Fundamentals of Micro and Nanofabrication
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Lecture – 10
Ion Implantation

Hello and this is Fundamentals of Micro and Nanofabrication, I am Sushobhan Avasthi from IISc Bangalore and today's lecture will focus on ion implantation which is one more method in which we create dopants inside silicon.

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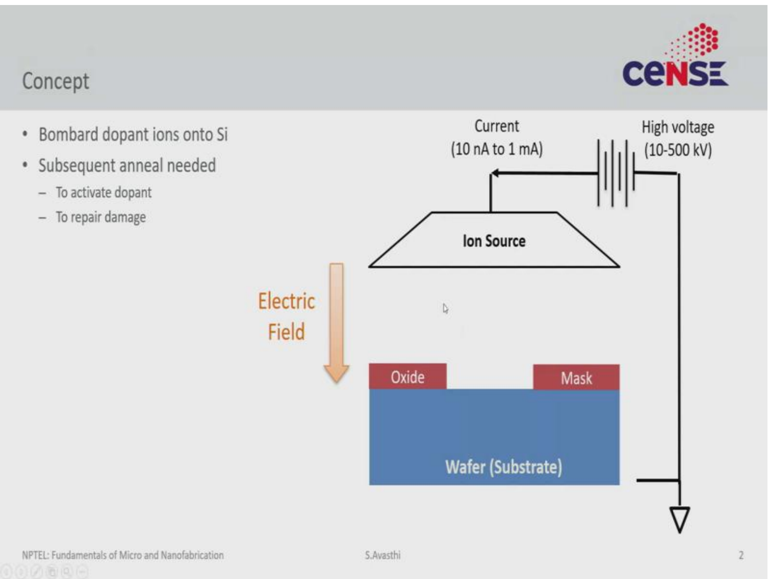

The basics of ion implantation are fairly simple. Instead of diffusing ions, we shoot them from an ion source at the substrate with a lot of speed such that they get embedded in it. This ion source would change with the dopant. For phosphorous doping, the ion source would be phosphorous, boron for boron implantation. Ions carry a charge that can be used to accelerate them at very high speeds using an electric field that attracts the ions towards the substrate. If this process is done in the vacuum and the mean free paths are long, the ions will not lose any energy while they go from the source to the silicon and will bombard the surface in a way very similar to sputtering.

You can measure the flow of ions by measuring the current (carried by the charge on the ions) flowing through the voltage source to the ions source to silicon to the ground terminal. Ions collide with the substrate and penetrate it because of their very high speed,

creating a layer of doped silicon. One of the issues and the main challenge with this approach to be solved before the technique became widespread was the damage caused by mechanical bombardment unlike diffusion, which is a very gentle process. Atoms automatically come into the substitutional position in the diffusion process, however, the ion implantation does not promise that. So, you have to do some subsequent annealing to make sure that the dopants sit in the substitutional sites as only they create carriers. A dopant sitting in an arbitrary position inside the lattice may not lead doping.

You do not just create dopants inside silicon through this process, but also displace the silicon atoms already present in the lattice. Those displaced atoms need to be put back into their correct position, else you will not retain the properties of silicon. So, these two issues: lack of substitutionality and lattice damage both require annealing.

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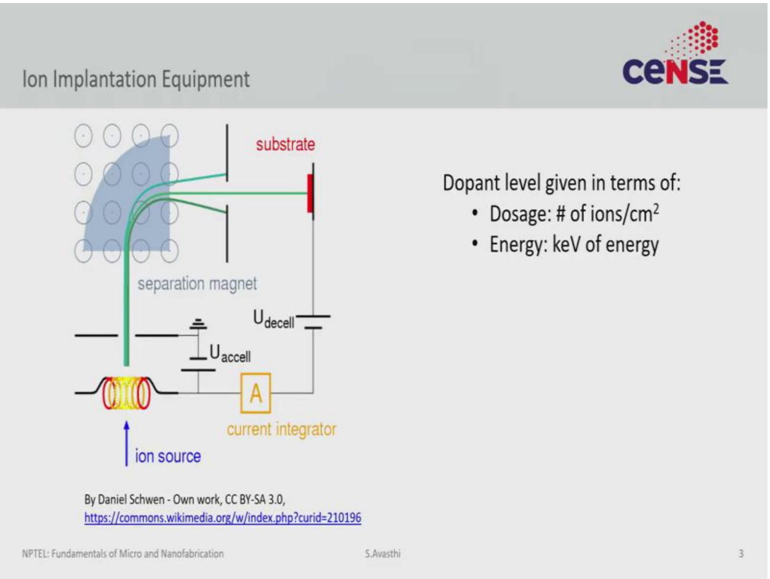

Here is a typical ion implantation instrumentation. Ions are thermionically generated and accelerated by an electric field U. A separation magnet is used to allow the ions with a certain mass and charge, very similar to how mass spectroscopy works, where you can detect the mass of ions by putting them in a magnetic field and allowing only ions of a certain mass to reach the detector depending on the path curvature. So, only the ions with the right mass by charge ratio would be able to go through and get bombarded the substrate, not the impurity ions.

The substrate is internally connected with the current integrator. Every ion has a charge, so if you deposit 10 ions into the silicon substrate, you will measure a 10 electron worth charge. Measuring the amount of charge or the current flowing in this whole system, you can get a very accurate measure of how many ions have been bombarded. This is much more accurate than the diffusion process that we had discussed previously. In diffusion you just had a model and based on the model, you predicted a certain profile. Any error in the modeling would lead to an error in the estimation of the dopants. There is no explicit control over the number of dopants. You just hope that your model is accurate.

While that modeling is extremely well understood, there still are a lot of confounding factors. For silicon, we may understand them all, but for an arbitrary material, that may not be true. Implantation, on the other hand, can allow more accurate and precise measurement of the amount of the ions going in the substrate. Ion implantation is superior in the cases where very high accuracy of doping is required, which is pretty much most of the modern electronics.

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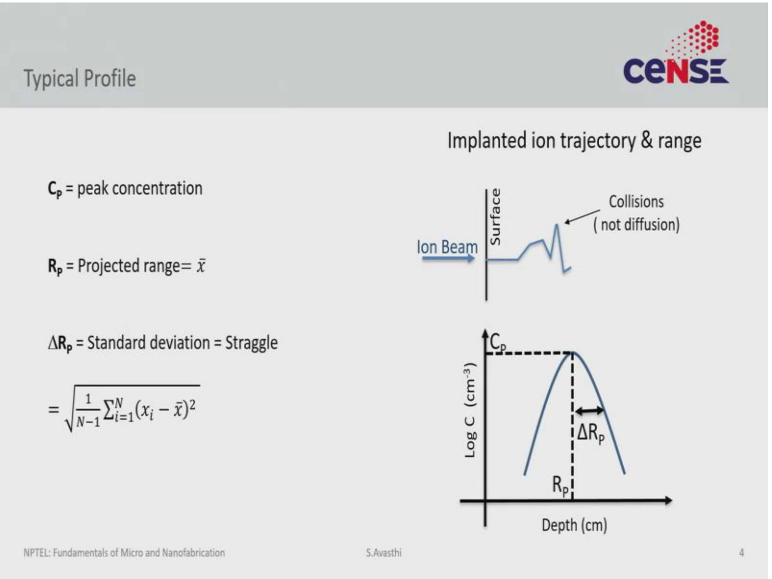

Typical profile with ion implantation resembles a Gaussian. It is similar to the finite dopant case where we got a Gaussian profile. The difference is that in diffusion, you only get half of a Gaussian, while in ion implantation you get the full Gaussian. One way to understand why that is happening is to just look at the figure here. In a vacuum, the beam comes straight without any hindrance and then hits the surface and starts encountering

the silicon atoms, and every time it encounters them, it suffers a scattering event that deviates its path a little bit and it loses a little bit of its energy. After several of these successive collision events, at some point, the energy is completely dissipated and the implanted ion comes to a stop. To clarify, these are collisions and not diffusion. Diffusion also does a random walk, but this is not a diffusion but a ballistic collision mechanism. At some point, the ion comes to a standstill and this process happens again and again. Because this is a stochastic process, there is no one depth at which all the ions will stop; some will stop a little earlier, some go a little deeper depending upon the angle of collision, and overall, for a large number of ions, you get a Gaussian profile.

Because of the very nature of this process, you see both the halves of the Gaussian. There is a peak in the middle and that depth is called the penetration depth (R_P) where you get the maximum concentration, called the peak concentration (C_P). The measure of the deviation from the projected range ΔR_P is called deviation or straggle. So, unlike diffusion, the parameters of interest here are the straggle of that implantation and the penetration depth.

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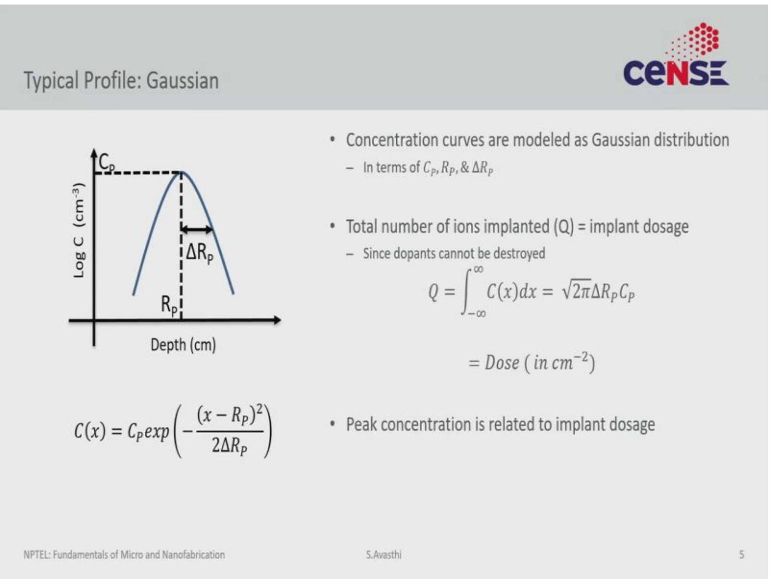

Here is the mathematical expression for the concentration profile. C(x) is a Gaussian as we have discussed. The total number of implanted ions or dose is the area under the C(x) curve. As we have discussed before, this dose can be very accurately measured. It is

directly proportional to both the straggle as well as the peak concentration right. If you want higher doping, increase the dose.

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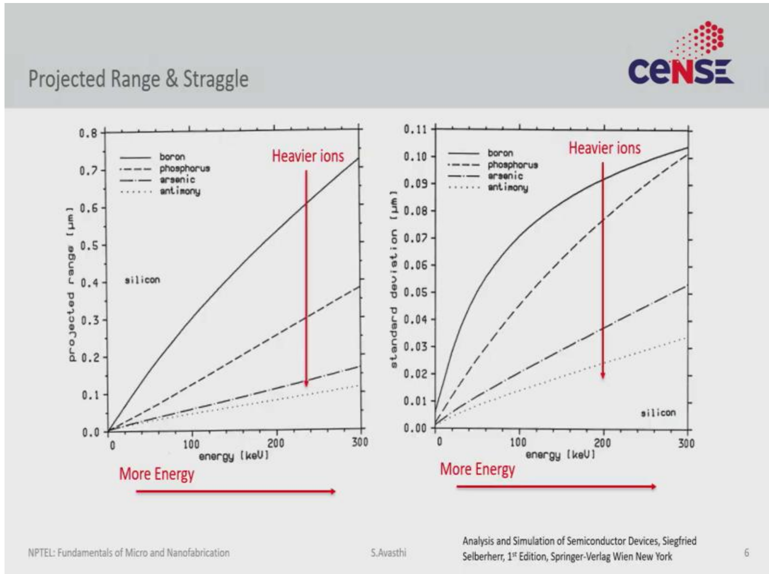

The other controllable parameter in the ion implantation is the acceleration voltage that controls the speed at which the ion impacts on the silicon. This kinetic energy is the energy of the implant. So, the ion implantation machine controls the dosage (the total number of ions) and the implant energy.

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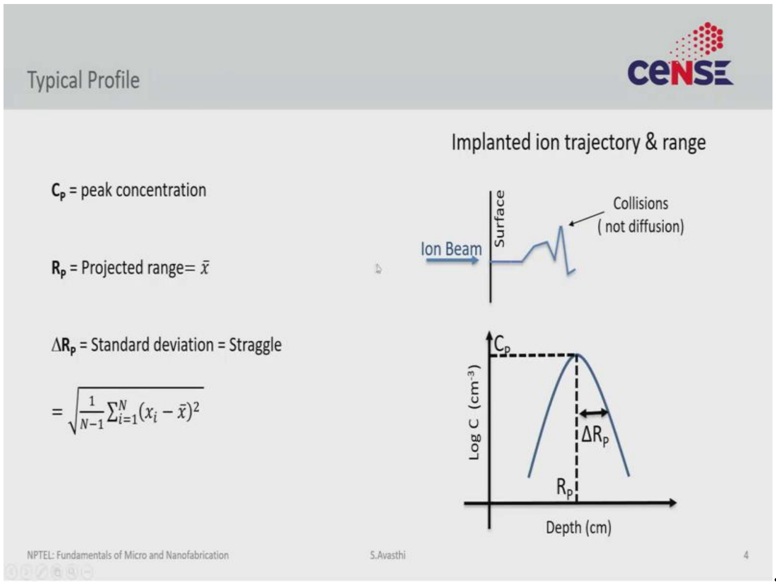

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If the ion beams are coming with higher energy, they will penetrate more into the surface and they will on average take longer or penetrate deeper before they come to a standstill. So, this is easy to understand - the more energy you implant, the projected range or the depth of the implant (R_P) increases.

For the same amount of energy, heavier the ion, the less it will penetrate because the heavier ion will have a lower velocity and hence, will suffer a fewer number of collisions before coming to a standstill. Intuitively, a big ion will have a lot of problems getting into and moving in silicon. A lighter ion will just go through. As you go towards heavier ions from boron to antimony, the projected range reduces for the same energy.

More the energy, the higher the standard deviation. Again, there is an effect of mass. As you go for heavier masses from boron to antimony, the standard deviation reduces. You get a more repeatable or more accurate implant with antimony than with boron.

There are a few other general trends you can extract. You to remember these values; we have simulators for that which have all these numbers stored in. So, you can just put in the numbers and extract your profile, but as an engineer, it always helps to have an intuition about what is happening. The next few slides are to help you develop that intuition a little bit.

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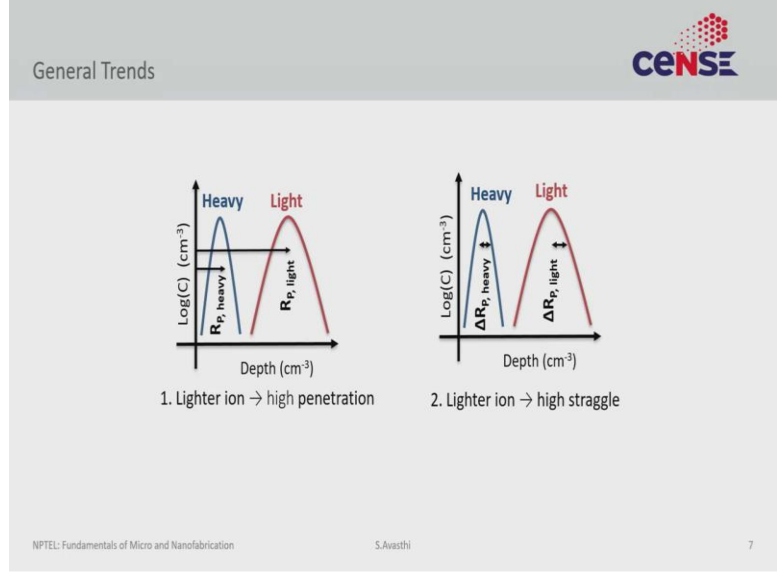

For a heavy ion, like arsenic and a lighter ion like boron, you get these two types of profiles. A lighter ion will typically penetrate more than a heavier ion, and will probably have more standard deviation than a heavier ion. The straggle will be lower for the heavy atom, higher for the lighter atom.

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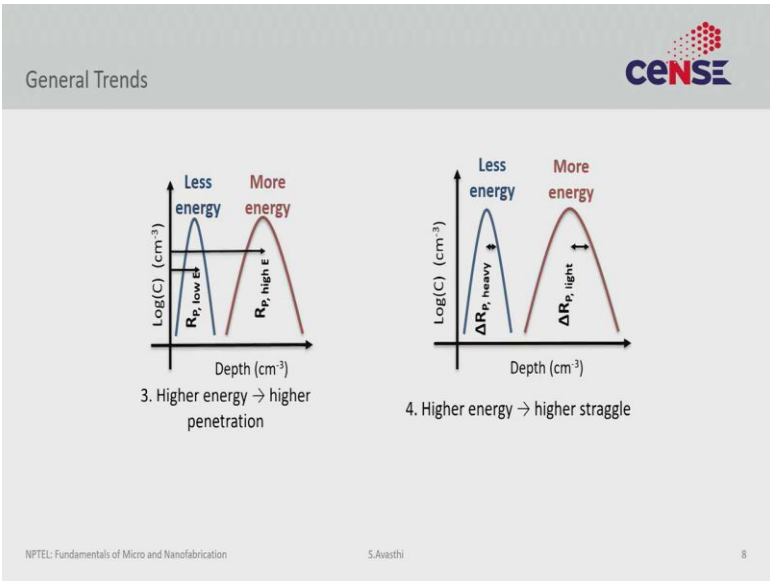

Similarly, if you have a lot of energy for the same ion, you will have a higher straggle and less straggle for lower energy for the same ion. With more energy for the same ion, you will have more penetration compared to less energy.

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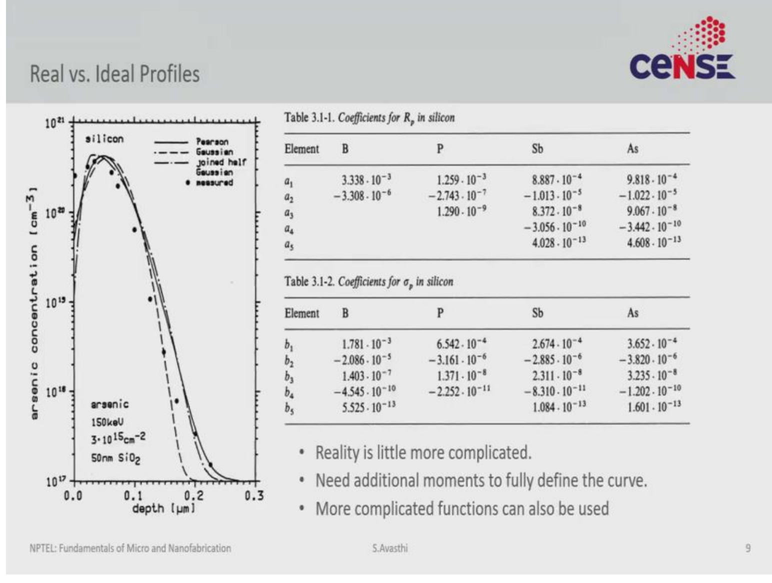

Table 3.1-1. *Coefficients for R_p in silicon*

Element	B	P	Sb	As
a_1	$3.338 \cdot 10^{-3}$	$1.259 \cdot 10^{-3}$	$8.887 \cdot 10^{-4}$	$9.818 \cdot 10^{-4}$
a_2	$-3.308 \cdot 10^{-6}$	$-2.743 \cdot 10^{-7}$	$-1.013 \cdot 10^{-5}$	$-1.022 \cdot 10^{-5}$
a_3		$1.290 \cdot 10^{-9}$	$8.372 \cdot 10^{-8}$	$9.067 \cdot 10^{-8}$
a_4			$-3.056 \cdot 10^{-10}$	$-3.442 \cdot 10^{-10}$
a_5			$4.028 \cdot 10^{-13}$	$4.608 \cdot 10^{-13}$

Table 3.1-2. *Coefficients for σ_p in silicon*

Element	B	P	Sb	As
b_1	$1.781 \cdot 10^{-3}$	$6.542 \cdot 10^{-4}$	$2.674 \cdot 10^{-4}$	$3.652 \cdot 10^{-4}$
b_2	$-2.086 \cdot 10^{-5}$	$-3.161 \cdot 10^{-6}$	$-2.885 \cdot 10^{-6}$	$-3.820 \cdot 10^{-6}$
b_3	$1.403 \cdot 10^{-7}$	$1.371 \cdot 10^{-8}$	$2.311 \cdot 10^{-8}$	$3.235 \cdot 10^{-8}$
b_4	$-4.545 \cdot 10^{-10}$	$-2.252 \cdot 10^{-11}$	$-8.310 \cdot 10^{-11}$	$-1.202 \cdot 10^{-10}$
b_5	$5.525 \cdot 10^{-13}$		$1.084 \cdot 10^{-13}$	$1.601 \cdot 10^{-13}$

Reality is a lot more complicated. This stochastic process is represented by a Gaussian, but that is an approximation; sometimes the profiles are not exactly Gaussian. Here is an example of these dots that are the measured values of concentration and the dotted line is the Gaussian and you can see that it is an approximation. We can try fitting it to other popular profiles such as a Pearson model or a joint half Gaussian - half Pearson model etcetera. Some of them are more accurate than the others, but of course, nothing exactly captures the real data. The way this is solved is by using simulators that remember not just one or two, but a lot of parameters. For each ion that you can probably implant, you can theoretically measure the first moment which is the mean, the second moment (typically the standard deviation).

For Pearson and Gaussian models, these two moments are enough to perfectly define it. However, for an arbitrary profile like the one represented by this dotted curve, you have to measure higher-order moments like the third or the fourth moment. More moments you add, the more accurate your profile will be. For various types of ions, the simulator measures these moments a_1 to a_5 or more, a_i being the ith moment of the distribution. You do not need to remember these numbers; they are given so that when you use a process simulator, you have an idea of what is happening.

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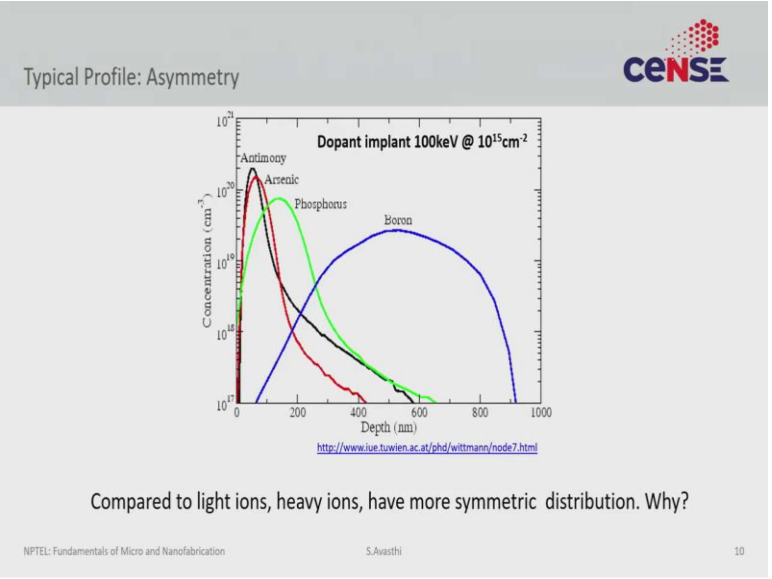

Let's discuss some complications that you would measure in the real-life implantation for the first asymmetry. If you measure the concentration of the dopants like antimony,

arsenic, phosphorus or boron as a function of depth, you would notice that they are not exactly symmetric. So, not only are they not exactly Gaussian, but they are not a very symmetric either; a lot of them would show tails as you see in the red and green curve. The distribution is a Gaussian, but towards the end, there is a significant deviation and you see these tails. In boron there is another problem; compared to a Gaussian profile, the concentration is a little bit higher on the left and lower on the right as if the boron concentration is biased towards the lower depth. We shall discuss why this is so, in the subsequent slides.

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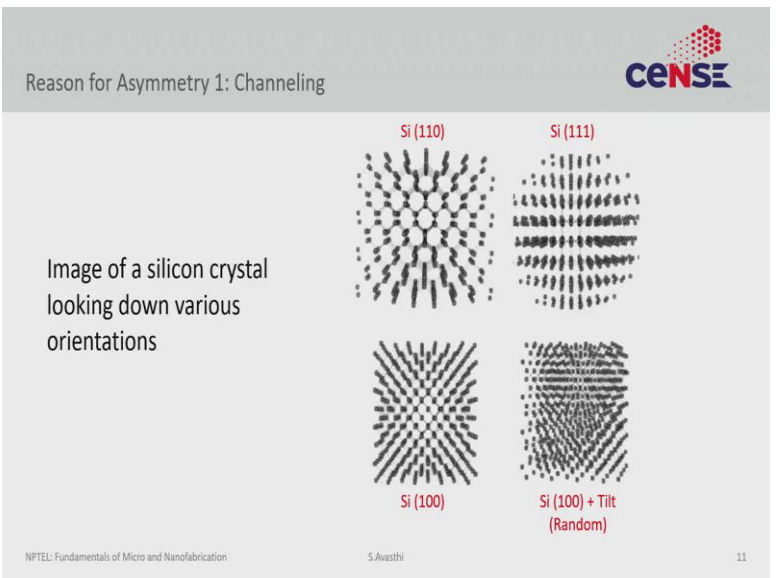

The first important aspect to appreciate in ion implantation is channeling. Here you are looking at the silicon lattice, viewed from various angles. Looking at it from the [110] direction head-on, you would see hexagons, squares from [111] and parallelograms from [100]. This is what the cross-section of that lattice orientation looks like. However, you may notice that even though silicon has a certain atomic density, the apparent density of atoms/cm^2 looking at these 3 different orientations is different. The silicon (100) seems to have a different aspect ratio hole than the silicon (110) or (111).

This has an impact on ion implantation as the number of atoms an ion encounters on the surface will depend upon the orientation of silicon. In the (fourth) extreme case of randomly tilted (100), these holes completely disappear as the atoms are not aligned one behind the other. You see a much denser face of silicon.

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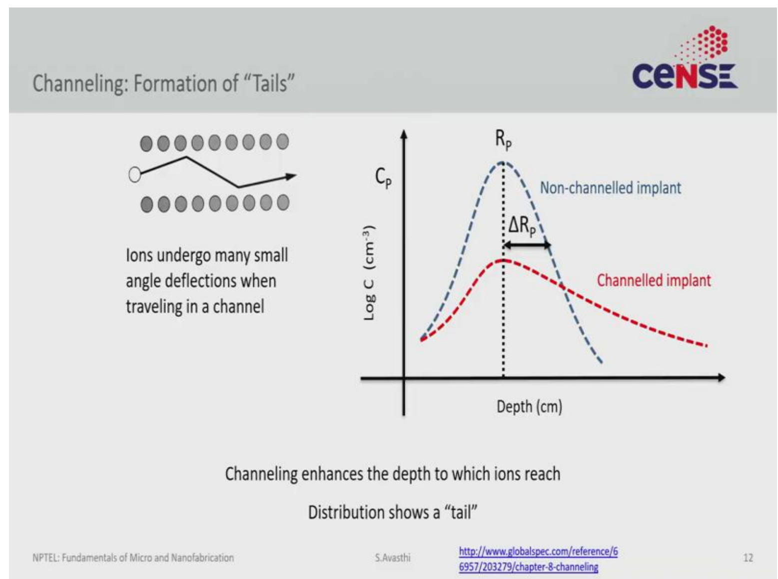

This leads to channeling. The ions undergo many successive collisions, but every now and then, they enter this sort of a channel. These hexagon or square holes/tubes are channels where there are no silicon atoms. Silicon atoms in a lattice will line up one behind the other. So, in between these lines of silicon atoms, you will have a little space. If the ion is small enough (a lot of ions are), they would suffer collisions and ultimately get constrained in this channel. They will hit silicon, but then get scattered or piped into these channels like how the light gets coupled inside an optical fiber. Every time they collide into a line they get channeled into one of these channels.

Once the ion is in the channel, it does not encounter as many silicon atoms it should have if it was in a random direction and that leads to it going deeper inside the silicon before coming to a standstill. You expect a concentration profile like the blue curve, but you measure a channeled profile like the red curve, where the concentration at higher depths is higher. The ions take longer to stop then they would have in case of a simple profile. Channeling is a very common effect in ion implantation and as a process engineer, you should always be aware of it.

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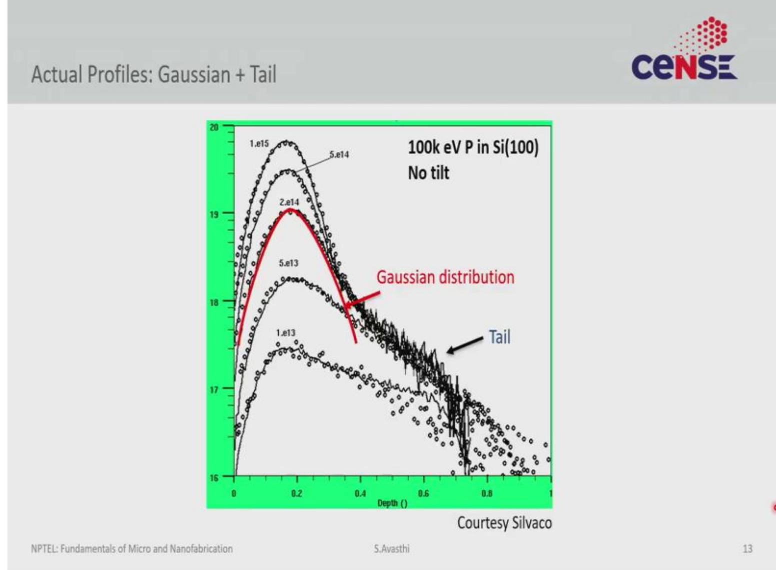

These are some simulated profiles from a simulator from Silvaco. I think Centaurus and other companies also sell similar simulators. Using a whole bunch of existing data from papers they have the ability to give you profiles that are fairly accurate. Here is a profile that you can simulate for $10^{15}/cm^2$ dose and 100 keV phosphorus implant in silicon (100). Initially, the profile looks Gaussian profile but you will start seeing a tail because of channeling. The open circles are actual data points, so, you can see that the simulator does a fairly good job of predicting what the actual profile is going to look like. You see such tail at a range of concentrations (at high dosages as well as low dosages).

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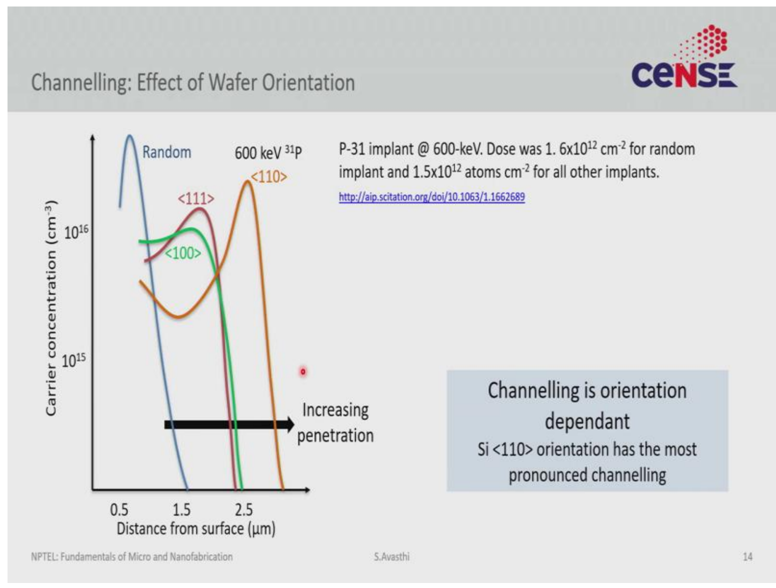

And because the apparent density of atoms is different for (100), (111) and (110), when you look at the mahjong, you see a difference in the probability of channeling. Compared to a randomly oriented silicon where you would expect a clean Gaussian, if you were to expose a (111) or (100) or (110) orientation, you would get very different profiles. The channeling is the highest in the (110) direction because the number of atoms/cm^2 are so low, you have these large channels with a hexagonal cross-section. The profile looks completely different from a Gaussian; it is high at lower depth, has a local minima and then goes up and comes back down.

Channeling significantly changes the depth of the implant, and if you are not careful you will end up underestimating the depth of the implant. Silicon (100) is the one that is the most common and even that shows a channeling behavior which leads to a flat profile and then a sudden drop. What can we do about this?

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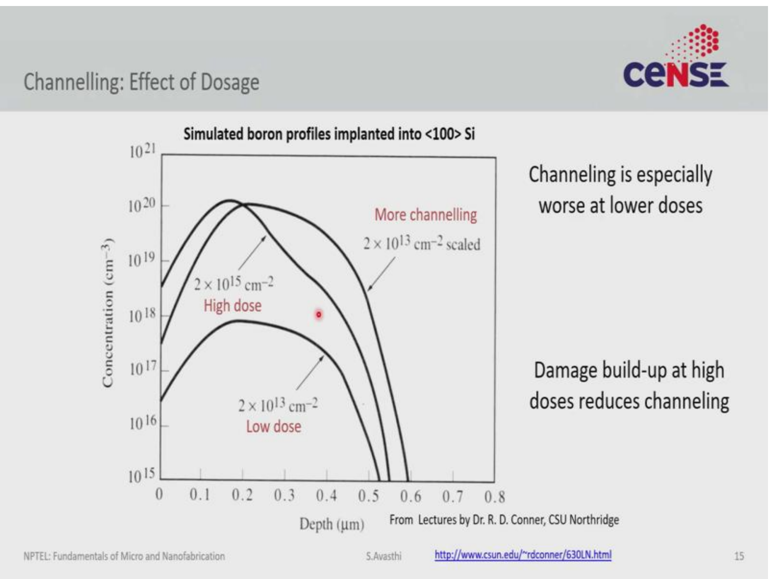

But let us first also appreciate the effect of dosage. Is channeling higher at a higher dosage, or at a lower dosage? If you were paying attention when we were discussing the Silvaco profile, the same data was there. Here, I am representing this data again to highlight this.

For a dose of 10^{15}/cm^2, you get this profile. This is our high dose profile and you see a second hump because of channeling. A low dose ~ 10^{13}/cm^2 profile also shows you a tail. It is hard to directly compare these curves because they are at a different dose which is

directly proportional to peak concentration. So, the peak concentration of the high dose is much higher (10^{20} vs 10^{18}). To compare them, we will scale the low dose curve up artificially to avoid the confounding effect of change in concentration. Clearly, the scaled version has more channeling than the higher dosage case. Why does that happen? partly because of the accumulation of damage. Implantation is a very mechanical or ballistic process. Every time the ion comes and collides with the silicon atom at very high speed, it leads to some damage in the silicon lattice that will accumulate with more ion bombardment. In a sense, it is destroying the lattice and that also destroys the channels that exist in the lattice. So, the channeling phenomena become less prominent. Because of the accumulation of the damage, the channeling is a little lower in higher dosages.

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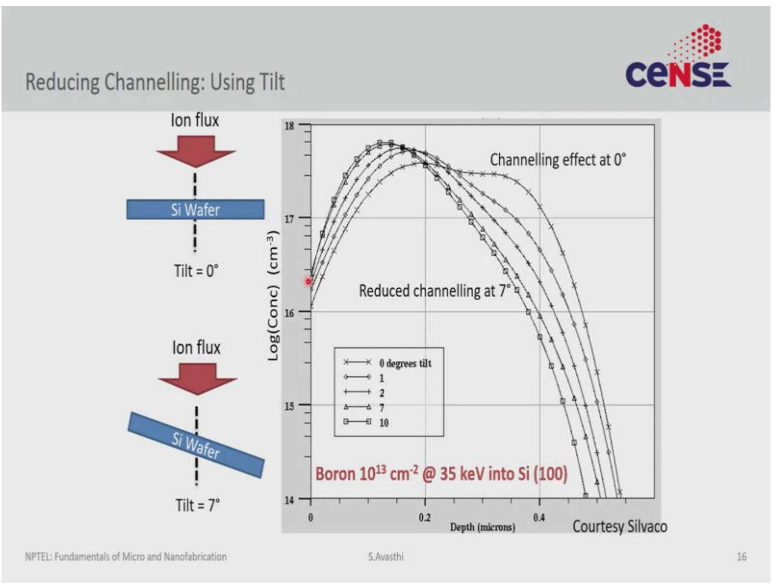

As we have discussed before, (100) orientation with a little tilt prevents the silicon atoms to line up and prevents the formation of these channels. This is a common technique to fix channeling instead of implanting on the silicon wafer at a 0° tilt which is what you would do if you were to naively do this process. A small tilt, say 7° significantly reduces the channeling. In the graph, the crosses are the data at 0° or a flat wafer, and as you increase the angle, the channeling keeps reducing and at 7°, you get a very low amount of channels. This data is also from the Silvaco simulator. This technique is so common now that it is the standard. If you send your wafer out for implantation, unless you say otherwise, they will probably do it at 7°.

Another common method is to grow a screening oxide. In the simplest case, during implantation on a silicon wafer, there is no oxide on top. If you were to grow a very thin layer of silicon dioxide on the top, which is amorphous and does not have any crystal orientation, it would not have any channels either. Even though there are channels below the silicon oxide, the first layer of few atoms do not have any channel so, the implanted ions do not get channeled. The silicon dioxide sort of diffuses the ion flux so, the ions are not incident at one angle but have multiple incidence angles and hence, they will not channel as easily. This is seen in the data; compared to the native oxide which grows automatically on the silicon surface, a 10 nm oxide or 100 Å significantly lowers the channeling.

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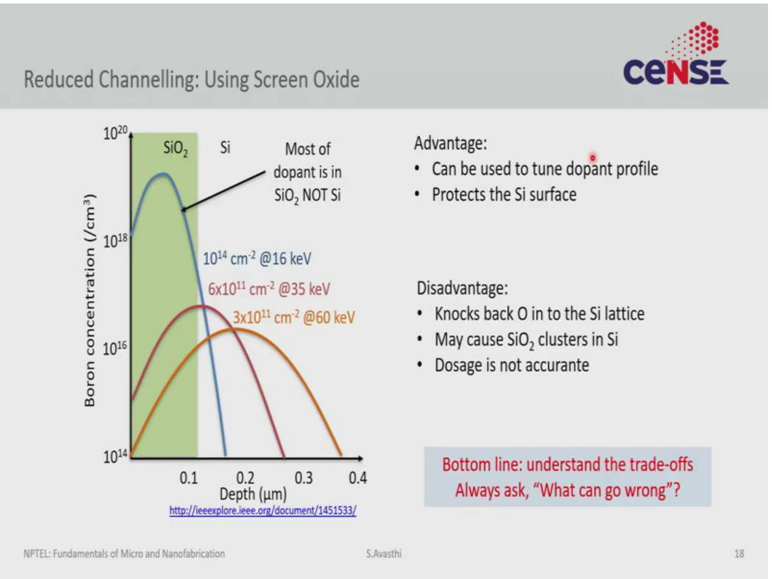

However, this screening oxide does not come without its own challenges. One of the challenges is that the amount of dopants becomes harder to characterize. This is an example from an actual paper describing various implants done on a silicon wafer with around 100 nm screening oxide grown on top. You would get different profiles when you do your implant at different doses and energies.

To first order, assume that silicon dioxide and silicon have the same penetration and the straggle. So, the blue curve is what you would get at 10^{14} dose and very low energy. The low energy implant depth would also be lower. The red curve has slightly higher energy and hence implant depth, and this orange curve has the lowest dose but the energy is

higher so, the implant depth is higher. The peak concentration reduces as you reduce the dose. If you measure the actual doping in silicon, you would notice that the blue curve does not have much doping at all as most of the dopants that you implant get stuck in the silicon dioxide. They need to be in silicon in order to be electrically active. On the other hand, for the red curve, around half of the dopants would be electrically active because and half of them get stuck in silicon dioxide. In the orange curve, the majority of the dopants are within the silicon.

This sort of mismatch can make you under or overestimate your doping if you are not careful. That is one of the disadvantages of using the screening oxides. The second disadvantage of using silicon oxide is that during this implant process, the damage also starts accumulating in the oxide. There is a small probability that some of the oxygen atoms from the screening oxide will get knocked into silicon during the implantation process and that oxygen can lead to some silicon dioxide clusters in silicon and that is not good for the device. Those are the two main disadvantages. The advantage, however, is that it can be used to tune the profile by tuning the screening oxide thickness. It also protects the silicon wafer from one of the challenges in doing a very clean implant; the whole implanter is typically made of stainless steel and the ions are being channeled. Every now and then. the ions will collide with the wall of the steel chamber and some of the iron or some other metallic impurity from that steel chamber will become a part of the ion flux. As the ion flux hits your silicon, so will those metallic impurities. As you have learned in this course, metallic contamination is deadly for silicon devices.

Ion implantation is fundamentally a little dirtier process than diffusion because it leads to this metallic contamination. Adding a screening oxide can sometimes help reduce that metallic contamination. With that, we end this lecture on ion implantation. In the next lecture, we will look at some of the more advanced concepts of ion implantation and also look at the lattice repair.