Electronic Materials, Devices and Fabrication
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Lecture - 24
Doping: Thermal and Ion Implantation

So, we are looking in detail at the various processes that are involved in IC fabrication. So last class, we looked at an example of layering operation, where we looked at grown layers specifically oxide layers. We saw that, your oxide layer can be grown on top of the silicon the consuming the silicon that is lying underneath so that is why, it is grown layer. We also saw different models of oxide growth, we saw that if you have a thick oxide layer the diffusion of oxygen or the diffusing species through that oxide layer is the 1 that that determines the growth rate so this we call parabolic growth.

In the case, of thin films the reaction of the diffusing species with silicon, in order to found the oxide determines the growth and this gives you the linear growth rate. So, what is true for oxidation is also true for nitridation; in case you want to form a nitride layer an similar model can also used performing oxynitride layers. Today, we are going to look at 1 of the other processes in IC fabrication.

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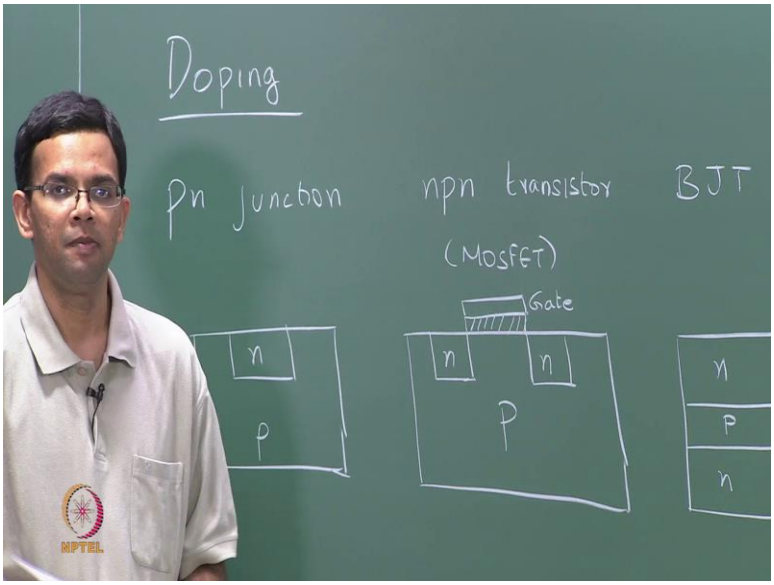

So, today we are going to look at doping. So doping is important, because we saw that in the case of extrinsic semiconductor where we are specific amount of impurities or dopants to your silicon, we can precisely control the electronic properties. Similarly in the case of devices, we always want to form junction and these junctions are between differently doped materials. For example the simplest thing is your P-n junction that is formed between a P-type and then, n-type material off course, the material can be the same. In this case, is be a homo junction or the materials can be different in which case, you have a hetero junction. We will be mostly focusing on homo junctions, when we talk about doping.

So, if you think about simple P- n junction, you can start with a P- type material and then you can dope a specific area to be n-type. So, in that case you have a P-n junction. We also looks at junction in terms of your transistors; So, your simple npn transistor once again you have P-type, you have 2 regions; that are doped n-type there is an oxide layer and there is the gate. So, this is your structure of your MOSFET where once again, we have to dope specific regions n-type, we are also seen your bipolar junction transistor, in which case specific regions with depth have different dopants. So, you could have an n p and the n.

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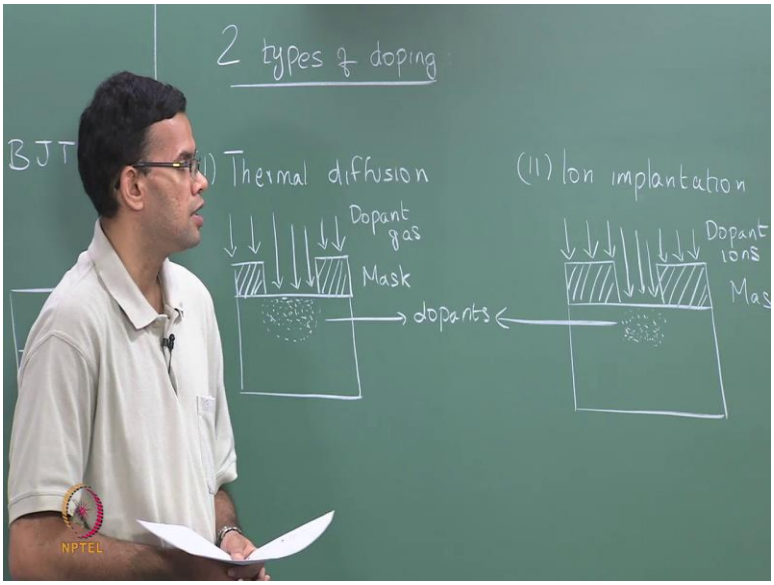

So that here, you have emitter base collector all with different dopants. In these regions again, you could have different dopant concentrations over all the important point to note is that doping

is an important step, in your IC manufacturing because, it is used to establish the different junctions that ultimately form your device. There essentially 2 ways doping is carried out; we saw this briefly when we are looking at the overview of the IC fabrication crosses, the 2 way doping is done is Thermal diffusion and Ion implantation.

In the case of thermal diffusion just to give you an example, we look at it in detail later. We have your wafer usually there is some sort of mask; the mask is used if you want to dope certain portions of your sample. In the case of thermal diffusion it is usually high temperature process. So, the mask you use is typically an oxide layer or it could be an nitride layer; so, dopants are introduced. In this particular case, your dopant could be a gas; so that, there is some concentrations of dopants at the surface.

Now, because it is a high temperature process you have diffusion of these dopants within the material; in order to create some concentration gradient. The maximum concentration is near the surface, but there is also some diffusions of these dopants within the depth and this depends upon the time, the concentration on the surface, the type of dopants and so on. So, we look at that in detail. This is thermal diffusion the other way of diffusion is ion implantation; once again, you have your surface and you have mask, ion implantation can be done at low temperature in fact it can even be done at room temperature. So that, you can use a mask like a conventional lithography mask we will see that, when we come to lithography what a lithography mask is, but you could use lithography mask and you can also dope in smaller areas.

So here, you have dopants in the form of ion's in pinging on to your sample and these ion's penetrate into the silicon wafer and lead to certain concentration. So, the concentration is the maximum at a certain depth, within the silicon wafer and this depth determined by the energy or the velocity of the ion's but once again you can get some distribution or some concentrations of dopants within the material.

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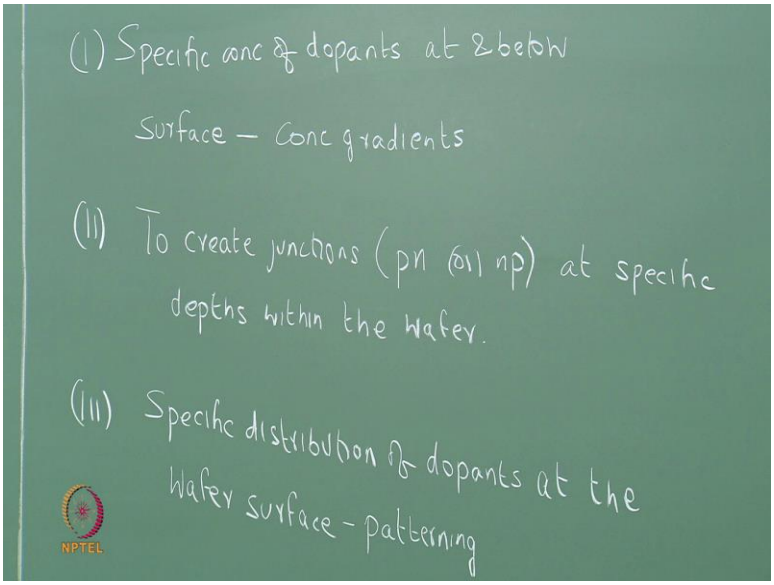

So, let me just mark the dopants that are embedded within your wafer in both cases. So, these are the two common ways by which doping is carried out; so let us look, at some of the goals that we need to achieve by using doping. So, we can define some process goals, for doping. So, the first goal is you should be able to create a specific concentration of your dopant atoms, at the surface and also below the wafer surface. So, we need a specific concentration of dopants at and below the surface. This idea is related to the concentration gradient of the dopants within the material. The concentration gradients are again different, if you think about thermal diffusion was is ion

implantation the gradients are different if you different sources for dopants.

In the case, of thermal diffusion or if you have some sort of pose diffusion annealing; so, all of those processes will affect the concentration gradient. So, we should be really clear on to what kind of thermal budget the wafers will see after the doping process is carried out. For example: after doping, the wafers are subjected to some high temperature process later then that high temperature process can again effect the concentration of a dopants which can affect the properties, another process goal is to create junction. So, these junctions can be pn junctions in which case, we have a P-type doping into n-type or an np junction, which is the other way around.

So, these junctions are to be created at specific depths within the wafer this will again effect the properties of the wafer to give you an example, in the case of a bipolar junction transistor we have to dope the material twice. For example: if you an npn transistor we start of with n-type, we dope with a P-type in order to form the base and then, dope again with n-type in order to form the emitter. So, you have 2 pn junctions there and these pn junctions have to be created at specific depths within the wafer. And then finally, we should also be able to create a distribution of dopants across the wafer surface.

So, we want a specific distribution of dopants of the wafer surface this is relating to patterning because in the case of blank wafer we going to use to form an IC device, we will have transistor at different locations we could have simple diodes. In which case, we need to form these junctions or we need to dope in specific locations on the wafer surface. This is achieved by patterning and as device dimension shrink so that you have more and more transistors that are packed in a smaller area. So, that the individual size of the transistors are lower we need to be able to pattern smaller and smaller regions in order to able to dope.

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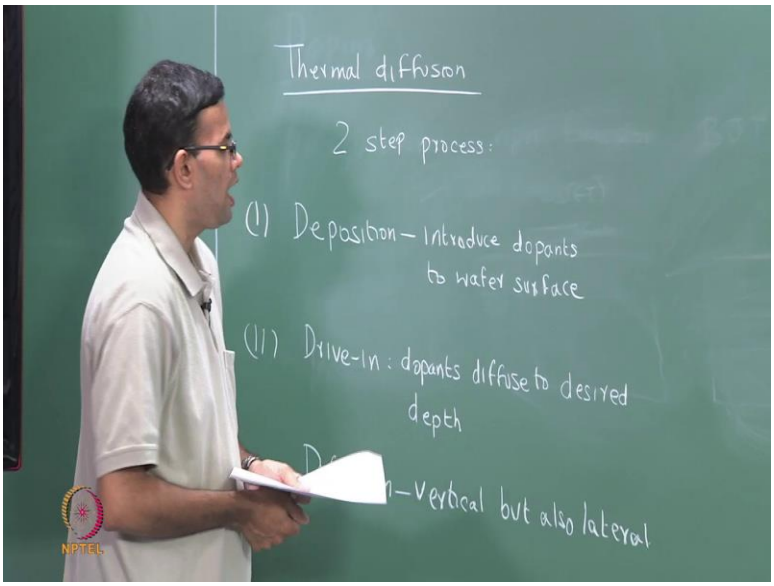

So, the 3 processes goals are to establish a concentration gradient within your material to form junction a specific depths and also to combine your doping process with patterning. So, that you can dope in really specific region so first we look at the thermal diffusion problems. So, we going to look at thermal diffusion thermal diffusion can be thought of as a 2 step process in the first case, we need to introduce you dopant atoms to the surface of the wafer. So, this process we call deposition where we introduce dopants to the wafer surface. We will see, in the minute that there are different ways in which you can have your dopants. So, these could be solid liquid or gas but whatever be a source some dopants atoms have to be introduced to the surface so that they can defuse and that is the second step which is called drive in so here the dopants, diffuse to specific depths or I will say a better word would be to the desired depth.

So, if we think about a wafer and the surface with dopant atom on the surface diffusion not only occurs laterally into the material, but diffusion is usually isotropic which means, you not only have lateral diffusion in to the material, but you also have sideways diffusion as well. So, diffusion is not only vertical but also lateral so this is 1 of the greatest issues, when we look at thermal diffusion. So, how to avoid the lateral spread this is 1 of the advantages using the ion implantation process where, the ion's are implanted at low temperature so that the lateral spread can be minimized.

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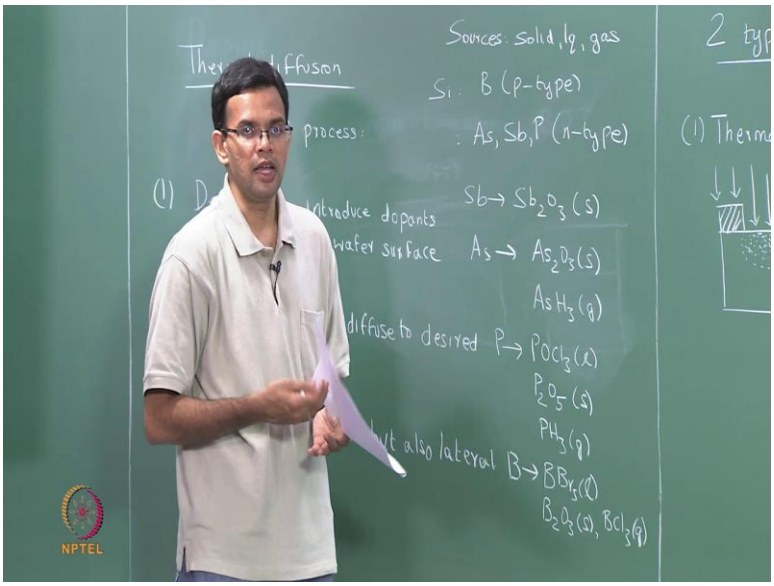

So, we can have different sources for diffusion, your sources could be a solid source liquid or gas. So, to give a example consider the case of silicon, we know that you can have both P-type and n-type dopants silicon is a group 4 element. So, your P-type dopant would be something from group 3; that has one less electron so, boron is your P-type dopant. On the other hand, your n-type dopants will be elements from group 5; because group 5 elements have an extra electron. So, these could be arsenic, antimony and prosperous these are all n-type dopants for these elements we can have different types of sources.

For example: if you have antimony, you can have a solid source Sb2o3, which is solid for arsenic you have a solid source a S2o3 or you can have arsine gas ash 3, which is a gaseous source prosperous if you have a liquid source Pocl3, which is a liquid you can have a solid source P2o5 or Ph3, which is a gas for boron once again you have BBi3 which is a liquid source, B2o3, which is solid source and Bcl3 which is gaseous source.

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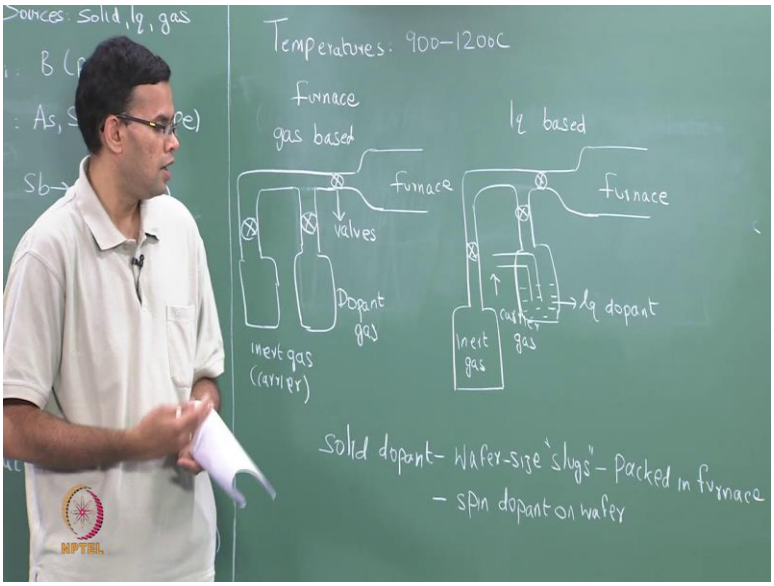

So, we can have source of dopants to be either solid liquid or gas in all these cases, they should establish a certain concentration of the atoms at the surface. So, thermal diffusion is a high temperature process, typical temperatures can be anywhere between 900 to 1200c. So, that the diffusion usually takes place in a furnace. So, the wafers are loaded with in the furnace and the dopant atoms or delivered to the surface of the wafers. For example, in the case of a gas source so this my furnace so usually, some sort of inert gas is used; typically argon gas is used as a source of inert gas in order to dilute your dopants to the desire concentration. And there is another bottle.

So, if you look at simple gas based dopant working with a furnace you have inert gas that usually acts as a carrier you have the dopants gas. So, in the case of arsenic this could be ash 3 in the case of boron this could be b c and 3 so these are mixed in order to get the desired concentration of dopants and introduced into the furnace. The wafers are usually loaded on to the furnace and then free heated to the desire temperature, the gases are introduced for the decide time in order to establish the concentration gradient that is require and then they are start of. So, this is in the case of a gas based system you could have a similar set up in the case of a liquid base system.

So, once again you have a furnace. So, we can have the inert gas the dopant is in the form of liquid and then some carrier gas is bubbled into the dopant so if in the dopant in the form of

liquid, has some wafer pressure on top of it a carrier gas is used in order to draw the wafer along with a inert gas and these are again introduced in to the furnace so the set up for both the gas base and the liquid base is similar, the furnace set up is similar it is just that how the dopant is introduced is different. In the case, of both the gas base and the liquid base, liquid base dopants. The concentration of dopants is the surface is essentially a constraint, which will in turn effect the concentration profile within the wafer.

In the case of a solid state dopant for example, if in the form of oxides usually the oxide materials is prepared in the form of a slug. So, for solid dopants you have wafer size slugs; so, your material was made in the form of a slug and introduced along with wafers into the furnace. So, that these slugs are placed in close proximity with a wafers so that at high temperature material defuses from the dopant into the wafer; they are packed in the first, the other way of introducing your solid dopant is to actually a spin a layer of the dopant on to the wafer so you can also spin, so the dopant is usually dissolved in a specific solvent and this solvent is just pennon to the wafer the similar way photo resist is pennon a way for during lithography in this wafer is than taken into the furnace and heater at high temperature. So, that diffusion of the dopant material is take place.

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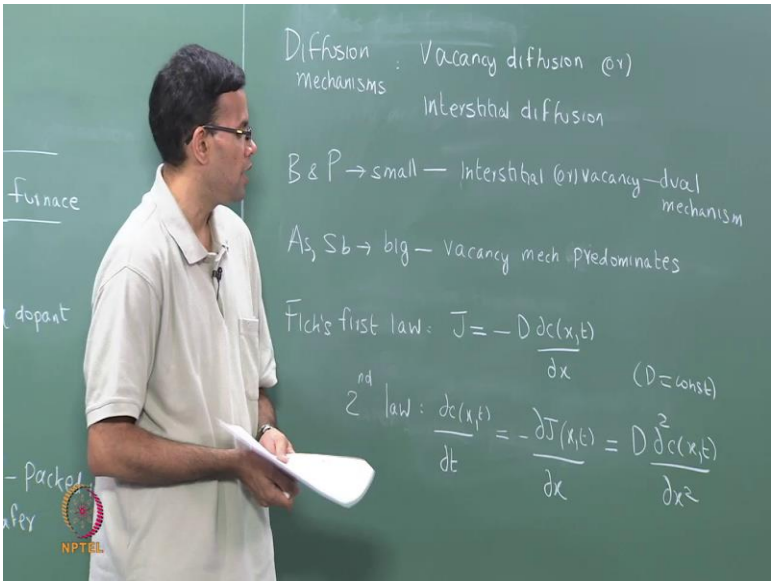

In the case of a solid dopant the initial concentration of the dopant is constant but there is no

external source, in the case of a liquid or a gas base. So, as the material diffuses within the wafer the surface concentration will essentially drop, this again will affect how the concentration gradient within the wafer looks like at the end. So, we can have different concentration profiles for the wafers; so, to understand how the concentration profiles of the wafers look we need to look at the mechanism of the diffusion So, diffusion in the case, you can easily take place either by a vacancy diffusion mechanism or an interstitial diffusion this intern depends upon the size of your dopant atoms. So, Boron and Prosperous are essentially small atom so, they can diffuse by interstitial mechanism are small.

So, they can diffused by interstitial or by vacancy so this is some sort of dual mechanism; on the other hand arsenic, antimony are big the atomic size is comparable to that of silicon. So, that diffusion takes place predominantly by vacancy diffusion. If you look at diffusion then the first thing that comes to mind is off course fick's law can be used in order to understand how the concentration at a particular depth changes as a function of time. So, there are 2 fick's laws 1 is your fick's first law, which says that the plugs is proportional to the concentration gradient so dc over dh. Your fick's second law, relate how the concentration changes as a function of time to the rate of change of plugs with distance.

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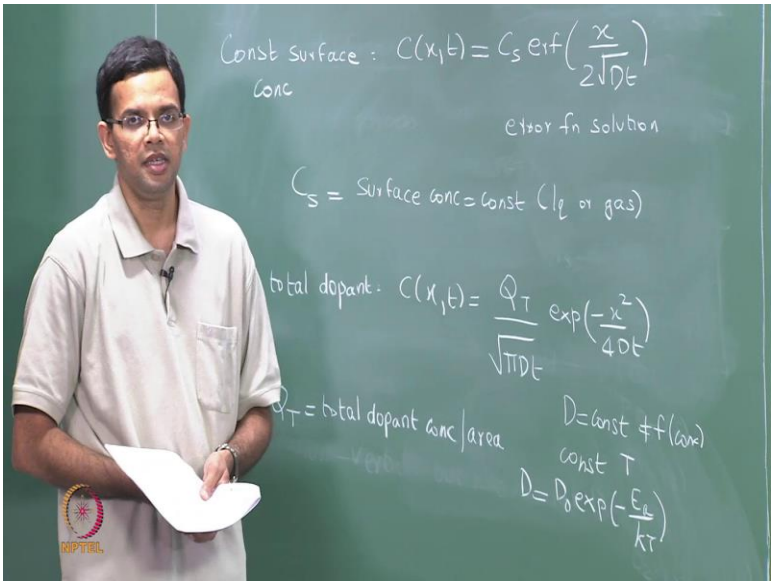

If d is assumed to be a constant; So, we have the 2 fick's laws to the first law and the second law

and these can be used to get C as a function of both x and t. So, we saw the doping can be done either by a solid source liquid or a gas source. In the case of, liquid and a gas source we found that the concentration of dopants at the surface is constant. So, if you a diffusion length is much smaller than the thickness of the wafer and the typical wafer thickness is around 500 to 700 micrometers so slightly less than a millimeter and typical diffusion distances or of the order of a few micrometers. So, for a liquid or a gas base source we can consider diffusion from constant surface concentration.

So, this is very standard problem in the case of metallurgy this is something, we use when you look at say carburizing or nitriding of a steel sample. So, here your solution is given in the form of an error function. So, that C of x comma t is Cs error function x divided by square root of Dt. This is your error function solution Cs is the surface concentration, which is the constitute so this could be from a liquid source or a gas source. On the other hand in the case of, a solid source either we have a way for slug or the material is span on to the wafer. In this case, the concentration is not a constant you have a starting initial concentration and as the material diffuses within your wafer the concentration drops.

So, here if you have a constant total dopant, the solution is an exponential solution Qt over square root of pie Dt exponential minus x square over 4 Dt, Qt is the total dopant concentration for unit area. So, the assumption in both of this is that D is a constant and it is not a function of concentration. This is not completely true, for example: there could be some cases where the diffusion coefficient will also change with concentration or in other words it will change with debt. So, that the equations are modified but here we are assuming that, D is constant and all of these processes are at constant temperature. So, the D can be written as a simple D naught exponential minus ea over Kt. So, D naught is the pre activation factor and ea is the activation energy.

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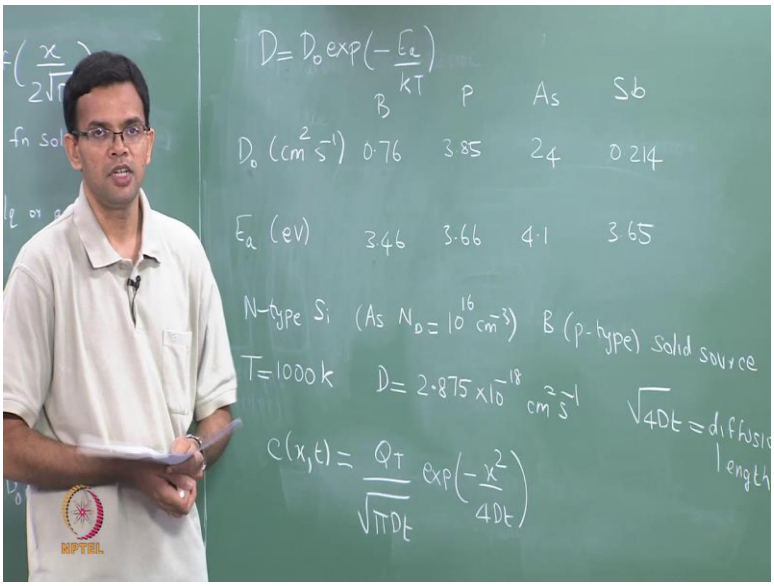

So, in the case of thermal diffusion we can write D; as D naught exponential minus ea over Kt. So, these values can be tabulated for the different dopant materials unit of D naught the same as D. So, centimeter square per second or meter square per second Ea is electron volts so you have boron, prosperous, arsenic antimony 0.76, 3.46 is Ea 3.85, 3.66, 244. 124, 3.65. So, these are some typical values for Ea and D naught for the different dopant atoms in the case of silicon. So let us look at an example, in the case of doping with silicon so, consider an n-type silicon wafer so, we have arsenic concentration of 10 to the 16 per centimeter 3. So, we now want to form a pn junction in this by adding boron is P-type and we are going to use a solid source something like we are going to do this at a constant temperature.

So temperature is equal to 1000k; so, the first thing we need to do is to calculate the diffusion coefficient of boron. So, we have the values for D naught and Ea so for boron it's 0.76, Ea is 3.46; so, the diffusion coefficient D can be calculated using this expression, the value for D is 2.875 times, 10 to the minus 18 centimeter square per second. So, again here we have a solid source so that we have, constant concentration of dopants on the surface or we have a constant initial concentration of dopants.

So, the expression is C of x is nothing but, Qt square root of pie Dt exponential minus x square over 4D. So, this term 4 Dt a square root of 4 Dt is usually called a diffusion length it is an

estimate of how far the dopant atoms have moved within a given time t; higher the temperature, higher the diffusion coefficient D because, temperature is higher correspondingly the diffusion length will also be higher.

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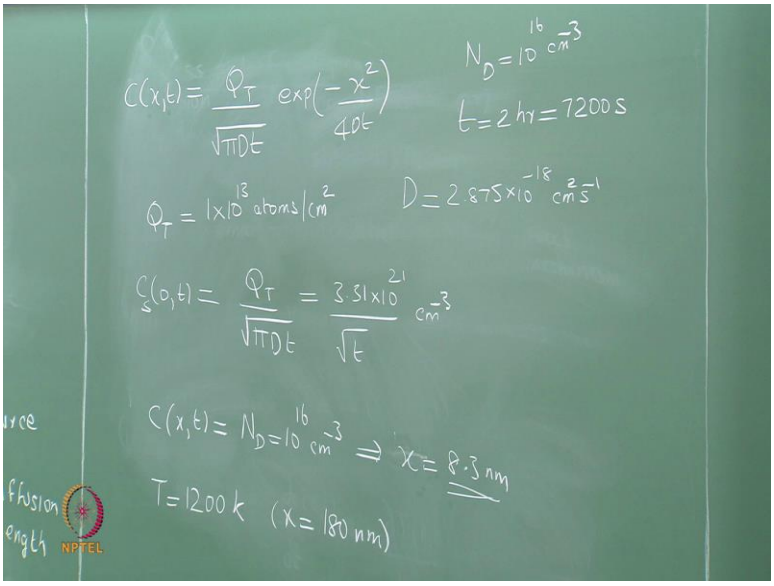

So, in this particular case let me take a constant value for Qt; so, we are looking at solid state diffusion of boron into an n-type silicon we found that the concentration gradients of x comma t pie Dt exponential minus x square over 4 Dt. So, let me take the value of Qt to be 1 times 10 to the 13 atoms per centimeter square. So, this is the total dopant concentration which is the constant when you start the experiment. So if you want to know surface concentration changes x is equal to 0; so, this is just qt over square root pie Dt x 0; so, this term is 1 if you substitute the numbers is 3.31 times 10 to the 21 square root of t per centimeter.

So, as the material constantly diffuses within the silicon, the surface concentration drops and it goes at the square root of the time. So, we want know at what depth the pn junction is formed in this particular example, where you already have arsenic with concentration of 10 to the 16 so on. D is 10 to the 16; so, I want at what depth my pn junction is formed. So, if simply matters I will assume that ND is the constant throughout the material and does not change during my doping. Let me also take, time be pretty long so I will take 2 hours which in seconds just 7200 seconds so

t is something that, we know we want to calculate x all the other terms in the expression is known

So, D we are already calculated to be 2.875 times 10 to the minus 18; so, we want to calculate the depth at which the concentration of my P dopants which is boron is equal to ND, which is 10 to the 16 per centimeter Q; substituting the numbers and simplifying we can get time or we can that distance x time is 2 hours, 2 be around 8.3 nanometers at around 1000 kelvin which is roughly around 700 degree C; we find that your pn junction is established at a depth of just 8 nanometers below the surface.

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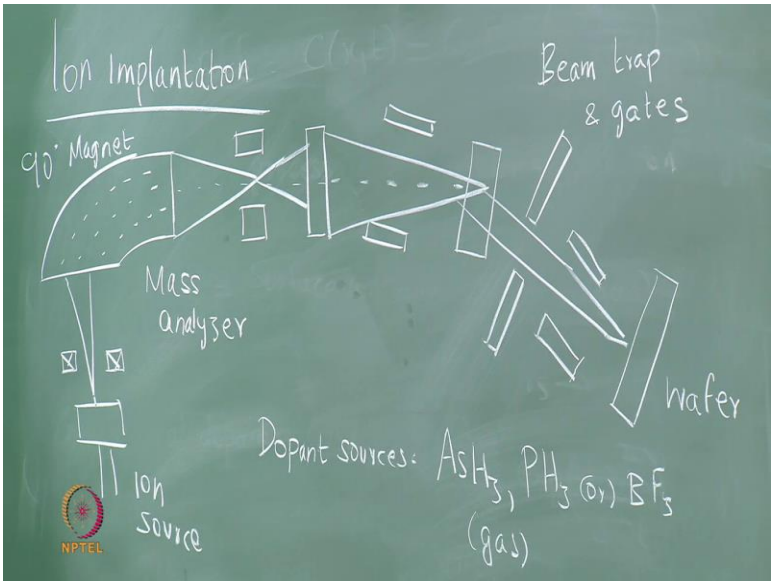

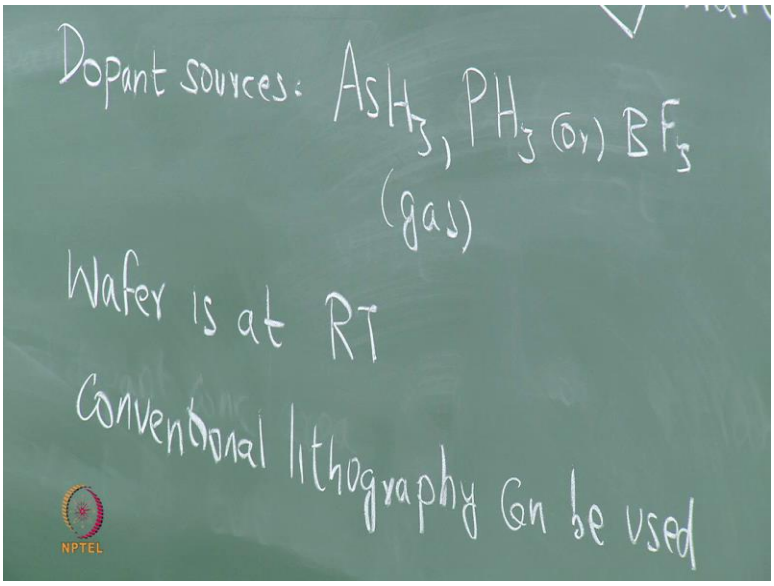

In order to increase the depth the simplest way is to increase the temperature you can also increase the concentration of dopants at the surface. If you do, the same calculation with temperature equal to 1200 k so that the increases by 200 degree centigrade x is now 18 nanometers. So, same calculation for the temperature is 1200 k to so far we have looked at thermal diffusion, where you have a concentration gradient that is established by a diffusion of dopants within the material; we next, look briefly at the ion implantation process.

So, 1 of the drawbacks of thermal diffusion is that you not only have diffusion vertically within the material, but you also have lateral diffusion. So that, you always have a spread of the dopants within the material so this can be avoided by using ion implantation which is a low temperature process. So let me draw a schematic of the ion implantation process, typically there is an ion source the ion source, is the source of the dopants ion's are produced by bombarding the dopants with electrons. So, these in turn create ion's are accelerated to a magnet it's call a 90 degree magnet. This is used in order to select ion's of the specific mask, which relates again to ion's of the specific charge.

So, these ion's are extracted that typically accelerated through a specific voltage and then they pass through a whole bunch of been traps and gates. These ion's are then finally deflected and then fall on the wafer .So, the dopant atom are ionized so typically, dopant sources are gas based sources; so, they could be gases like arsenic or PH 3 or BF 3; sometimes, the element can also be used so elemental boron or elemental prosperous is used.

So, these dopants found the ion source they are produced by bombardment with electrons in order to form the ions. These ion's, are selected using the magnet, the magnet is also called a mass analyzer. Because it separates the material based upon the mass, they are then accelerated and then using specific lenses are focused on to the wafer. So, the advantages of ion implantation are that the wafer is at room temperature or it is very close to room temperature, which means; that we do not have to worry about lateral diffusion from the mass, which is an issue when we look at thermal diffusion also because the wafer is at room temperature. You can use conventional lithography to pattern.

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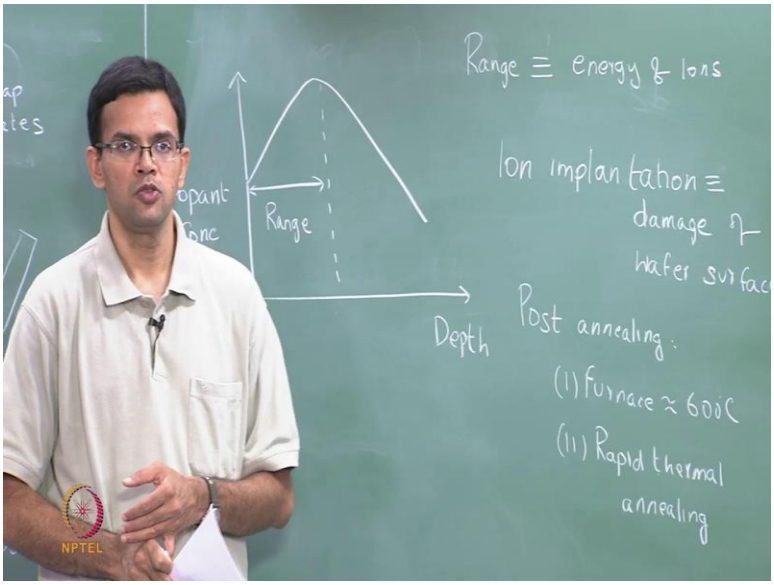

So in the case of thermal diffusion, because of the high temperature of the process typically a oxide or nitride layer has to be used for patterning, but in the case of ion implantation conventional lithography can be used, ion implantation also produces wafers with a concentration gradient. If you look at dopant concentration verses depth here, the wafers here the dopants in pinch on the wafers with some velocity and are implanted into the material. So, that there is higher concentration at some depth and this is called the range.

In the case of thermal diffusion, the maximum concentration is usually at the surface and then it drops as you go within the material here the maximum concentration somewhere within the material. The range depends upon the energy of the impinging ion's so that, the increasing the

energy the ion's can be implanted at a greater depth. The concentration depends upon the current or the beam current of the ion's. So, that by having more ion's you can increase the concentration it is also possible to combine ion implantation, with some sort of restoring or scanning procedure. So, that the ion beam can essentially scan the wafer surface.

Usually; ion implantation reach to some sort of a thermal the damage to the crystal, this is because you are impinging crystal surface with high energy ion's so it leads to damage of the wafer surface. So, ion implantation is always followed by some post annealing this can again, be done in furnace with typical temperature around 600 degrees or you could do some sort of rapid thermal annealing, where we can go to higher temperature, but the annealing time is very short. So, today we have looked at doping is 1 of the steps in your IC fabrication, we saw the there were 2 techniques thermal diffusion and ion implantation. Thermal diffusion usually used at the beginning of the process, in order to define large dope areas as process get get's refined and we need to dope in smaller regions; we typically, go for ion implantation. In the next class, we look at other IC fabrication technique which is lithography.