clear? So mask is not that crucial in my decisions. So many a times I may use resist itself is a mask because I have done a lithography so there any way I will start implanting okay. So I don't need to do anything there, that's the biggest advantage implanter provides.

Just a resist it is roughly a high energy implanter may be 300 to 400 KV implanter they cost around 10 million dollars to above. So it's a very expensive system, of course there are many gadgets these days inside and implanter. But apart from the gadgets the cost is very high. So not

everyone can buy including our CN doesn't have an implanter okay for the same reason. Our majority of the money would have then gone to implanter okay. Ha so that is what I said, equivalence we will do some other day.

(Refer Slide Time: 13:01.8)



The next and the most important reason why it was used in VLSI technology was that it allows you to create what is called as self-aligning structures we will show you this little later another very big advantage on this is that in the case of solid state diffusion think of a situation I want to make an NPN transistor and I have a N collector substrate so first I will have to do base diffusion and then inside that I will do a phosphorus or arsenic another diffusion. So first base (13:32.6) and then followed by arsenic or phosphorus. In implant that's not so I can first create emitter and then push the impurities down for p which will make base afterwards okay so it is the order of impurities are not very crucial of course it's not so trivial but it's not very crucial as in the case of solid state solid state you have to first create base only then you can push the emitter impurity that's not so much in the case of (14:00.3) I can just adjust energies whichever earlier is not important. They will decide by the energy where they will come and rest. This is what someone was asking may be sir mahapatra gave you problem.

Arbitrary impurity profile any random profile not necessarily Gaussian or not necessarily error function or exponential or linear grade you suggest a very random profile and I can create any random profile using implanter okay. Now question one have is why do we need random profile

well we don't need all kinds of random profiles but there is a sub junction which is called hyper abrupt junction. Have you heard of the word hyper abrupt junction, thoda padho. (14:48.4) devices which are used in microwaves for generating the sources or they are also used in the paramps parameter amplifiers for microwaves they actually need such high frequency varactors and you need a hyper abrupt junction okay. Hyper abrupt is some kind of inverse abrupt normally it is like this here it is afterwards okay.

So it is some kind of (15:19.5) script and we do that in main a sub CV adjustments. So for any arbitrary profile possibly can only be done through implants and no other solid state will never allow because it will always through Gaussian or complimentary error. All good things have some bad things with that. The disadvantage is of course there is this throughput rate world has not that small it was as it was earlier. Earlier we used to have a chuck which can have at best 12 wafers. Now we've implanter which can hold 48 wafers, so it's okay. System will bake energies are higher, this half kind of at least half half is the implanter so many wafers can be simultaneously implanted. Multiple beams can be done. So many tricks have been tried at the cost of money. You put money and may be you can through put can increase okay.

However for all small implanter which we couldn't buy even in our lab which may have 12 wafers at a time 8 inch wafers earlier we had 3 inch wafer so it's much easier to put 12. Now with the same size only one wafer may come, so it's a very tough situation if you change technology. You change wafer size the every tooling changes every tooling. Wafer lots wafer furnace everything changes, so much money. So no one wants to change state of it, now market is available buy it, no no no is it worth buying okay. The second advantage disadvantage is like in the case of diffusions uhh every drive-in cycle is with the oxygen oxide. So it will self-oxidation is done there so that next layer is on the top is oxide.

So it create mask automatically okay. So it's called passivation. It doesn't allow other impurities to get in. However in the implant since it need not be oxide there at all and therefore there is no self-passivation in the case of implant. You may have to actually dump oxide if you need. Since ions have high energy may be as high as 300 KV because of that this energy when it imparts to an atom. The first atom it will hit with such a large energy and momentum that it will displace that atom itself. It is likely that the silicon atom itself may get displaced, so the near the surface



much of silicon atoms will not be in their latest positions. They will get damage or amorphized at the surface.

However they are not so far away from their original positions and therefore what will happen some thermal cycle it can be retrieved back okay. But there is a dimension, the crystal gets damaged at the surface at least because of high energy being delivered. There are also problem which are called anomalous expansion enhance diffusion suddenly we find that I change the energies for some depth change the profile should have atom should have ions should have somewhere here but I see a tail. They have gone much deeper we never thought of it but it went in okay. It's called transient enhance diffusion. So there are issues which probably are for different impurities at different times different doping of substrate may create what is called as tails. These are called PFs and Tails. Now this is not every time true for every process.

So one doesn't know depth they have really gone okay. So there is sometimes some issue which is called transient enhance diffusion TEDs since you're putting ions and if there is an SIO<sub>2</sub> layer here and we have just now read understood thermal oxidation process we say all SIO<sub>2</sub> if you put charge in it gets there and that's the VT problems we're kept saying that. We're putting ions anyways, so you're charging the insulator sitting there okay which essentially means either the charge has to be removed or otherwise it will create threshold problems if the charge is not withdrawn okay. So there is a issue in the case of implants that ions charges insulators. So that's the way it is as I say already the equipment's are very costly compared to solid state diffusion cost even for 12 inch papers the furnace cost right now 1 million dollar 4 stack. Implanter may cost smallest 8 inch 4 wafers may cost 10 million dollars minimum okay. So it's a cost wise it's very exorbitant. However as I said if you look at the advantages okay which solid state cannot do then there is nothing else at par. I mean I cannot do, so I will do whatever I have to.

So I will put money and will charge their customer at the end of the day okay, that's the way I will do.

Student: ( ) (20:27.4)

It does uhh it is difficult because oxygen is not inside oxygen is if there is oxide there is an advantage or disadvantage it's called precipitation. So one of the problem of this is some precipitation near the surface which is very bad situation because it will actually act like a

recombination centers so one avoids oxygen dope wafers peculiarly we must avoid oxygen at the surface. So there is a process of what we call as ionic cleans. And we actually remove the surface so that no oxygen is sitting at the surface okay.

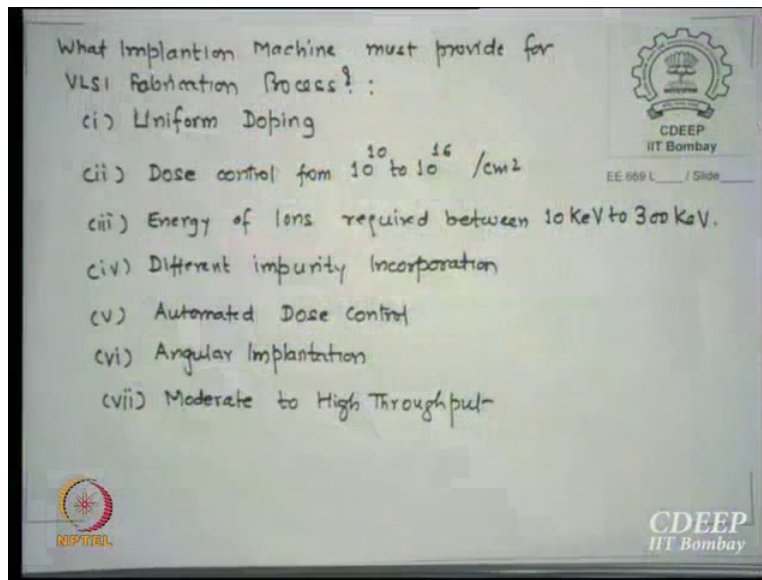
Student: ( ) (21:11.3)

Actually heating up is not that bad as you're thinking because there is a chuck on which this is sitting is pooled chuck. So the heat is immediately removed. But yeah I cannot say when they impinge they don't increase the temperature. Energy is given so  $KT$  is provided. But the chuck on which wafers are sitting have a huge pulling traffic. So it removes the heat very fast relatively fast. So I am not trying to say that it will not heat but it certainly will not be so high temperature that will damage you too much. See let say it goes for 100 degree nothing happens okay but if goes to 800 700 then I have a worry but that temperature it will not allow to reach.

Student: ( ) (21:59.1)

Your ion ( ) (22:01.0) means the junction may be far away where we don't want. I want the junction depth of half a micron or 2000 angstrom it may go to 1 micron. No but impurities will further go down. If the drive-in will further push them out. So the junction will further move away. Any tail during drive-in will go ahead so that issue will even be worst of course fear and force formula suggest how it can be done and what cannot be. But I think I will not go so deep because ion implantation itself requires 20 hours to teach okay. So I will not do that, I will just tell you basically what we use. Okay so typically a machine requires what, what should the it should provide for VLSI process it should be able to give us uniform doping's.

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Uniform doesn't mean not profile but uniform means once I do it I repeat, it should give the same profile. I should be able to put a dose of  $10^{10}$  to  $10^{16}$  per centimeter square to as high as  $10^{16}$  per centimeter square. Can you think what will be  $10^{16}$  dose will be roughly in a 1000 angstrom depths. This will be  $10^{21}$  per cc. So it's a huge concentration I am talking about.  $10^{16}$  per centimeter square is very very heavy dose.  $10^{10}$  is  $10^{15}$  per centimeter cube roughly. So therefore it is normal doping's okay. So we must be able to adjust doping from  $10^{10}$  per centimeter square to  $10^{16}$  at best because more than still lattice will not be lattice.

Student: (0)(23:45.6)

Area into depth is volume. Abhi thousand angstrom is minus 5 centimeters micron so. So minus ko karo multiply divide karoge to 21 ho jayega. Thoda jo bhi depth loge usko use multiply karo (0)(24:09.7) area ko to volume par cc. Apko per cc karna hai na to neeche aur ek division lagao. Minus 5 se divide kiya to 21 ho jayega. Okay energy of ions required with typical energy required for it can be in some cases very shallow implants I need then I may have implanter must have energy of ions as well as 10 KV and if I want deeper implants I may or what we will see later higher current implants at higher energies. We may be able to so of course I did not say that larger the dose will require larger current implanter so implanter are classified as low current

implanters, medium current implanters and high current implanters depending on dose you're really looking for.

Similarly energies could be 10 KV small energies and to be as high as 300 to 400 KV energies are required for pushing ions well within the dust. Like I will show you a figure a P well or N well may require a micron or a half micron now. Whereas the source drain may require 0.1 micron okay. So I want a deeper junction, also I want a shallow junction. So I need energies varying from very low energies to very high energies. We should be able to incorporate all kinds of impurities, whatever we could do in solid state luckily for us if I do a carbon implant or what is called as nickel complex implants on steel it becomes hardened one of the method of hardening steel is to implant either silicon or nickel complex as they call. And once you implant this, the tip of this where from this there is no one from mechanical where to use such things? The high speed tools which are used with lathes have actually tip which is high speed steels okay with such hardness in that, because they should be able to etch the uhh cut the steel itself. So their tip should be even harder and that is how it is done.

So that's what I say implants are not new implants are of ages old process actually. We want to have a dose once I fix a dose it should be stopped after that I don't want oh watching hoga kya. No nothing like that, it should happen that's the end of it. It should show end mark everything should shut off. So it should be automated. We also should be able to tilt the beams to a certain angles if I need. I don't want always normal incident I want 3 degree 7 degrees can I do that. So it should be able to a even angular implants. In many processes of LDD structure of a MOSFET we do 7 degree implants. So that one side there is no impurities and the other side you understood? This is a mask if I do implants like this, this side I won't get impurities but this side I can so I can reduce my doping on one side this is called asymmetric MOSFET they are used using a symmetric implants okay or angular implants okay.

Of course one will expect all implanter should give at least moderate throughput or high high throughput if it is possible. This is requirement may or may not be meant depends on the money you have this will be met okay.

(Refer Slide Time: 27:54.7)

In MOS Technologies (CMOS, FINFET & others)  
One needs:

- (a) P-well    (b) N-well
- (c) Channel Stopper
- (d) Depletion Implant for Depletion Transistor
- (e) Source & Drain Impurity Implant with Higher Doses
- (f) Threshold Correction

Few Terms of Interest in Implantation

(i) - DOSE = ions/cm<sup>2</sup> =  $\frac{1}{qA} \int_0^{t'} I(t) dt$

(ii) Range and Projected Range

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For there are technologies like CMOS, double gate FET or FINFET or all kinds of structures normally require following areas are made there P well N well I have a figure I will show you. Then we need channel stopper depletion implant for depletion transistors. Source and drain impurity implant with higher doses but smaller energies, threshold corrections. All these are requirements in a MOS technology. I will just show you a figure after you write down this. Why are we trying to learn all this because when I go into the lab I should be able to know where I am going to use what kind of implants okay. At the end may be after this implantation is done we will before we do repeat action or CVDs I assume you can deposit by some technique done and will show you actual IC fabrication 16 mask process, Plummer's process or many other. I will give you modification to FINFET what could be done what processes are changed to make a FINFET okay.

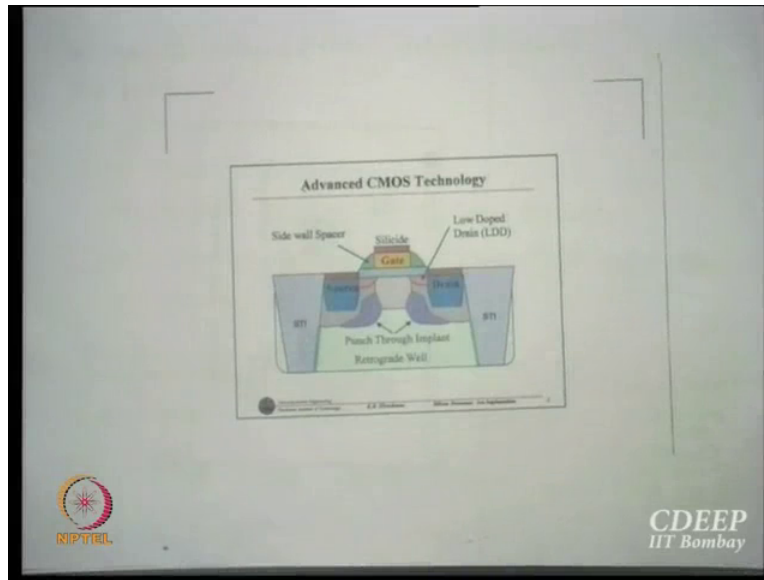
So first thing we will do is we will finish implant because without implant it's not proper to do full processing though we also need lot of CVDs but right now that time we assume I can deposit okay by some technique. You could have said that you could have also said here, anything could be no I think implant would be more important and therefore I thought I will first finish implants and then start looking for actually IC wafer fab. Our course is asking you to actually know how a fabrication process step goes through. 16 mask process will how many real life processes, as I

keep saying typical processing sequence require 450 steps even for 16 mask. What is worst in this all processing? There are no retrace paths is that word clear to you? If I make a mistake on 336 the whole wafer is, wafer lot is thrown. So there is no hopes that okay I can make an error you can't. If you can make error you will out so are the wafers okay. So no mistakes.

So why so much automation? The reason is this because they should not be any possible mistake. Of course all said and done nature doesn't believe all that. It does make mistake itself okay and then you're happy about it, I have not done it. The term which we were going to use soon not terms rather but one of the major 2 terms which are there one is dose and I say number of ions per centimeter square okay. If A is the area then if the ions constitute a current, what is current charger per unit time okay. So current divided by charges ions numbers, this number in a given time T dash if I integrate over a given time divided by area is the dose is that clear?

Current is charge per unit time so current by charge is time uhh is this. So for a given time whatever is the integral of total this divided by number divided by area is essentially the dose. So what is the method now I am suggesting. Monitor the current okay and through which how I monitor with what kind of system? And integrator so if I, I use an integrator and see that after a given time how much is the dose I can actually calibrate and say okay here is the dose okay. This is what the circuit will be allowing you to monitor it. And also therefore control it as soon as you compare it with a given value of a particular voltage drop it will shut off the source inside okay, this is what automation will be done, but let's see.

(Refer Slide Time: 32:17.3)



This whole figure the whole of this may be understood through this figure this is taken from Rochester Institute of technology professor Hirsh Hirschman's lectures of available on website. I was looking for a good photograph so I got one. I wanted also color photograph so I was looking many sites in which good color photograph is there. Okay so here is a typical CMOS process okay in this only one of the channels is been used either N channel or P channel. One can see from here this is STI it's a trench isolation silicon trench isolations. This is a new process last 10 years. Earlier we used to do only channel FOX kind of this (32:58.3) now we will do STI. Then we have a source drain here we have a this LDDI I was just saying low doping density somewhere here. Low dope drains. So we can use this okay. Then we have a gate which may be any insulator and there will be separation from the drain to this is the spacer okay.

Then there is a contact to the gate either it could be metal, poly or can be molybdenum or any other material which can form silicide's. Okay why silicide's it should replicate metal. Okay what is the advantage of metal it's a conductive very highly conductive material. So any silicide should be as conductivity as possible and should also be able to stick to the gate insulator okay. So silicide's moly silicide, titanium silicide, tungsten silicide all can be done moly is the most popular one which we use for work function engineer 5 ms can be change through this okay. Then there is a something called punch through implants which actually does not allow this channel to be connected to elsewhere okay. And this well itself is retrograde, retrograde means

the doping normally how do you put an implant doping profile. Higher doping ahead earlier high and then diffusion down. What is retrograde? Lower above and higher below is retrograde okay.

So you need a retrograde well so how good implants allow you to do this. So these are processes for typical one of the device which is either n or p equivalently there will be other device, so when you do this you would get that when you do this you block this and you will do processing for both n channel and p channels.

Student: (0)(35:02.8)

In normal solid state diffusion either the source if you're creating error function it will start solid solid (0)(35:10.0) so it will be always higher. So as you go down that is in the depth it will always redistribute and smaller values will come ahead okay. I want this area to be higher dope and the upper area lighter dope because that is going to decide my implants I mean my thresholds. So I want retrieve it. Ha to implant me karte hai, isiliye to ye dikhaya ja raha hai ki what is the biggest advantage implants allows. Implants allows to do any kind of that's what I say any profile, use any profile and I will say yeah how it can be done, that is the biggest advantage implants allow. There is something we're doing through spaces, firstly you can think of it, this source drain somehow are not getting something which is related to silicide's but there is a possibility what is recalled as boron depletion. So I am trying to avoid it. So I will see why I need a specific.

Boron (0)(36:07.3) is always through oxide it has a distribution coefficient which will go in. Boron has a very high segregation coefficient.

Student: (0)(36:14.7)

This is here no no no, when I do this implant I do not want that to be seen by this as much. So I am isolating gate with source drains by implants okay. So that spacer is the one that stops that. Let's wait I will give you a actual FINFET or every year why the major result of a process actually on a FINFET current is a (0)(36:45.0) spacer thickness which is very funny people never realize that the space is really causing so much worry. So it is a space which is deciding the currents.

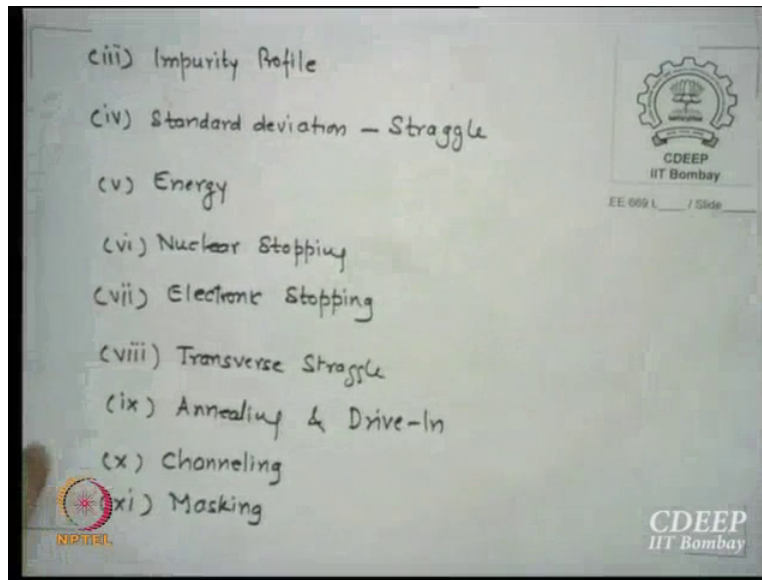
Student: (0)(36:57.0)



Fringe of course it depends on high K if it is a low K it's not that worry some you're right high K of course because thickness are high there is a huge fringe but otherwise it's not so serious. Okay so this figure was not to discuss on CMOS right now this was only to show you how many place I may require implants. I will do source drains I will do retro-grade I will do punch through implant I may do for silicide, I may do side walls I do everywhere, everything through number of implant processes. And which each will have something different profile and different depths and different doses. That is the game we want to play okay. From where all these are coming from my RV characteristics of a transistor I figured out, this is what I should get.

If I have to get it I went back and looked into structure, isko thoda hala de to acha ho jayenga, chalo hilao. So that is how this is DR programs or center allows you to know which areas need some control okay. That's what you do simulation, isko upar karo isko neeche karo ispe profile dalo, kyo dekhte hai because we want to see how how what will actually affect the performance. Once I know that then I will say you will come to tell this technology man, ae I want this. You say are you kidding, then he will say no I want it, he say okay I will create a new technology okay. That is how the process is build up okay. I think first two things I said about okay I just forgot this, two things I said first is dose and second the most important thing is a range and associated word which we will use is projected range okay we will see what is it.

(Refer Slide Time: 39:00.0)



After these two we have a impurity profile I want to know profile how many how the impurities are inside the silicon. Since it's a Gaussian system it will always have some variance or what we call as standard division and in plant that word is called Straggle, the standard deviation is called Straggle. So I want to know what is the straggle. I want to know at what energy this is to be done so I need to know energy. Then I also have two terms of my interest how do energies are lost inside a lattice of ions. So we say either they will interact with ion uhh atoms or they will interact with electrons. So there are two ways energy can be lost one is through interaction with atoms nuclei the other through electrons. So if they interact more with nuclei then we say nuclei is stopping. If they interact also with electrons then they will call electronic stopping. We will see this, this is our research. I mean this is what we want to learn.

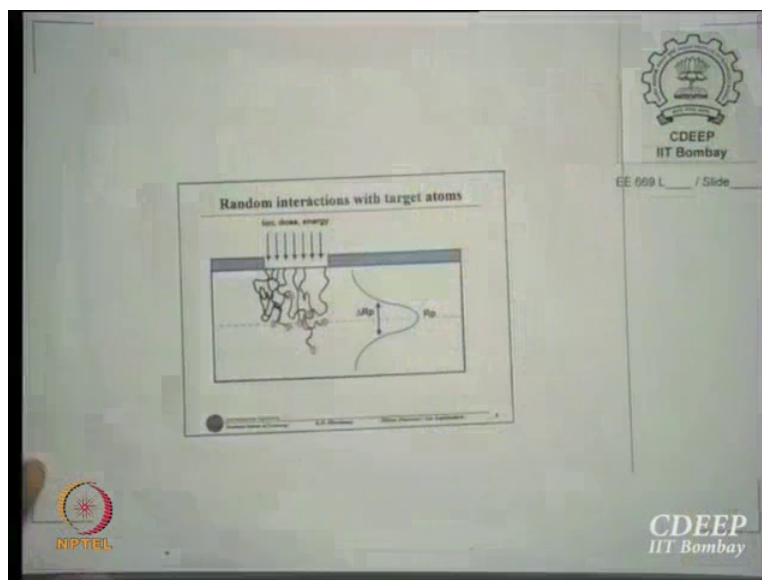
We also figured out that when we do implant through a window apart from this side vertically down it also goes partly lateral way, is that clear. If impurities are coming like this, they also go laterally, this is called transverse straggle.

Student: (0)(40:26.2)

This is one direction and normal to that is transverse to this so any variation. Abhi variation itna depth me hai profile now on the side it may vary. So this range is has a profile ke ye jo profile

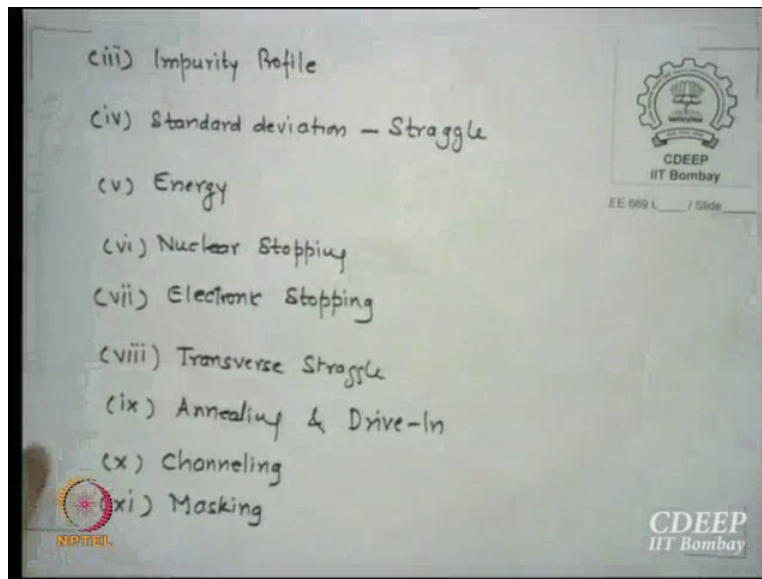
hai ye depth me hai. But naturally bhi profile aa sakta hai, uska bhi variation ho sakta hai. That standard variation is called transverse travel we will show you that, that is our research. Then there are two terms which we often use annealing because crystal is going to be implanted with high energy ions they may damage a crystal so we must recover it back and also during this thermal process or additional process afterwards we may push the profile to a know depth where we want okay so we must push this by a process drive-in. There is also a word which we will come later which is a channeling something which we didn't wanted to happen okay and we say why it happen. And of course we will try to know which mask material we use during implant.

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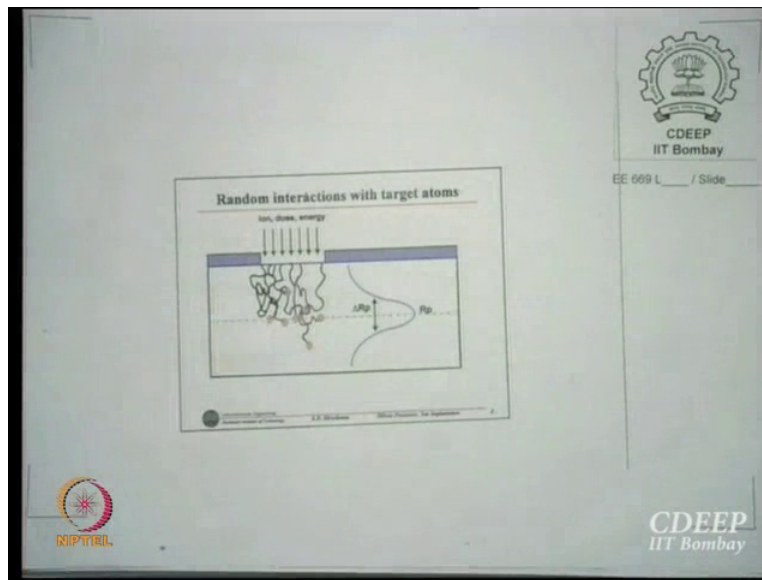
Now this is another figure taken from the same people. you want to still write on that there is nothing as I said these all known when you do math's you will see all these terms.

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I will discuss almost everything when I actually do the maths for that okay. Because for example if I am passing an implant through nitride how much thickness a nitride should keep or if I am passing through a resist how much resist thickness should be? If I am passing through oxide how much oxide (42:17.0) I will figure it out how much so I will actually evaluate that value how much okay. So it's not very random, though process is random, we still can get some but how do you get from very random process something by a method which is called mean value theorem. Gaussian profile can always generate a mean (42:43.1) so we can average out many of the effects and say okay here is the way we can, average is this okay. As soon as your normal distribution much gain can be  $\int X F(x) dx$  upon something is average effect. So we can always figure out a very straight forward averaging effect okay.

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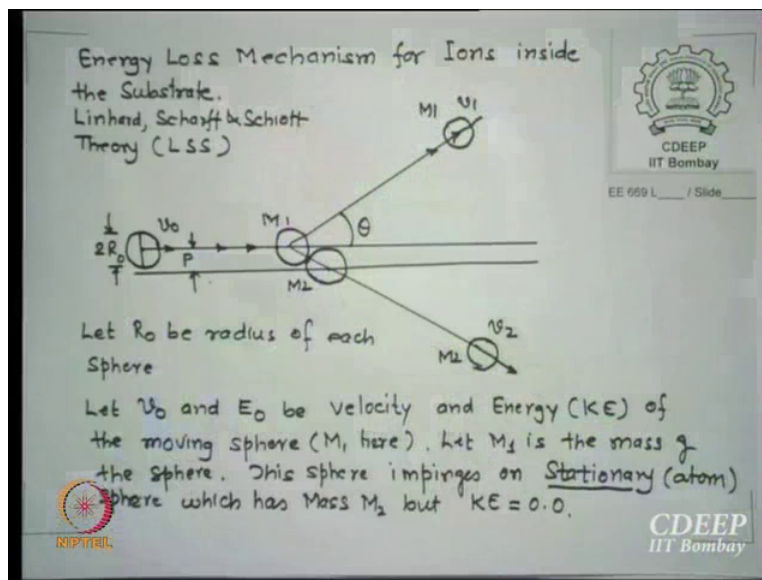
So do some math's uhh here again the figure from same Mr.Hirschman this is how it looks to be. And since it looked very random I thought this figure was brought especially for this ions are getting in they are moving here and there okay. Interacting with ions, interacting with electrons and these are the positions at which they will come to rest okay. And equivalently if we say there will be a profile in the depth, number per cc profile in the this. Maximum is available here so that is the peak value. Minimum somewhere beyond this and this distance as we call is the straggle or standard deviation is  $2 \Delta RP$  and we will discuss how much  $\Delta RP$  so we have a graph which will give you uhh  $RP$  against energy at  $\Delta RP$  against energy and also  $\Delta RT$  against energy what is  $RT$ , transverse straggle so 3 graphs which are provided to you with your initial this, you can see that there are 3 graphs given to you.

One is giving the projected range versus energy, this is only for SIO system with know impurities. Then we have given it for straggle which is  $\Delta RP$  which the value has been given and we have also have given a graph which is straggle  $\Delta RP$  versus energy for all impurities okay. So these graphs what is why we have given you graph? Solving every time this equations and getting the value may not be easy because it's a non-linear equation though we average out it's fine but these graphs are monitored graph. What do you mean by monitored? Are actually did implants number of times measured actual ranges, projected range as well as straggles on profiles. This is done by actually physical measurement technique called SIMs, some other day okay. Secondary Ion Mass Spectrometry we do SIMS and we can do exact profiles atom by

atom. I won't say atom by atom but large number atoms. But much more accurate profiling can be done.

There are also processes measurement technique ESKA but since it's better than ESKA SIMs can be used almost in all cases ESKA is only in certain cases only then we can do XFS, we can do many measurement techniques which can give you actual profiles, so x-ray photoluminescence so they are same. Some call ESKA some call XFS. So there are number of instrumentation techniques available also in IIT Bombay there is a center which is now called NANOCENTER or something, is that okay so what is the way it is? Is that now clear, random word is how random? So you can see that actual, that's why as I say last one hour I was trying to see various figures so that I can explain you what exactly I am on, I was saying random what random? Now you can see what random, so I was trying to make a visual experience for you. So if I can do it of course you don't have time you can claim that. You may have time for many other thing but for this so okay I will do for you okay.

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Before we, we start now the little bit of modelling though we will not go into too deep because this model which I am suggesting is credited to 3 people called Linherd, Scharff and Schiott or called LSS theory of this energy loss mechanism. LSS was very popular theory till may be 95 or 98 till that time this theory was used very heavily by everyone. By 90 ends we have learnt a better technique of doing this of course even it was known earlier but we started using in our

electrical engineering more vigorously which is called Monte Carlo technique. So once we have Monte Carlo we can have a pseudo random generator program then it became very easy to do a Monte Carlo system this and much easier way to do this. However Monte Carlo does not give physics it just simulates something. LSS will at least tell you what is the mechanism going on. What is the even modern version of Monte Carlo? Another example CSA CSV come out and gave a good name you know because we're very fond of our lineage. So genetic algorithms, they are modified versions of Monte Carlo genetic algorithms.

So there are many more, now you come out with something else and you say okay here is another algorithm. Basic idea is randomize the process and take average out of it okay. So do whatever it takes. So you must be aware not aware but all these techniques we learned ourselves because there was no other background with us okay. Now there are books, there are journals but in our time.. but that was fun. Okay may be this is also a fun. Let us say  $M_1$  is that maybe I will, this is also  $M_1$ .  $M_1$  is the ion and small  $m_1$  is the mass of the atom or ion which is travelling normal and say this is our substrate surface where it impinges okay. Now as it starts travelling with a velocity  $V_0$  so we may say it has a kinetic energy half  $M_1$  square and it has an energy equivalent of  $E_0$  which is kinetic energy.

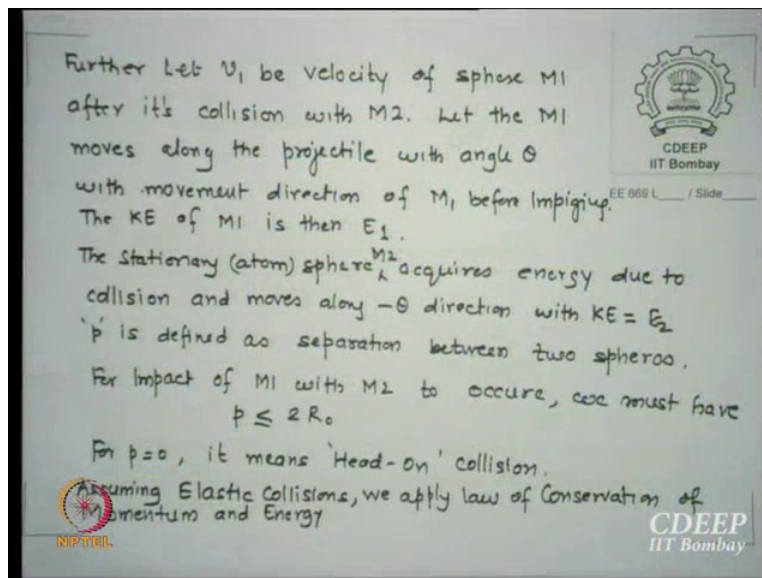
Ions are accelerated so they have a kinetic energy which is half  $M_1 V_0$  square equivalent to  $E_0$  okay. Before it impinges on  $M_2$ ,  $M_2$  is the substrate atom okay which is at what is  $M_2$  status? It is at rest okay now our first assumption in this all kinds of this is I think way back in our schools or may be in first year, no schools only these days if may in fourth standard, in my time it was in 12<sup>th</sup> or something. We used to have the theory of elastic collisions and non-elastic collisions okay so all other assumptions is they are all elastic collisions and which essentially means there is any reflection of this does not lose extra energy on that okay. Otherwise that  $E$  restitution coefficient has to be added to that.

So all are elastic collision, so as soon as it hits stationary atom  $M_2$  which has a mass  $m_2$  for example I just casually either capital  $M_1$  or  $M_2$  also has a mass. So don't as we capital  $M_1$  and  $M_2$  same okay. As soon as it hits it due to a recoil depending on this it may go into one direction at an angle  $\theta$  to the direction in which it was appearing and by saying this this will give you a recoil now. And this  $M_2$  will also move the other side, is that clear. So I want to know this is called the  $\theta$  which is called cosine  $\theta$  is what I want to know how much is the angle

through which (51:32.0) moves away. Is that clear? It's impinging at 0 degrees okay and then bifurcates at the... this may still have an energy which is  $E_1$  which is mass  $M_1$  and velocity  $V_1$ .  $V_1$  will be less than  $V_0$  because it has lost some energy but  $M_2$  has gain some energy  $E_2$  it therefore creates a velocity  $V_2$  and this.

Please remember this also is now moving okay. So is that clear why random because this atom itself is not at its original position. So when the next something here it may hit somewhere else now. So there will be a random process going on okay. Is that okay? Stationary atoms have kinetic energy 0 moving atoms have kinetic energy  $MV^2/2$ . Whatever I said we need not write we can say it.

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This is projectile  $M_1$  moves along the projectile with an angle  $\theta$  from the direction of  $M_1$  before impinging and stationary atom  $M_2$  moves in a direction  $\theta$  opposite side. Let us say  $P$  is defined as a separation between the 2 spheres. Atoms are assumed as spheres okay. When the collision will occur the dia is  $2R_0$ .  $R_0$  is let's say radius so if  $2R_0$  if  $p$  is greater than  $2R_0$  then there will be separate na it will go away they won't it. But if their  $P$  is separation is less than  $2R_0$  dia then only they will hit, is that correct? There are 2 planes one this and one this. So if they are like this they will not hit, but they are there then they will hit okay. So the condition of impact is that  $P$  should be less than  $2R_0$  and when is  $P$  is equal to 0 means head on collision.



Of course our assumption is elastic collisions and therefore we can apply laws of conservation of energy and momentum. 2 equation energy is conserved and momentum is also conserved. Ek aya hit kiya naya aya. Is that okay? One atom ion is hitting to the next, it moves away with some velocities so the output velocities are, output energies are half  $M_1 V_1$  square plus kinetic energy is half  $M_2 V_2$  square must be equal to how much? Half  $M_1 V_0$  square, because that's the net energy, energy is conserved okay. Is that okay? Whatever I stated I just wrote down also. So that for your sake, this is also given in Plummer's book. Of course this is their nomenclature my nomenclature may not the may have angle there is another angle 5, we will not go into too much detail, there are very interesting theories of LSS but some other day those who are interested. May be 3 hours I can give you what is the implant theory.

We have never said it so far, we have never said it so far. What I started there is a mass  $M_1$  I never said charge. There is an atom with mass  $M_1$  so kinetic energy is half  $MV$  square.

Student: (())(55:16.0)

No P may not change that's the whole fun we will have some distribution just wait for it.

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We have for Energy Conservation:

$$\frac{1}{2} m_1 v_0^2 = \frac{1}{2} m_1 v_1^2 \cos^2 \theta + \frac{1}{2} m_2 v_2^2 \cos^2 \theta \quad \text{--- [1]}$$

clearly here  $E_0 = \frac{1}{2} m_1 v_0^2$  or  $v_0 = \sqrt{\frac{2}{m_1} E_0}^{1/2}$   
 & Similarly  $v_1 = \sqrt{\frac{2}{m_1} E_1}^{1/2}$   
 &  $v_2 = \sqrt{\frac{2}{m_2} E_2}^{1/2}$  }  $\rightarrow$  [2]

From eq [1]  $\cos^2 \theta = \frac{m_1 v_0^2}{m_1 v_1^2 + m_2 v_2^2}$   
 or  $\cos \theta = \frac{\sqrt{m_1} v_0}{\sqrt{m_1 v_1^2 + m_2 v_2^2}} = \frac{E_0^{1/2}}{\sqrt{E_1 + E_2}} \quad \text{--- [3]}$

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From the law of conservation of collisions half  $M_1 V_0$  square is half  $M_1 V_1$  square cos square theta half  $M_2 V_2$  cos square theta.  $V \cos$  theta is the in the direction okay. So this clearly the kinetic energy of incident ion was or incident atom was half  $M_1 V_0$  square and therefore initial

velocity is  $2 \text{ by } M_1 E_0 \text{ to the power half}$  by same argument  $V_1$  is  $2 \text{ by } M_1 E$  to the power half  $E_1$  to the power half  $P_2$  is  $2 \text{ by } M_1 E$  to the power half okay. So I can I know the mass and I know the energy at which this or I know the velocities they are related so I know energy is root of  $E_1$  root of uhh velocity is root of  $E_1$  on each okay. From equation 1 we can find out  $\cos^2 \theta$  we write  $\cos \theta$  root  $M_1 V_0$  upon this. And replace  $V_0$  from here so I got  $E_0$  to the power half upon  $E_1 \text{ square plus } E_2 \text{ square}$ .

So  $\cos \theta$  is energy dependent is it okay?  $\cos \theta$  minus is minus  $\cos \theta$  so it's same angle. So here this is incident if you're going this side is still  $\cos \theta$  this angle is still  $\theta$ , it recoils that's why elastic. Whatever goes up with the same angle this will go down okay. So I have a  $\cos \theta$  which I was looking for, I can get one more relationship of velocity with  $\cos \theta$  by which theory. What is been conserved here energy but now we can also conserve momentum is that okay to all of you. I repeat all that given in Plummer's book.

Student: Can you show in the previous slides at  $\theta$ , for second term. This should be 95?

No no that is E if I say 1 then it will always be, it will always split that is why I have kept saying I am using my theory well. If you have written down this then I can also conserve momentum. So I have  $M_1 V_0$  is equal to  $M_2 V_2 \cos \theta$  plus  $M_1 V_1 \cos \theta$ . And from there again I can get  $\cos \theta$  term and using the last 2 equations, I can write  $\cos \theta$  in terms of energy and mass. I have just copied it may be check ho sakta hai may be some  $E_1 V_1 E_2$  may have gone wrong but 99 percent they may be correct. 1 percent error stands because I did not substitute myself and verified it but hopefully it is right.

Okay in case now I know in case of ion implantation the kinetic energy  $(\text{()})$ (58:33.6) to momentum gain by atoms of  $M_1$  and  $M_2$  this is what we're saying. Change in momentum is essentially force, so we're really looking for conservation of energy and momentum and we know the angle through which it will get deflected will be essentially related to incident ion energy, the energy associated with incident uhh deflected ion as well as deflect stationary atom and energy so a mass associated with them okay. So this relationship is not really used very often, this is just to show you that if I know my  $\cos \theta$ , I am not interested in exactly the position where they are. I will show you what we're interested. But this  $\theta$  I know it's there. So I have figure out how much is the  $\cos \theta$  okay.

Now your answer you were saying na. What you were saying that after all you're not having a neutral atoms okay so when you're interact neutral mass, this conservation of  $M_1 M_2 M_3$  is fine okay. Momentum energy, but you're now looking for ions okay, ions are charged species and therefore they will also have some kind of potential associated with essentially they will follow coulombs law. They will follow coulombs law. Is that okay expression? This potential due to electric nature of ion essentially it will modify the actual transverse motions okay. It's called screening, screen means weighing something. So if you're passing through to a screen some may go some may not. As it's trying to wade a initial process change the input. So what this VR a potential associated with ions is, it will actually modify the theta what you're saying, it will modify.

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However due charged nature of ions, they also experience Coulombs force. This lead to Potential  $V(r) = \frac{q^2 z_1 z_2}{r} \exp(-r/a)$

where  $z_1$  and  $z_2$  are atomic no. of atoms with mass  $m_1$  and  $m_2$ . The parameter  $a$  is called Screening Parameter given by

$$a = \frac{0.885 a_0}{[z_1^{2/3} + z_2^{2/3}]^{1/2}} ; \text{ Here } a_0 \text{ is Bohr's radius}$$

The Screening potential  $V(r)$  is integrated along the path of ions to get Scattering angle.

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However due to the charge nature of ions they all experience coulombs force this leads to a potential VR which is by coulombs  $4 Z_1 Z_2$  by R. Exponential minus R by A. This is solving the poisson's equation in this case radially okay. R is the position take R theta is any coordinate poor coordinate where  $Z_1 Z_2$  are atomic number of atoms.  $M_1 M_2$  are respect to their masses. And we define a parameter A which is called cleaning parameter which I said I will not solve but this is related to this calculation using VR it's little long because you have to first then figure out how much they diversify then this diversify due to electric field is how much it affects the mechanical energy so, little complication the final answer is this 0.885 is 0 upon  $Z_1$  to the power 2 by 3 plus

$Z_2$  to the power  $2/3$  where  $A_0$  is called Bohr's radius. Which is typically some number of angstroms 5 to 0.2 for different material.

So basically what we're saying that they screen potential VR is integrated along the path of ions to get the scattering angle and that modifies the conservation of momentum and energy paths. So both together modify and depending on how strong is your VR it will actually modify larger or smaller okay. This is what LSS theory is all about okay. How do we now do it? I have a number of atoms with random energies and I will put a charge with them and will expect I will allow them random ions to move inside a lattice with random number available and I will say whenever this average energy goes to 0 find out for each of them okay. Number of such permutations hittings okay. So some will stay off some will stop and I will see whether it still give Gaussian. If it gives all these theory is not needed because at the end I will find that they have given me Gaussian profiles okay.

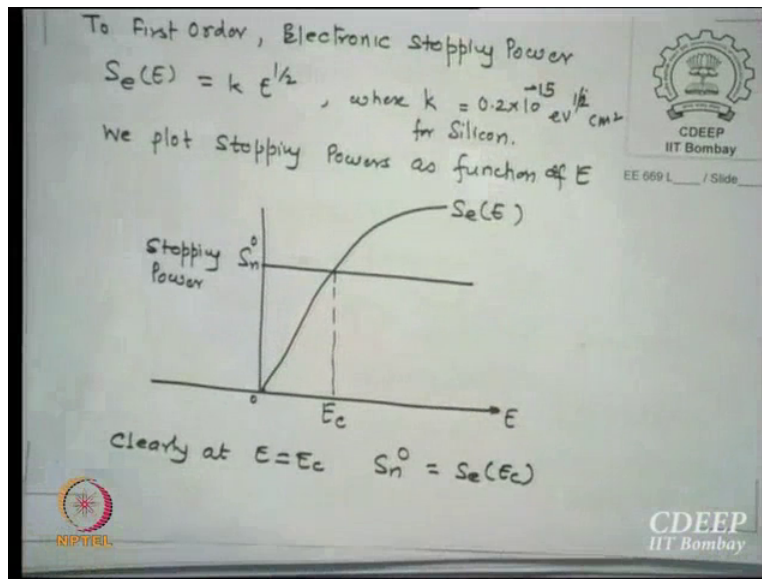
So Monte Carlo technique is much faster programs are available you should need you need to have a pseudo random generator which most program these days are available. The randomness should be at least 1000s or above okay. If you're only doing 10 or 20 don't do say it's a random. So if your random numbers are very high then certainly you can do as much correctness as LSS theory wants okay. Okay so is that to some extent I have answered you? Before we quit we will just show some important things to happen, as we have said there are two ways of relaxation of energy or scattering or losing an energy. One is we say one is we say nuclear stopping power and the other we call it electronic stopping power. The rate  $DE$  by  $DX$  which is the radiant of energy loss okay as it moves from the surface  $X$  is the direction in the lattice okay.

Energy is at the  $X$  is equal to 0 and then it goes in, atoms are getting in. So once in if  $N$  is the number of atoms per cc involved from the substrate then  $d$  by  $dx$  is minus  $n$  times  $S_n$  e into SEA. Where  $S_n$  is called nuclear stopping power and SEA is called Electronic Stopping Power. The nuclear stopping power has been derived and then its equivalence has been found to a great I mean to first approximation the nuclear stopping power is more decided by the charges and the masses and not so much by energies. And therefore  $S_N E$  is equal to  $S_N 0$  and this function has been derived  $2.8 \cdot 10^{-15} Z_1 Z_2$  upon  $Z_1$  to the power  $2/3$  plus  $Z_2$  to the power  $2/3$  to the power half  $M_1$  upon  $M_1$  plus  $M_2$  and the units EV centimeter square energy centimeter square. Where I repeat  $M_1 Z_1$  are incident ionic masses and charge atomic number or

charge associated and  $MZ$  are substrate atoms with mass  $M$  and atomic number  $Z$  substrate ions.

So  $S_N^0$  what is the approximation we made,  $S_N E$  is independent of  $E$  so  $S_N E$  is  $S_N^0$  which is constant okay which is constant. Why are we doing this? There is some reason of doing this, is the following. Is that okay? This is first approximation which is called Pearson's approximation. Pearson 4 formula as it is called okay. This is LSS; Pearson is actually worked with LSS theory so this VR term was actually brought more by Pearson rather than LSS. LSS is a uniform theory for any mass okay; Pearson is the man who actually worked for implants okay.

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By similar argument it has been found that if I look for electronic stopping power then it is proportional to the  $E$  to the power half and proportionality constant is related to substrate which is called  $K$  and for silicon it is  $0.2$  or rather  $2$  into  $10$  to power minus  $16$  root of  $\text{EV}$  centimeter square. Why root this is  $E$  to the power half okay. So root of  $E$  that is why it will give  $\text{EV}$  then, SEA should also have unit of  $\text{EV}$  centimeter square so this is root  $\text{EV}$  this is root  $\text{EV}$  so  $\text{EV}$  of that okay. Multiply kareng to  $\text{EV}$  ho jayega okay. So this is for silicon for different materials this  $K$  values would be different okay. So if I now plot energy versus stopping power is that clear what do I plot, energy versus stopping power. What is  $S_N^0$  we said it is a nuclear stopping power. Power independent of energy first approximation so I plotted  $S_N^0$  which is independent of energy.

However electronic stopping power is root of E which is parabolic in nature so I draw a parabolic nature for ACE. And I figure out somewhere at E is equal to EC SN0 is equal to ACE is that okay. I plot ACE I have SN0 here when they intersect at that energy SN0 is same as SAE okay. So can I found EC then? Because if equate ACE equal to SN0 at E equal to EC I will get the value of EC itself okay. Is that okay to you? SN0 is independent of E AC at EC is K EC to the power half equate the two terms and get the value for EC. Before we come to this figure let me show you this. Is it okay?

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$$\text{or } \frac{2.8 \times 10^{-15} Z_1 Z_2}{\left[\frac{Z_1^2}{2} + \frac{Z_2^2}{2}\right]^{1/2}} \frac{M_1}{M_1 + M_2} = K \sqrt{E_c}$$

$$\text{or } E_c = \frac{1}{K^2} \left[ \frac{2.8 \times 10^{-15} Z_1 Z_2}{\left(\frac{Z_1^2}{2} + \frac{Z_2^2}{2}\right)^{1/2}} \frac{M_1}{M_1 + M_2} \right]$$

Hence If  $E < E_c$  Nuclear Stopping is Dominant  
 but if  $E > E_c$  Electronic Stopping Dominates.

Example  
 Arsenic is Implanted in Silicon at  $E = 250 \text{ keV}$

Data :  $M_{1\text{As}} = 1.2433 \times 10^{-22} \text{ g/atom}$   
 $Z_{\text{As}} = 33$   
 $M_{2\text{Si}} = 4.6628 \times 10^{-23} \text{ g/atom}$   
 $Z_{\text{Si}} = 14$

So if I what I said just now equate SN0 to at E equal to AC K root of EC is equal to SN0. So if I do this analysis finally I get EC is 1 upon K square this this this M1 upon M2. Now one interesting feature about this is, if you see that graph what it is trying to say from the graph can you think of that I already written. If E is less than EC E is less than EC which value is higher SN0 or SNE SAE? SN0 because that is higher if E is less than EC just a minute if E is less than EC SN0 dominates higher value if E is greater than EC SAE dominates so if E is oh sorry. I am very sorry. If E is greater than EC electronic power stopping dominates if E is less than EC nuclear stopping dominates. I have done some calculations for you for arsenic impinging on silicon at 250 KEV if you wish you can call that E0 initial energy. I am implanting arsenic atoms with 250 KEV energy on silicon okay. These values are known to me M1 mask for arsenic is grams per atom its called gram molecular weight is 1.2433 10 to power minus 22. If I want actual grams what do I do divided by (70:00.2) number okay. Thodasa chemistry padhlo.

ZA arsenic is 33 Z for the atomic number for arsenic is 33, mass for silicon is 4.6628 10 to power minus 23 grams per atom. And Z2 for silicon is 14, so I now know M1 M2 Z1 Z2 and EA for silicon is also known to me how much? 2 into 10 to power minus 16 EV to the power half centimetre square so that K is known to me. This is known to me, this is known to me, this is known to me, this is known to me, all quantities are known to me so what can I calculate EC is that okay? I know EC I have all the values for arsenic implanting at this okay.

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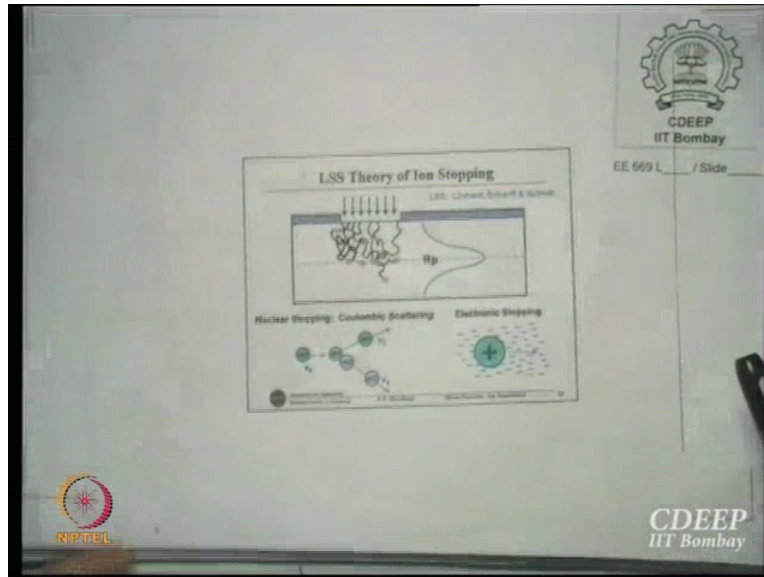
At  $E = E_c$   $S_n(E_c) = S_n^0 = S_e(E_c)$   
 $\therefore k E_c^{1/2} = S_n^0$   
 $\therefore E_c = \frac{1}{k^2} [S_n^0]^2$   
 For As-Si combination with  $R = 250 \text{ keV}$  implant-  
 $E_c = \frac{1}{(2 \times 15^2)^2} \cdot (2.34 \times 10^{-12})^2$   
 $= 13750 \text{ KeV}$   
 Clearly  $E_{\text{given}} \ll E_c$   
 Hence Nuclear Stopping dominates in  
 our case.

So if I do this what is the EC I got I got 13750 KEV kilo electron volt. How much electron I got, critical energy this EC. 13,750 KEV how much was my implanting energy E0 was how much 250 KEV so what is the condition we have? E is much less than EC so what will dominate nuclear stopping power will take care of actually energy loss mechanisms. So in d by dx what should I put the term now only minus n into SN0 because SAE is much smaller compared to SN0 is that clear? What is d by dx the energy loss is minus n time SNE plus SAE, if SAE is much smaller compared SN0, then I would say it is minus N SN0 then I can integrate this and find X at that where it will stop, that's my purpose of doing all this. Just for the before we come to end okay, here is a you have noted down.

So what is the way you have to do it, given an energy, given the species which is bombarding, given the lattice mostly this data will be given by me? Then figure out what is its EC, then compare that EC with implanting ion energy if A is larger than EC then you have a electronic

stopping, if it is less than  $E_C$  then it is nuclear stopping. So the  $d$  by  $dx$  relaxation term will have either SAE or SNE not both but may happen that at  $E$  equal to  $E_C$  both terms are equal so multiply it by 2 and use it okay. Last figure for the day.

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Last show this again from the same Rochester University Slide. One can see from here this is exactly what I wanted to show you this is nuclear stopping and this is electronic stopping okay. So you can have either nuclear stopping or you may have electronic stopping okay. And since we know either of them will be, we know the expressions for either of them I can always find energy loss at as a distance okay. That's my purpose of finding out. So how will I calculate where it will end? Where  $E$  will become 0 when the energy of ion become 0 the distance travelled is range, so we will calculate next time range  $d$  by  $dx$  is know so I know slope. So when the energy becomes 0 I will say it has stopped so the distance travelled is range. We will come back to it tomorrow.