Fundamentals of Micro and Nanofabrication

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Lecture - 11
Ion Implantation Continued

Welcome back. This is the second half of the lecture on ion implantation. In the previous lecture, we had looked at what is ion implantation, the parameters to be controlled - dosage and energy, the effect of the size, mass, energy, and the dose the ion. We also briefly discussed some non-idealities for example, channeling and backscattering. In this lecture, we will delve into a little more detail and look at some of the more advanced aspects such as arbitrary profiles, lattice repair, and rapid thermal annealing.

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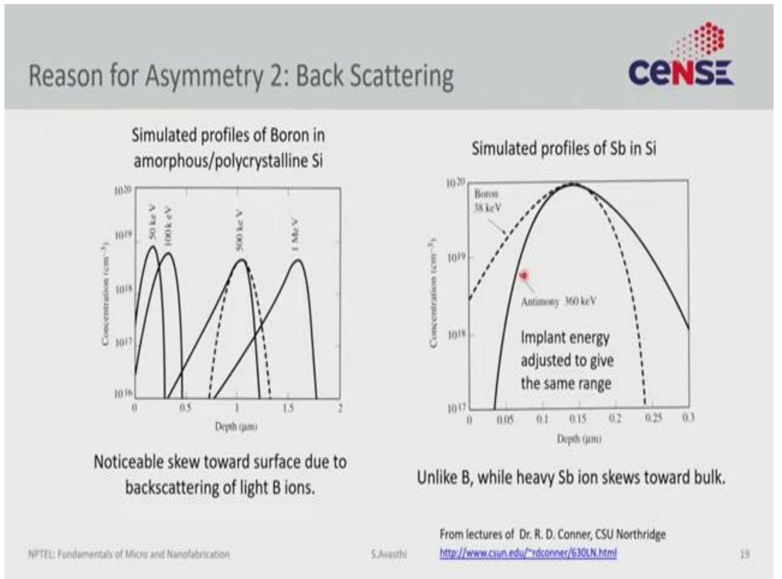

Channel is not the only thing that leads to asymmetry; another one is backscattering. What is backscattering? Backscattering occurs if the incoming ion has a much lower mass than silicon atoms. Imagine hitting a billiard ball with a ping pong ball. So, the billiard ball in this analogy is silicon and the ping pong ball is boron (lighter and smaller). You can imagine that if you do so, the ping pong ball will bounce back and the billiard ball may not move much. If you push boron at very high speed, it will just backscatter, it will hit silicon and come back. And in the implanted profile, you will see

that compared to the dotted case (ideal Gaussian profile), the concentration will be a little higher at the front edge and a little lower at the back edge.

Backscattering creates a front biased asymmetric profile of boron in silicon, which is completely inverted in the case of antimony, where antimony is now the heavier atom. Imagine shooting billiard balls at a lattice of ping pong balls; it will knock the ping pong balls off their place, and that is what you see in the profile. If boron is biased towards the front, antimony is biased towards the back and this effect is magnified at higher energies, say 500 keV or 1 MeV; In that case, you have to be careful about backscattering.

Very nifty use of ion implantation is in creating arbitrary looking profiles. Achievable dopant profile with the diffusion process is something between an error function and a Gaussian profile and it is very hard to make it anything else. If you do a second diffusion to try to create a new profile, it will change the profile of diffused dopant ions created in the previous step. Successive diffusion steps keep changing the previous ones in a manner that is very hard to reliably make an arbitrarily shaped profile. Implantation does not suffer this problem as it is done at room temperature. Since the wafer has not been heated yet, the dopant ions cannot diffuse much. So, you can create an arbitrary profile, by successive implantation steps as shown in the next slide.

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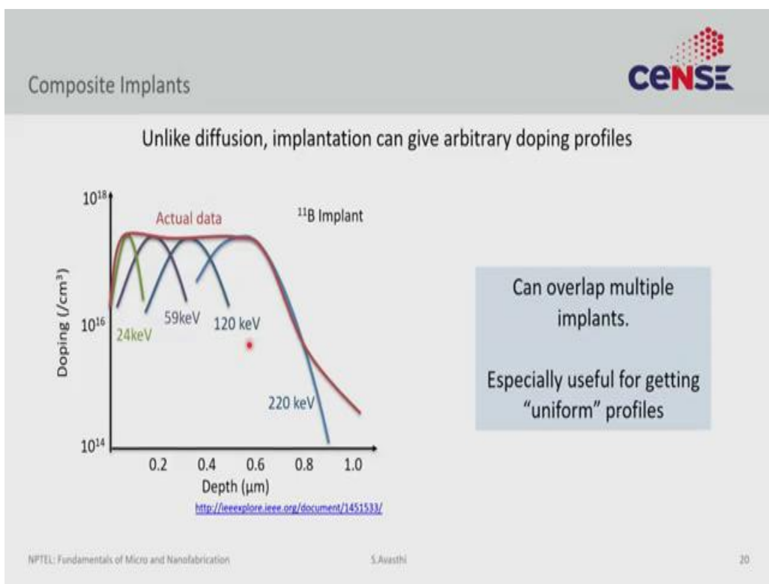

In this example, if you were to ion implantation at low energy (24 keV), you will get a shallow green colored profile. After that, without heating the wafer, if you do the second

implantation at slightly higher energy, and then at even higher energy, finally you will see this red curve which is the sum of all these individual component implantations. And after this, you do the anneal step to activate the dopants. What you have achieved is a very uniform looking profile at the surface which is very hard to make through diffusion, but possible with ion implantation. That is one of its great advantages.

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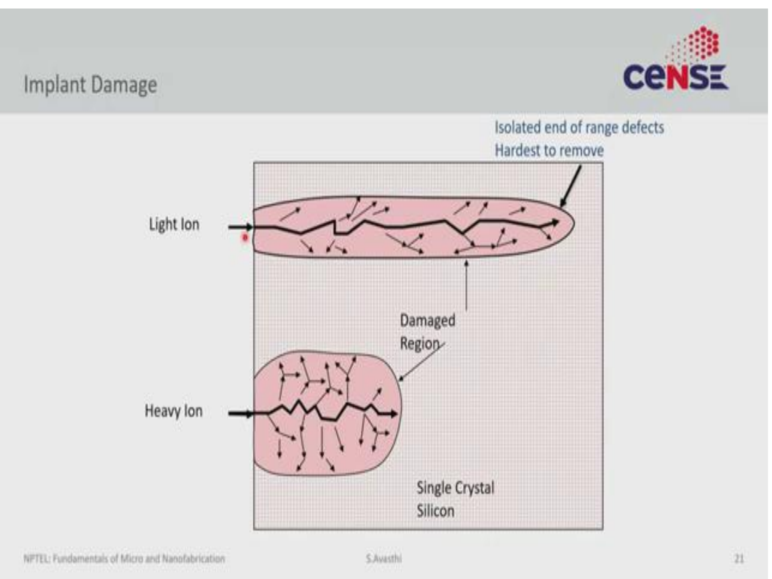

Now, let’s talk about the implant damage that always happens, and is one of the primary reasons why implantation was challenging for a long time. This is a visual representation of what we have discussed before. An ion coming with a certain amount of energy will suffer collisions, and with each succession collision, it would lose some of its energy and come to a standstill at some point. The depth will depend upon the energy. While the ion moves along this solid black line, the silicon atoms themselves get displaced. So, these small arrows represent that at each successive collision, a silicon atom will get displaced and it might then collide with other silicon atoms, displacing even more of silicon atoms.

Overall, once an ion is implanted in a material like silicon, it leaves behind a region of damage that scales the mass of the ion being implanted. For example, the light ion will go very deep but will create a narrower damage region. On the other hand, a heavy-ion like antimony or arsenic would not go very deep but it has the same energy that needs to be dissipated. So, all that energy is concentrated over a smaller depth and must have a

larger area. The successive collisions will be higher in the case of a heavy-ion than a lighter ion so you end up getting a larger damaged region.

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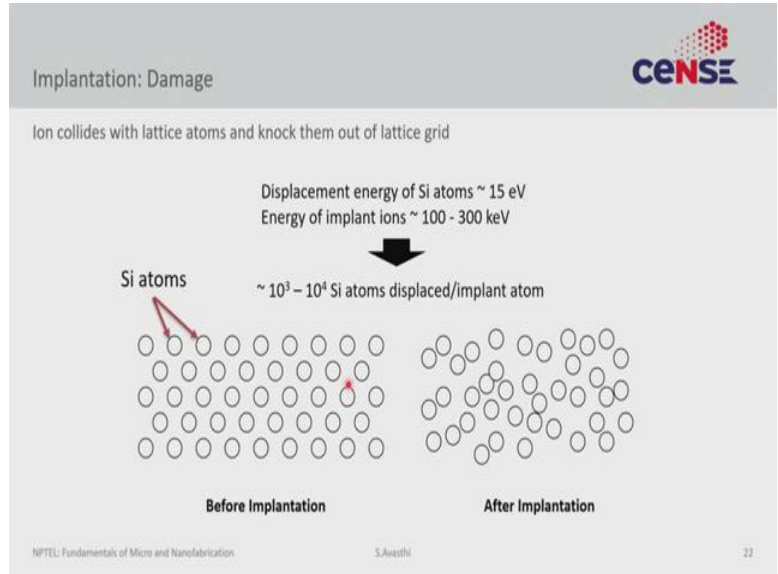

What does the silicon surface look like? After shooting a nice looking silicon lattice with ions at say 100keV energy, it will not be a perfectly ordered crystal but would have a much-damaged lattice where a lot of the silicon atoms have been displaced. The displacement energy of moving a silicon atom is ~ 15eV and you implant the ions of energy ~ 100keV, about 1000 to 10,000 times higher. On an average, one implanted atom of energy ~ 100 keV displaces around 1000 to 10,000 silicon atoms. So, that is why it has that huge damaged region.

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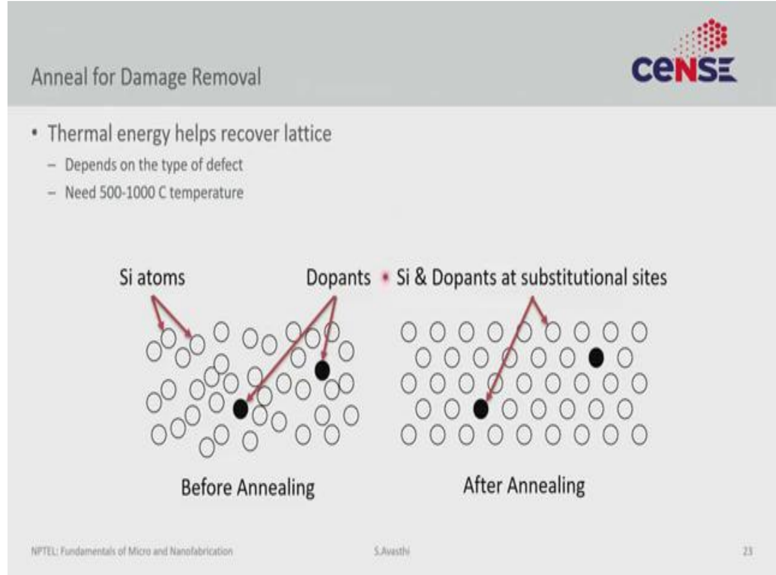

Now, what can we do about it? In the cartoon, you can see a damaged crystal on the left. Thankfully this isn't an equilibrium configuration as neither silicon nor the dopant atoms are in their lowest energy state. So, if you were to anneal the system, the atoms will have enough diffusivity to be able to reorganize and find the lowest energy positions. And that is when (almost) all these atoms are at the lattice position. So, not only will this anneal repair the damage, but it would also put these dopant atoms at a substitutional position where they become electrically active.

This process requires a certain temperature, typically around 500-1000ºC. What type of defects can and cannot be repaired with this anneal, depends upon the type of the defect. Low energy defects can be annealed away at a lower temperature, while high activation energy defects need to be annealed at higher temperatures. Implantation will always cause some damage that is very hard to repair (unless in some unique cases which we will discuss later). You have to do the annealing depending on what damage you can tolerate.

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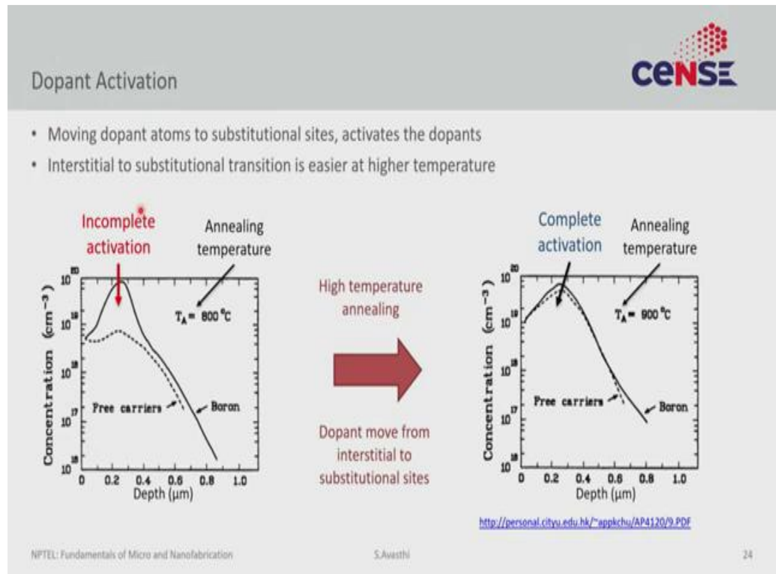

Let's explicitly talk about dopant activation too. If you do implantation and then anneal the substrate at 800ºC, and that is enough to repair some amount of damage and get some of the dopants to the substitution position, but it may not be enough to put all the dopants into substitutional positions. So, even though you have a certain amount of dopants, not all of them will be electrically active.

The amount of the electrically active dopants is represented by this dotted line. These are the free carriers, coming from the dopants and this difference between the solid and dotted line is all excess carriers or dopants that are not at a substitutional position and not electrically active. By annealing at a higher temperature, you can now move some of these un-activated ion implanted atoms to their correct substitutional position and increase the percentage of activation.

In general, around 900-1000ºC, you start to see almost complete activation. As a rule of thumb, make sure that you anneal your implant at around 900-950ºC to get nearly perfect or 100 % activation of your dopants.

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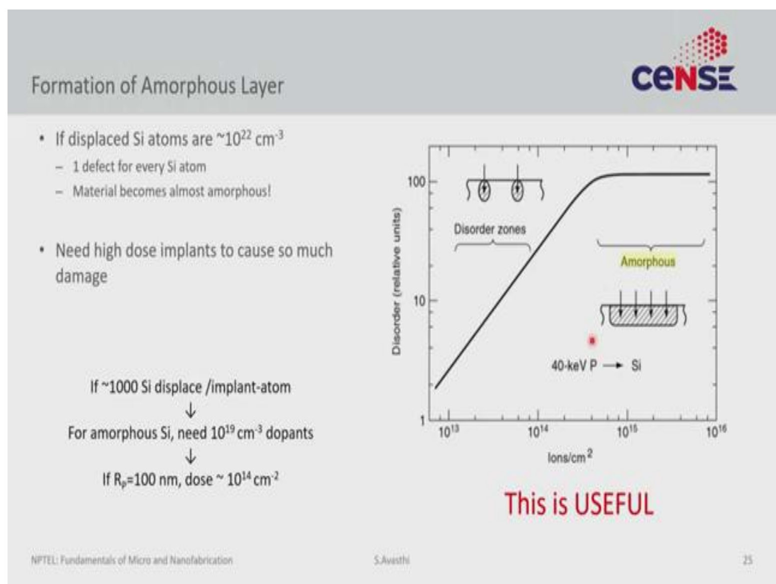

Damage from the implantation can make the film amorphous. You start with a perfect silicon lattice and bombard it with heavy ions, each with energy more than 1000 times the silicon atom displacement energy. Each atom moves around 10^3 silicon atoms, which is a lot of amplification. There must be some dose of the bombarded dopants at which all silicon atoms get displaced from their position. And when that happens, you don't have crystalline but amorphous silicon. At lower doses, you create these disordered zones and at high enough dose, these disordered zones start overlapping to a point where there is a continuous disordered zone that is essentially amorphous silicon.

You can do some back envelope calculations. Here, this transition where it becomes completely amorphous happens around $10^{14}/cm^2$. If ~1000 silicon atoms are displaced for every implanted atom, you need ~ $10^{19}/cm^3$ dopants to amorphize silicon (as $10^{22}/cm^3$ is the silicon atom density). And for ~ $10^{19}/cm^3$ dopants, you need $10^{14}/cm^2$ dose at a penetration depth of 100 nm. So, a penetration depth of 100 nm and a dose of $10^{14}/cm^2$ will give you $10^{19}/cm^3$ dopants. Around $10^{14}/cm^2$ dose, you get overlapping disordered zones and start getting amorphous silicon. While doing the crystal growth, we had done so much work to get this perfect silicon crystal that gets completely obliterated by ion plantation at a high dose. But surprisingly, this is useful!

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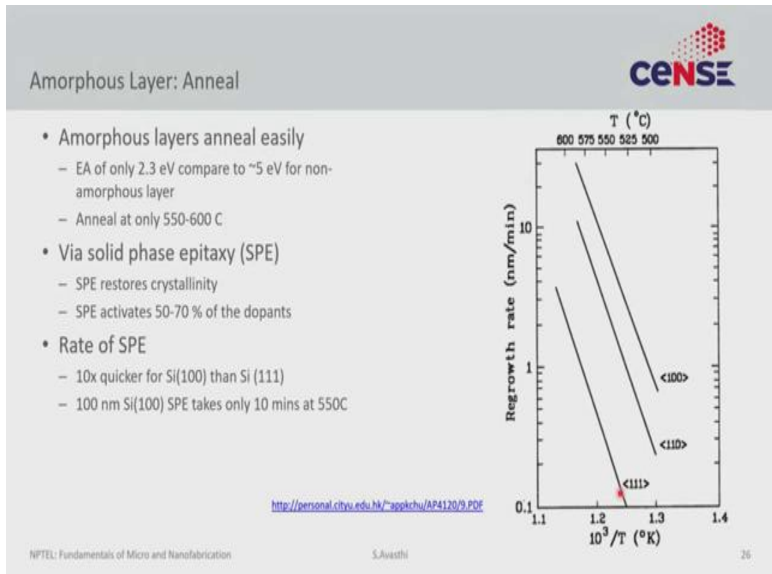

It turns out that these disordered zones anneal relatively easily because the silicon really likes to grow into a crystal lattice. If you look at what is the activation energy for changing amorphous silicon into crystalline silicon, it is only around 2.3 eV. So, at very low temperatures, 550-600ºC, this amorphous silicon layer gets completely repaired. It goes through a mechanism called solid phase epitaxy that restores crystallinity and also activates 50-70 % dopants, which is a relatively high number. The rate of SPE is very high and in fact, it is higher for silicon (100) than it is for (111). For 100 nm of a solid phase epitaxy, it only takes around 10 min at 550ºC which is not a lot.

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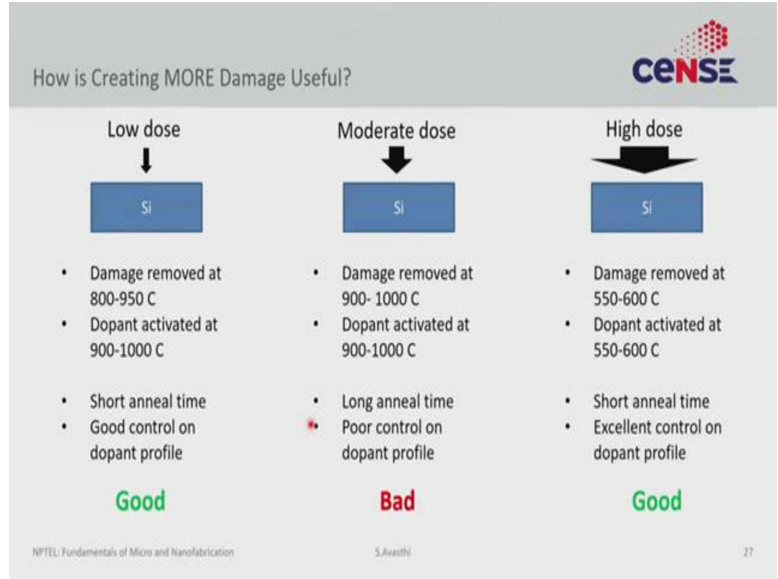

The existence of a solid-phase epitaxy leads to a deviation in how you would think about ion implantation. Generally, the damage to the crystallinity is bad. So, it is always better to do implantation at a low dose and low energy that cause small disordered zones that can be annealed away. Then, as you increase the dose, there will be a more disordered zone and each disordered zone will anneal slightly differently. It will take more energy and temperature to anneal away these defects which will lead to poorer quality films.

So, if we use a very high dose, the problem will be even worse right? Because you form this amorphous layer that can get annealed at very low temperature, you make the problem easier instead of making it worse. The temperature it takes to anneal away the damage is lower than what it would have been in the moderate case. So, the high dose implants are actually easier to anneal than a moderate dose implant. This is one of those lucky things that led to the adoption of implantation. It is a happy accident.

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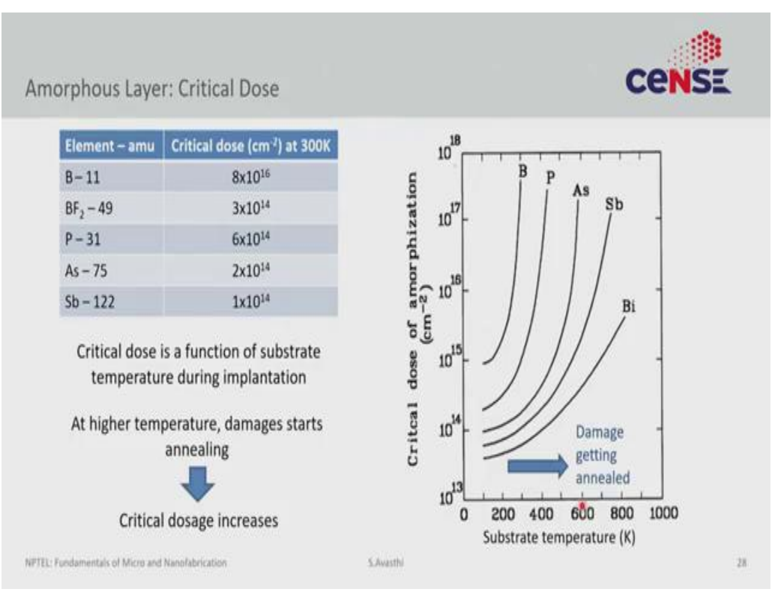

One easy way to amorphize the layer is to use very high dose implants. This dose is often called a critical dose, which is different for different elements. For boron, you need to implant more to create damage than antimony. This critical dose also depends upon the substrate temperature during the implantation. If you implant at a higher temperature, for example, some of the damage it gets annealed during the implantation itself and that increases the threshold of amorphization. So, if you want to create an amorphous film, do the implantation at lower or cryogenic temperatures. It is a little expensive but possible.

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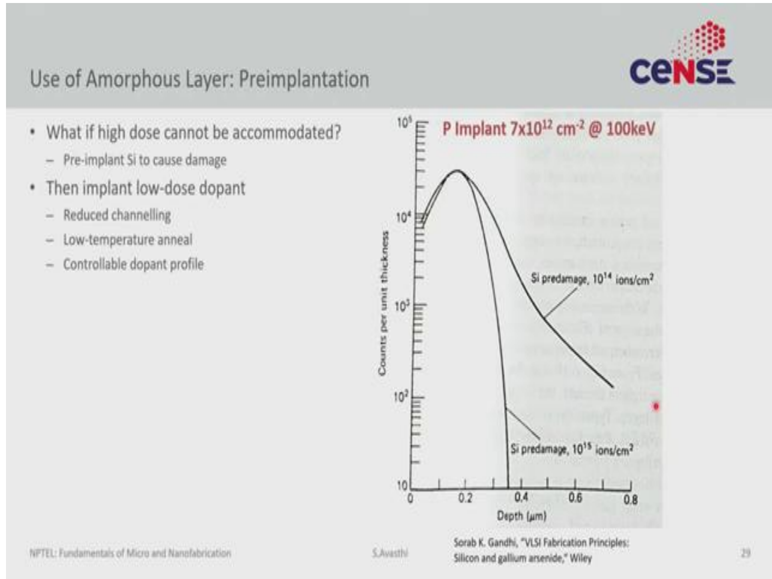

Now, if you cannot do a high dose implant is to amorphize the layer, you can do a silicon implant in silicon to create the damage and then do an implant whatever atom you want. Here is an example where silicon damage was done using silicon. Without silicon pre-damage, you get a profile with channeling, but if you do silicon pre-damage, you have completely destroyed the lattice and now have amorphous silicon on the top. So, now there is no channeling, and you get this sharp Gaussian profile. That is one way of amorphization without a high dose. As a side effect, there is a reduced channeling. As you do not need to anneal it at higher temperatures you get a very controlled dopant profile. So, this dopant profile looks much closer to a Gaussian than the one that you get without damage. However, that increases the cost so it is only done in rare cases.

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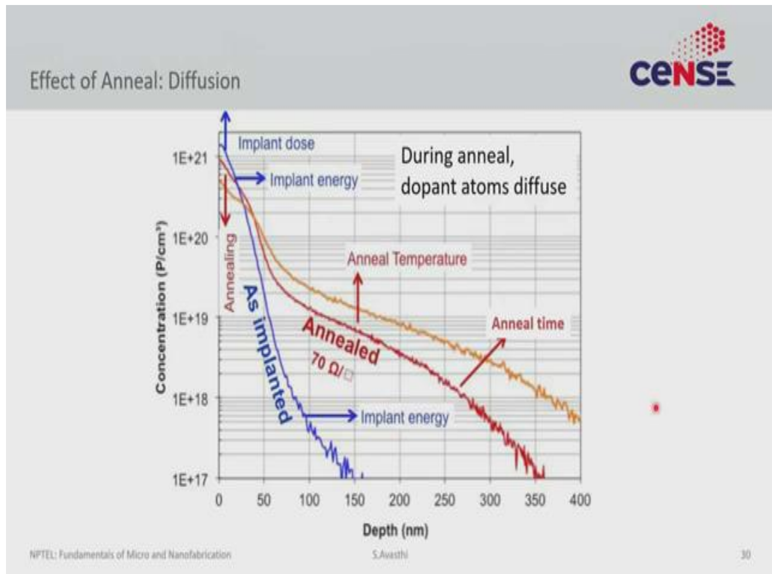

Remember that when you are annealing the damaging, diffusion will also occur. So, during the annealing step, expect the dopant profile to slightly change. In this example, the implanted profile of arsenic is blue. When you anneal the sample to activate the dopants and also to remove the damage, the ions will move during that process. Ions cannot be created or destroyed, so, from a perspective of diffusion, this is a finite source case, where the dose remains the same, the peak concentration falls and the depth of the diffusion increases. That is what you see in the red and the orange curve, as you anneal more and more: the peak concentration falls and the dopants diffuse further.

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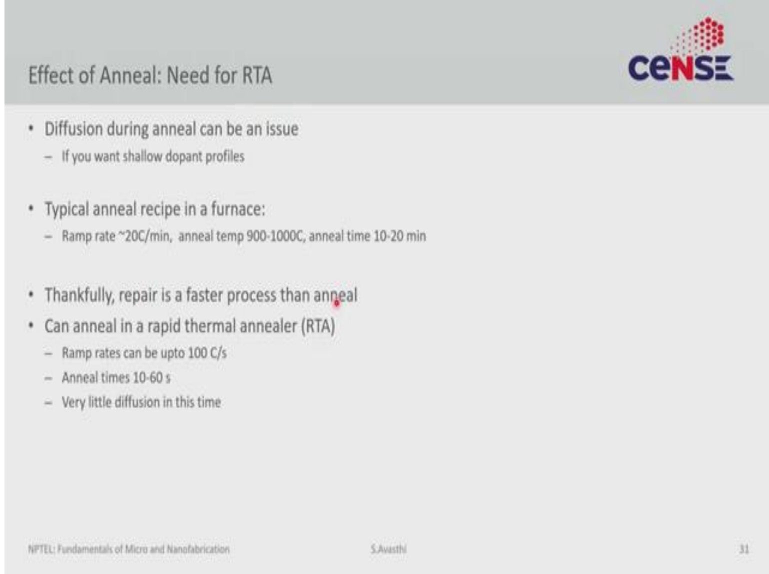

Now, this change in the profile is a challenge in the modern CMOS fabrication, because here we try to make a very shallow implant. If you want to retain the shallowness of your implant, you cannot do very long anneals. So, what people do is rapid thermal annealing (RTA), where the temperatures are still high because you need to anneal away your defects but the duration is short: instead of 10-20 min, you can it in 10-15 sec. The depth of diffusion is $\sqrt{(Dt)}$, so, by cutting down the time so heavily, you reducing the diffusion of the dopants. This is just a very little time for the dopants to diffusion so, the dopant profile is maintained.

And the reason we are able to do this is that the repair process is much faster than the diffusion. So, this small amount of time is enough for the lattice to repair itself, but not enough for the dopants to diffuse.

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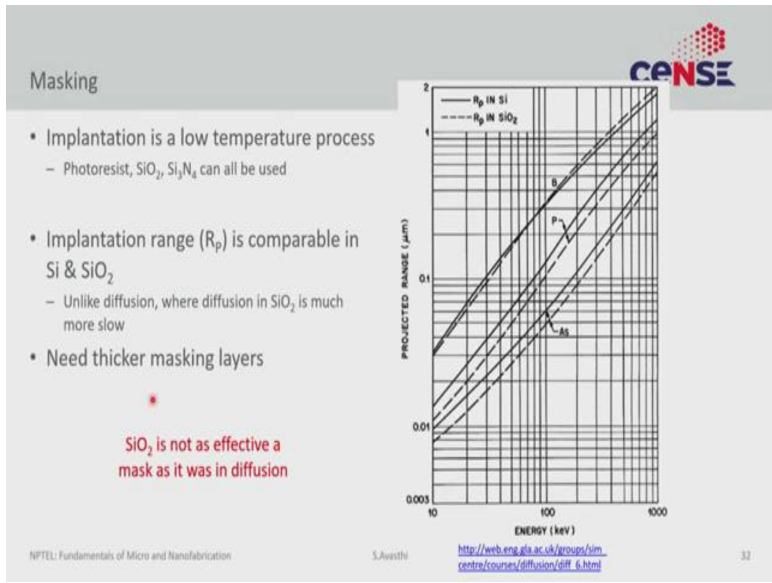

Finally, I would like to discuss the concept of masking. We have already introduced this during diffusion. You never have blanket dopants; you need to have a pattern. One way to pattern the dopant profile is to add a film on top that prevents your dopant from going through. That is masking. In the diffusion process, silicon dioxide and silicon nitride were good masking layers. So, can we use the same masking layers for implantation too? The answer is, not very effectively. Unlike diffusion, silicon dioxide and nitrate are not very good masking layer for implantation. The reason is that the projected range or the implant depth is not very different from silicon and silicon dioxide.

The solid line here is for silicon, the dotted line is for silicon dioxide and for boron the difference is minimal the, while for phosphorus and arsenic, there is a bit of a difference, but not significant. In diffusion, the diffusion coefficient of dopants in silicon dioxide was significantly (orders of magnitude) lower, but the in for implantation, the penetration depth does not change much. That means, is your mask with silicon dioxide or silicon nitride, the thickness of those films need to be about as thick as the range. In fact, a little bit more to make sure there are no tails. That makes it harder but thankfully, there is a more effective film for masking and a good example of that is photoresist.

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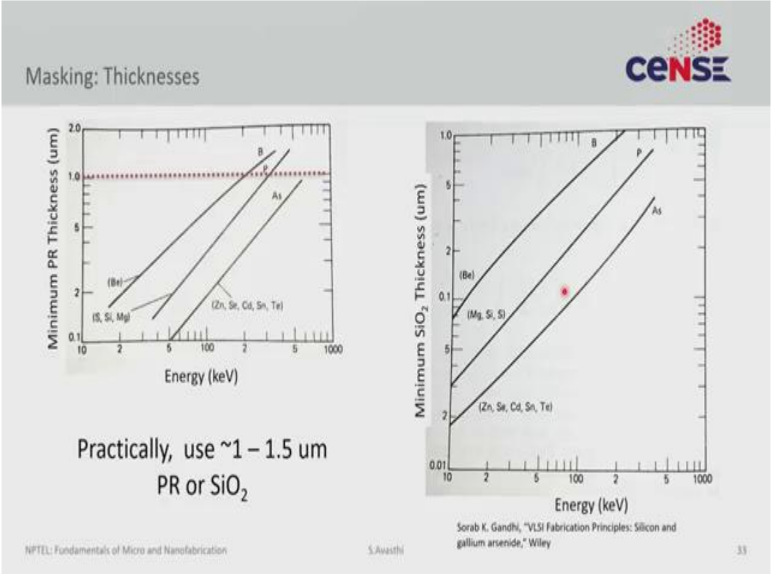

So, a photoresist is something that we use during lithography. Look at the penetration of the dopant ions in the photoresist. For various energies, the minimum thickness of the photoresist required to completely stop the implantation is ~ 1 μm. This 1-2 μm photoresist is not too thick as we will see during photolithography. This is very easy to deposit. So, the easiest way to mask is by not removing the photoresist pattern created during the lithography process but after the ion implantation done. So, a photoresist is the material of choice of mask for ion implantation. Here is a comparison of the minimum silicon dioxide thickness and the photoresist thickness.

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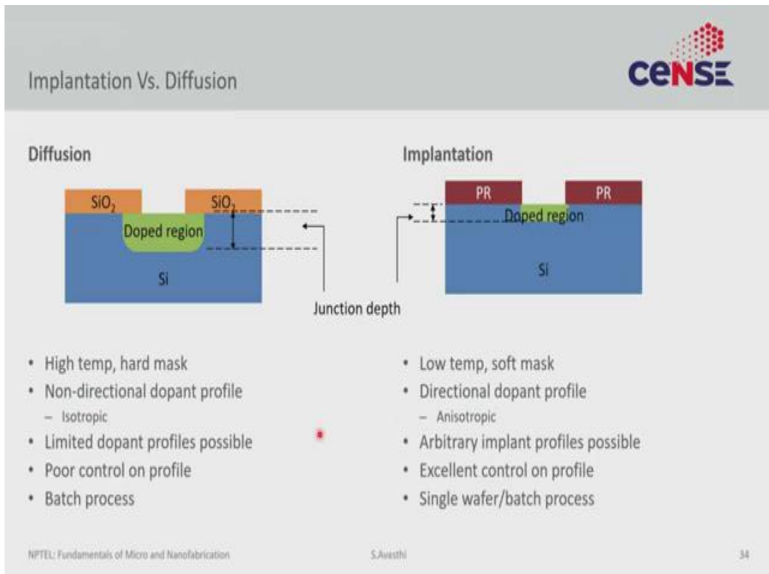

Let's compare these two processes for creating dopants. On the left is diffusion and on the right is implantation. Both of them will create a doped region but masking is a little different. On the left, you typically need a hard mask-like silicon oxide or nitride, which themselves take some high-temperature step to deposit. On the right, the masking can be easily done with just the photoresist making it a low-temperature step as the photoresist are often spin-coated at room temperature.

The other difference is in the flow of the dopants: diffusion does not care about the direction and the dopants diffuse in all the directions. So, the dopant profile will be isotropic. The green portion in the cartoon is smooth. Because the dopants always diffuse both down and laterally, it is very hard to constrain them in very narrow channels. As you scale the device down, diffusion becomes a lot more complicated. Implantation, on the other hand, is very anisotropic. The ion flux comes from the top with a certain direction. While there would be some lateral diffusion during the anneal process, the implantation on its own is completely anisotropic. The ion all go down and not laterally. So, that is very advantageous as you scale down the devices and make narrower doped regions. That is one reason implantation is so popular.

With diffusion, only a limited amount of dopant profiles are possible. You can get something between an error function and a Gaussian, but getting an arbitrary profile like

a uniform profile is hard. On the other hand, you can create arbitrary profiles by doing a series of ion implantations. Ion implantation is a little more flexible.

It is very hard to exactly control the doped profile in diffusion. We have discussed the two-step process. The reason we needed it is that it was very hard to exactly control the doped region profile and get exactly the same peak concentration and depth. Ion implantation, on the other hand, is much more accurate. The dose can be measured with arbitrary precision because it's equivalent to measuring the charge or current and we are very good at that. After measuring multiple profiles, the simulators have become very good at predicting what it would like after the ion implantation. And because we are doing RTA, the amount of change in the profile during the anneal process is also small. All of this is an advantage for ion implantation.

Diffusion, however, is a batch process. If you have a furnace, you can put a batch of 25 wafers, 50 wafers or 100 wafers. In modern solar cell production, diffusion is used because you can do it on 400 wafers in one batch. Implantation tends to be an individual process. You can implant some number of wafers, limited by how large implantation tools you can make. A modern implanter that can do 25 wafers is about as large as a room. If you want to do a batch of 400 wafers, that machine will be 16 times larger. So, those are some of the challenges with implantation.

For small volume, high quality and controlled production like in modern IC fabrication, implantation is better. For low cost, cheap, easy, and large scale doping, diffusion is better which is what solar people do.

With that, we come to the end of this lecture.