

VLSI Technology
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Lecture - 1
Introduction

In this lecture series, the subject we are going to discuss is VLSI technology.

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What is the scope of the subject? Let us start the discussion with that. VLSI - this is an acronym and when expanded, this actually means very large scale integration or very large scale integrated circuits. So to start with, let us first see what is an integrated circuit? What is a circuit? When you say circuit, what comes to your mind? Something like this?

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A printed circuit board with different components soldered on to that - capacitors, transistors, diodes, resistors, connecting wires, yes? This is a discrete circuit; a discrete circuit that is where I have discrete components, right, discrete components - capacitors resistors, transistors, like that. In contrast, in an integrated circuit, the entire circuitry that is the active and passive elements, by active elements I mean the transistors; it can be bipolar junction transistors or field effect transistors. There can be diodes, there can be resistors, there can be capacitors - everything is housed on the same substrate.

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This is a 4 mega bit dynamic RAM chip; 4 mega bit that is there are 4 million transistors housed in this small bit. Depending on the complexity of the integrated circuit, we call it small scale integrated circuit or SSI, medium scale integrated circuit or MSI, large scale integrated circuit or LSI and very large scale integrated circuit or VLSI. When you are talking about a circuit which has may be 10 to 100 transistors in it, then it qualifies to be a small scale integrated circuit, SSI. Hundreds to thousands – MSI, more than ten thousand LSI and for example the piece you have just seen now that is a VLSI integrated, VLSI circuit, VLSI chip which has 4 million transistors housed in that small bit. So, depending on the complexity of the circuitry, we call it LSI or MSI or VLSI as the case may be.

Now, VLSI technology that means we are going to discuss how this very large scale, very complex integrated circuits is made. What are the processes that go into making this very large scale integrated circuit? First of all let me tell you that more than 95% of today's VLSI chips are made out of silicon. Silicon is a Group IV element semiconductor. It has a number of very desirable properties, why it is so chosen. So, more than 95% of the VLSI chips currently in the market is made of silicon and that too single crystal silicon. The most important element in an integrated circuit, in any circuit for that matter, is its active

element. Like I have already told you, this active element can be either a bipolar junction transistor or a MOSFET. When we are talking about very high speed circuits, we usually have them in bipolar junction transistors.

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BJT's have very high speed and when you talk about very high packing density, we usually talk about MOSFET like the DRAM chip I just now showed you. This is based on MOSFET technology. 4 mega bit DRAM; 4 million transistors in a given area of integrated circuit, given area of silicon.

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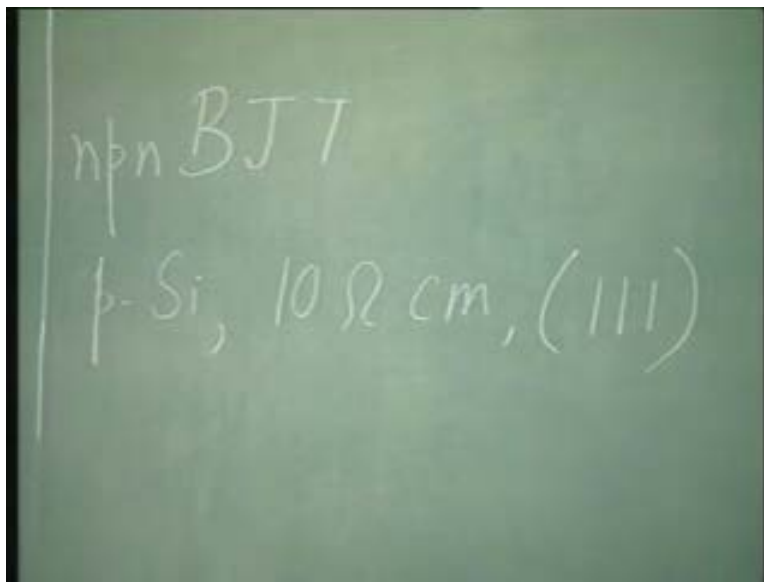
So, that is based on field effect transistor, MOS field effect transistor. Essentially you could say that VLSI technology can be branched in two branches. One is BJT technology and the other is MOSFET technology, but as the circuit complexity is increasing and as our requirements are becoming more and more stringent, we are also moving towards a marriage of these two technologies, which brings about the newest on the horizon - the BIMOS or the BICMOS technology in which the same circuit may have some active elements as bipolar junction transistors and some active elements as field effect transistors. Where all I need high speed, in those bottle neck points, I put bipolar junction transistors and where all we need high density, we put MOSFETS. Okay.

Now, I propose to organize the course in this manner. First of all we shall take these two technologies that is bipolar junction transistor technology and MOSFET technology. We shall try to realize a simple bipolar junction transistor as it is seen in an integrated circuit and see what the processing steps are we need to have in order to realize this bipolar junction transistor. Similarly we shall see what are the processing steps needed to realize a MOS field effect transistor. At the end of this exercise, we will get familiar with the processing steps. We will know what are the processing steps needed to realize these two most important active elements in an integrated circuit. Then, we will discuss the

processing steps individually and in detail. To begin with, let us start with bipolar junction transistor. I start with bipolar junction transistor, because it is the older technology. It is the older technology, MOSFETS are new comers in that sense. They are new comers in the integrated circuit era for various reasons, which we will discuss later.

So to begin with, let us start with a bipolar junction transistor. When we want to realize a bipolar junction transistor, a silicon bipolar junction transistor, we start with a p-type single crystal oriented 1 1 1 and with a resistivity of 10 ohms centimeter. These are usual, the most common starting substrate specification, when you want to fabricate an npn bipolar junction transistor.

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What do these things tell us? It tells us that one needs to have very stringent conditions while choosing this substrate. First of all the substrate must be single crystal; that too it should offer particular orientation. That means I must have some means, some ways and means in order to grow this single crystal substrate and some way to know what the orientation of this single crystal is. At the same time, there should be some means to dope the single crystal. You see, I want p-type silicon substrate. So, I must have some means to dope it p-type. You know, silicon has to be doped with boron in order to make it p-type.

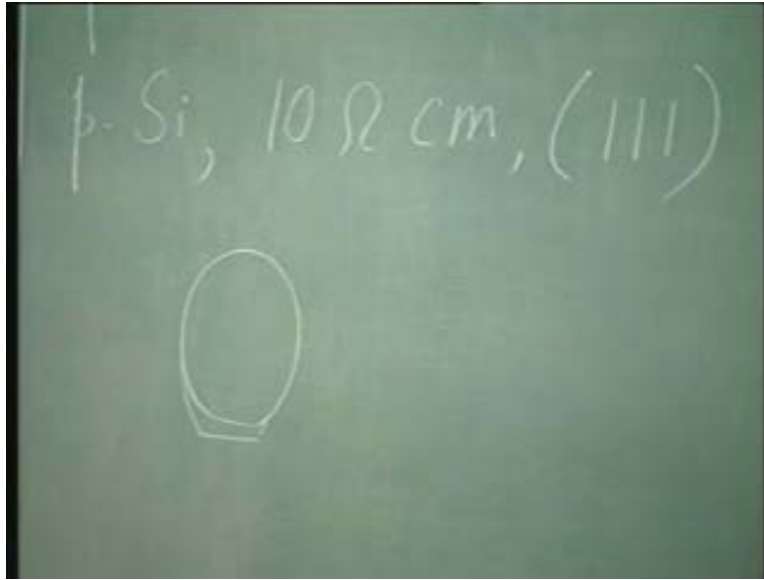
Boron is a Group III element, silicon is a Group IV element. Therefore, if you dope silicon with boron, you will have p-type substrate. That too, the amount of boron in silicon must be very carefully controlled, because I want to realize a particular resistivity - 10 ohm centimeter and you know the amount of the dopant is going to control the resistivity of this single crystal substrate.

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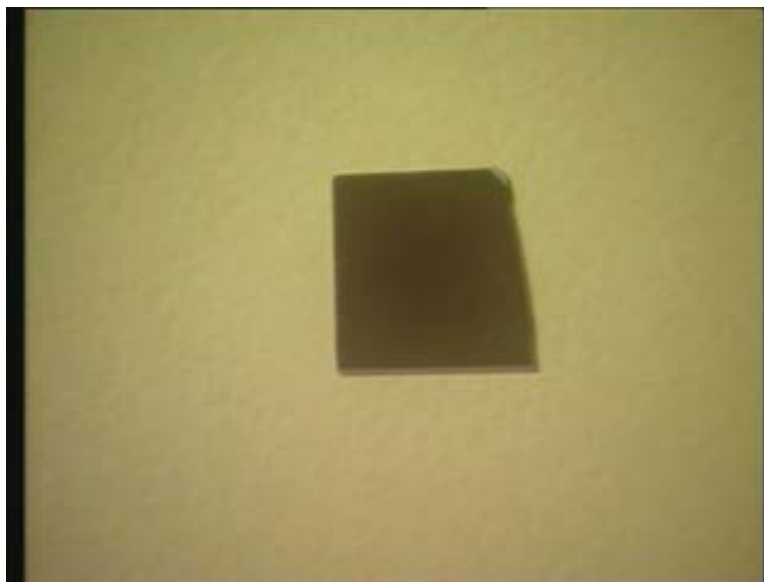
We have already identified the first processing step in VLSI technology, which is crystal growth, crystal growth and also we must be familiar with the concept of crystal orientation. Each particular crystal orientation will have some particular properties associated with that, which will also be very useful when we are discussing the device fabrication. So, it is imperative to know about, not merely about the crystal growth techniques, but also about the properties associated with different crystal orientation. So, this is the first unit step. Now, suppose I have grown by some means a single crystal of silicon with 1 1 1 orientation; you have grown a block of single crystal silicon. For integrated circuit fabrication, we have the substrate material in wafer form.

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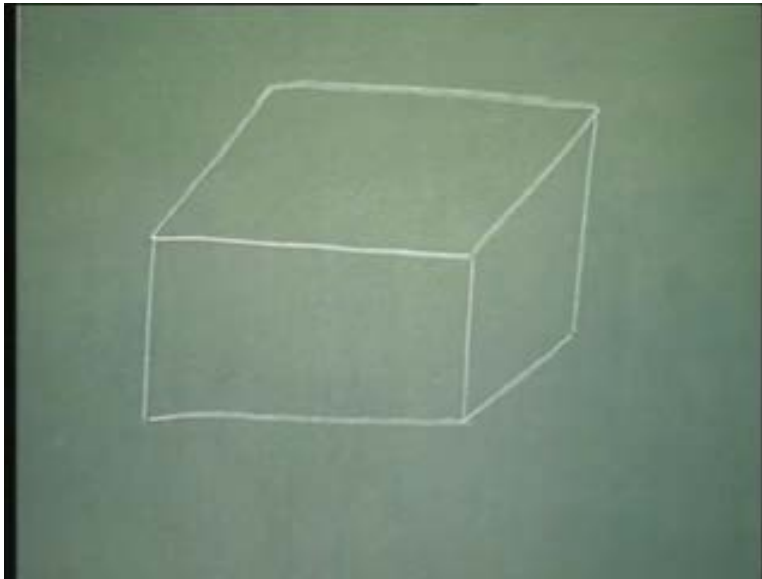
That is you cut a very thin slice out of that block, a very thin slice, usually in the form of a disc like this, thin. This disc has a particular thickness, usually about a few hundred microns thick, may be about 500 micron thick. The exact thickness will depend on the diameter of the crystal. The bigger the crystal, the thicker it has to be in order to give it mechanical stability. Okay. This is how it looks.

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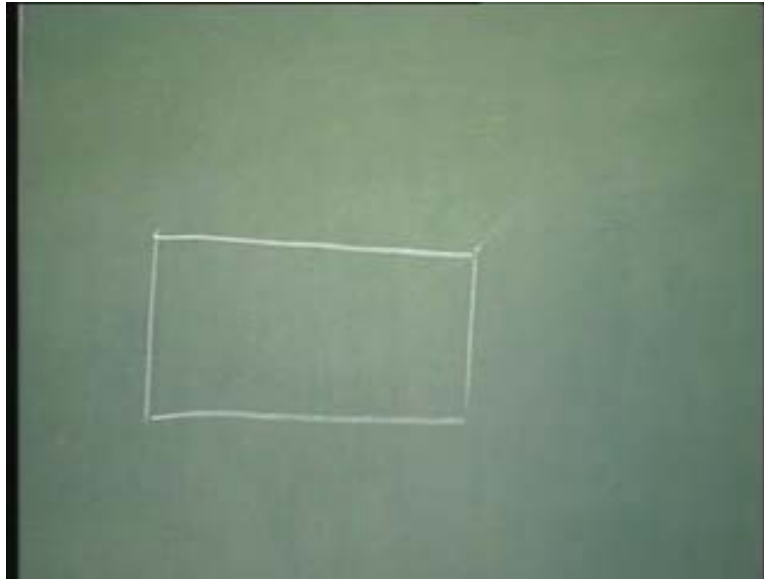
A silicon wafer, cut from a wafer; the full wafer was a circular piece, we have cut this piece from here. You can see it is actually a metallic grey in color with mirror polish on one surface. I have this silicon substrate. Let us assume that I have managed to dope it p-type also. I have realized the particular doping concentration, so that the resistivity of this silicon wafer is 10 ohm centimeter.

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If I now take a cross sectional view of this silicon wafer, it will look like a simple, plain rectangle like this; see, the three dimensional picture that will be like this. This is the block; this is the three dimensional view and if I take a knife and cut a cross section, then it is going to look like this.

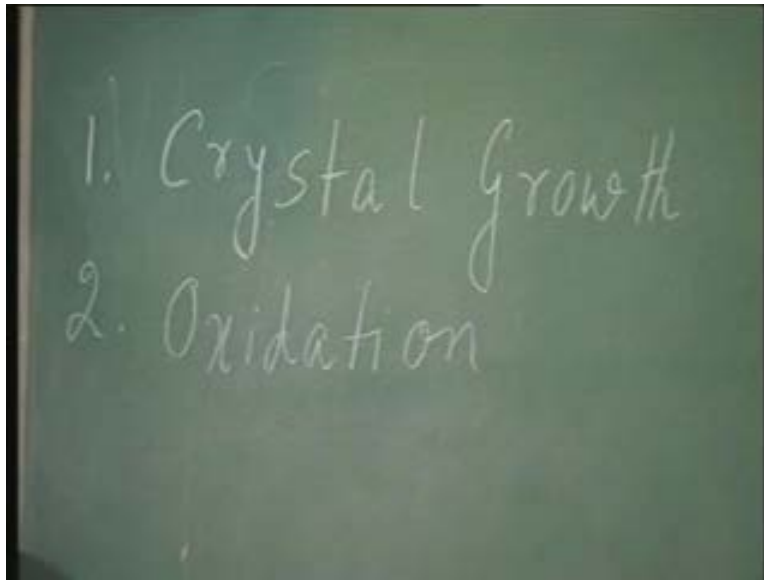
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Clear? The first step after you have this silicon substrate, the first step towards realizing a bipolar junction transistor is to grow an oxide; grow an oxide on the entire silicon surface. I told you that silicon is a particularly desirable material for this integrated circuit technology. There are various reasons for that. One important reason is that silicon is very easy to oxidize. You just have to raise the temperature, keep the silicon in an oxygen ambient. Silicon has a great affinity for oxygen, so it will form silicon dioxide, SiO_2 and this silicon dioxide is an excellent insulating and dielectric material. Not only that, it has very good masking properties.

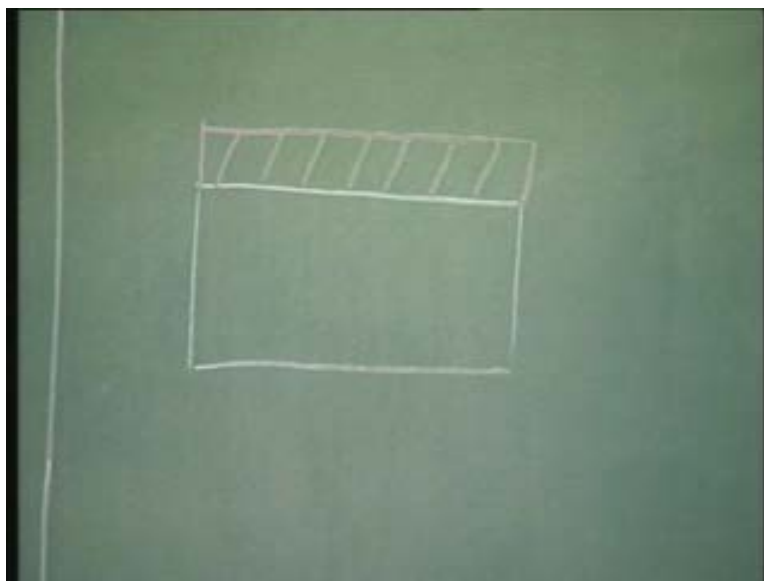
What do I mean by masking properties? That is I told you that we have to dope silicon. Now, it may be that you do not want to dope the entire block of silicon, you want to dope it selectively. So, the portions which you do not want to dope, all you have to do is to cover those portions with a layer of silicon dioxide. Silicon dioxide will mask against the doping. It will not allow the dopants to penetrate through this layer. So, silicon dioxide has excellent dielectric properties, insulating properties and masking properties, which brings us to the second unit process step, namely the oxidization.

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Once we have oxidized the silicon substrate, how does it look? Well, the silicon dioxide forms a transparent glass like layer, amorphous layer on the single crystal substrate and it shows a different color than the metallic grey bare silicon substrate. So, depending on the thickness of the oxide, the color will blue or green or pink.

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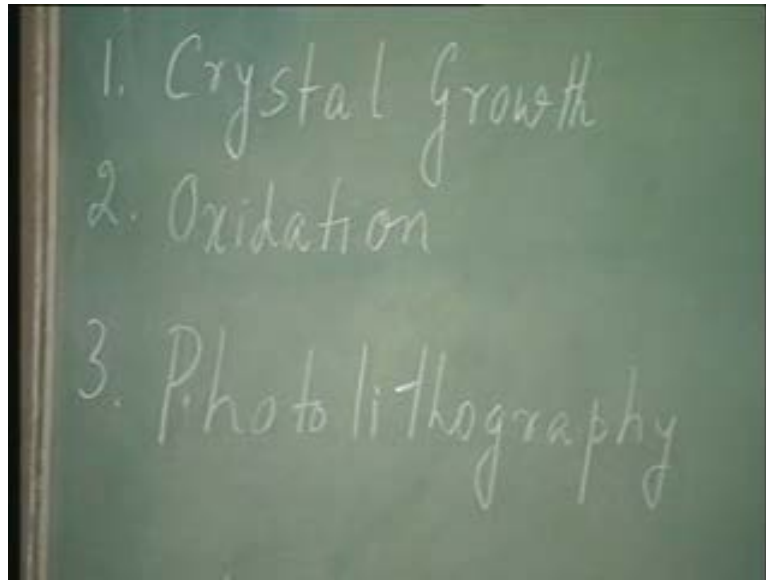
Let us say, I have grown an oxide on the entire silicon substrate like this. If you want to see the silicon substrate with oxide in it, here it is.

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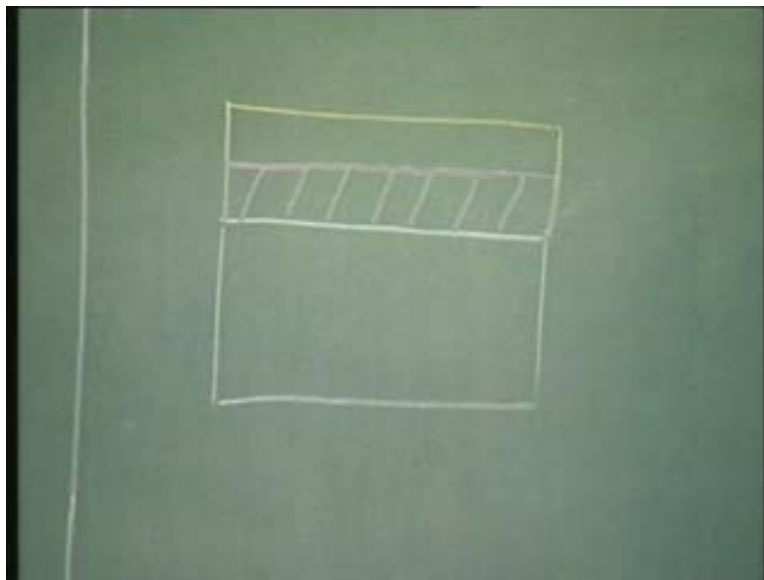
You can see the blue color on the silicon substrate. That blue color is the color of oxide; the entire substrate of silicon is covered with this oxide layer. Once the entire substrate is covered with the silicon dioxide, what do you want to do next? You want to selectively dope the silicon substrate. As I have already told you, in order to dope the substrate selectively, you have to keep oxide in some regions and remove the oxide from some other regions. Wherever the oxide is present, it will act as a mask against doping, so those portions will not get doped. The other regions from where you have removed the oxide, it will get doped when subjected to doping. Now, this selective removal of oxide is done by a technique called photolithography. So, that is our third unit process step.

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Photolithography - what we do in this case is we cover the entire surface of the oxidized silicon with a photo sensitive material called a photo resist.

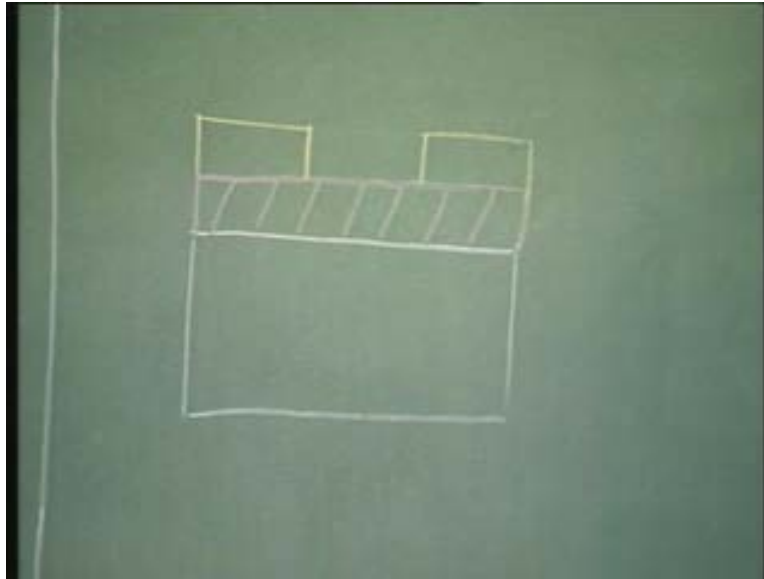
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You first put photo resist on the entire substrate. Then, you bring this photo resist coated substrate in contact with a mask. What is a mask? Mask is nothing but a glass plate with patterns etched in it; dark and transparent patterns etched in it and then you subject it to a

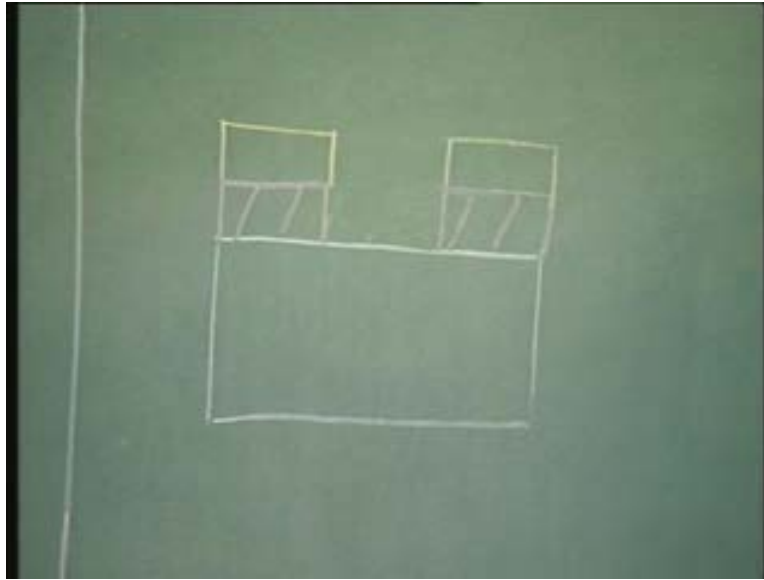
particular radiation most commonly UV radiation. As I told you, the photo resist is a light sensitive material. So, through the transparent regions of the mask, this photo resist is exposed to the UV light radiation and then its properties change, it becomes soft. It becomes easy to remove from those portions.

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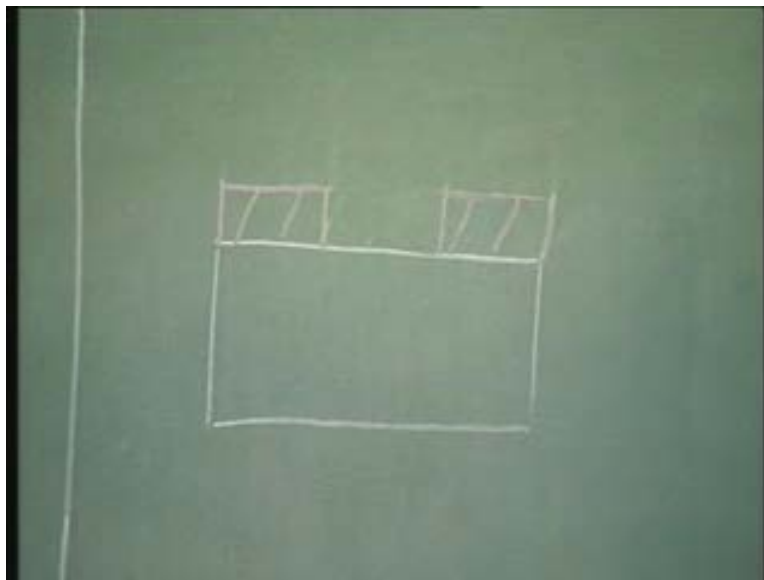
So, you can remove it selectively from some portions like this and the rest of the region photo resist is hard, it is difficult to remove, so it is going to protect the underlying oxide layer and then you subject this to etching, etching of oxide. You put it in hydrofluoric acid solution which can etch silicon dioxide, while not attacking the silicon substrate. When this is put in hydrofluoric acid solution what is going to happen?

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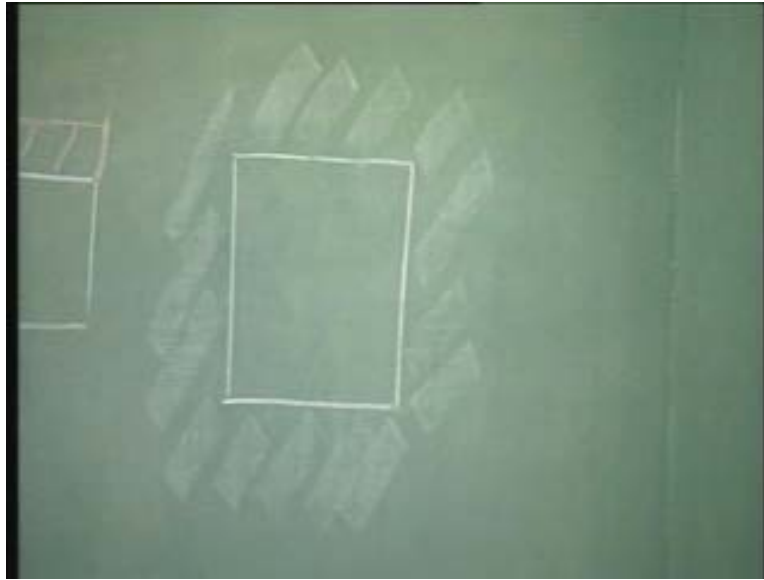
Only from this portion the oxide will get removed and then you can remove the remaining photo resist from the rest of the portions.

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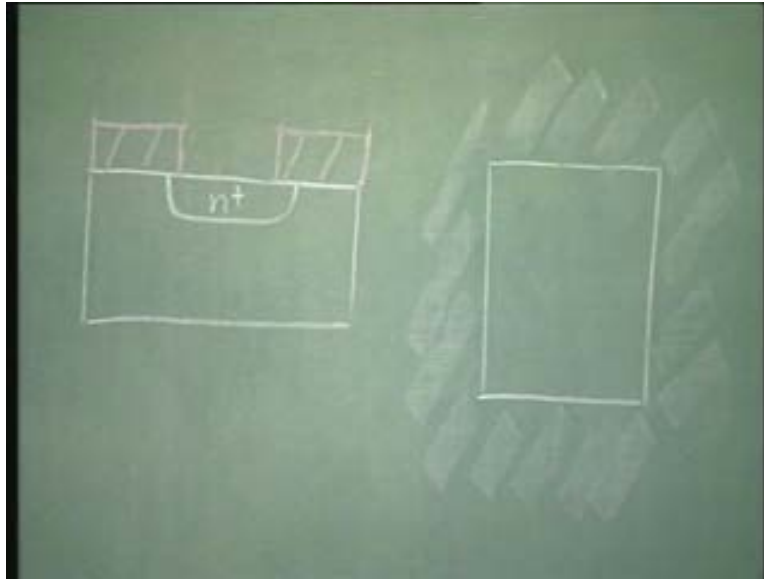
This is called opening of a window in the oxide. You have opened a window in the oxide.

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In order to open this window in the oxide, the mask you needed; remember, I am showing you the top view is some thing like this - one transparent window, while the rest of the portion is all dark. One transparent square box that is the top view of the mask plate, the rest of the portion is all dark. Only through this transparent square, the photo resist is exposed to the uv radiation. It gets softened and easy to remove, so that you can etch the underlying oxide when you put it in hydrofluoric acid solution. You see, photolithography is closely related to photo resist, masks and radiation. These are the three important points to be noted about photolithography. This mask incidentally is called the active layer mask in bipolar junction transistors. That is this is the active region where the transistor will actually be housed.

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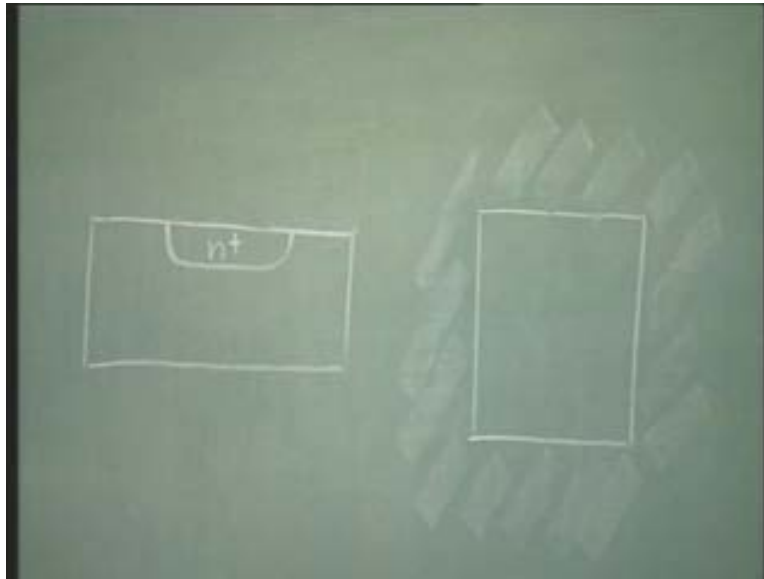
After you have realized this window pattern, the next step will be to dope the, dope through the window, dope through the region where the oxide is not present and we usually do a diffusion, an n plus layer diffusion; n plus that is very heavily doped n region. This is usually done by diffusion. So, that is our fourth process step that of diffusion.

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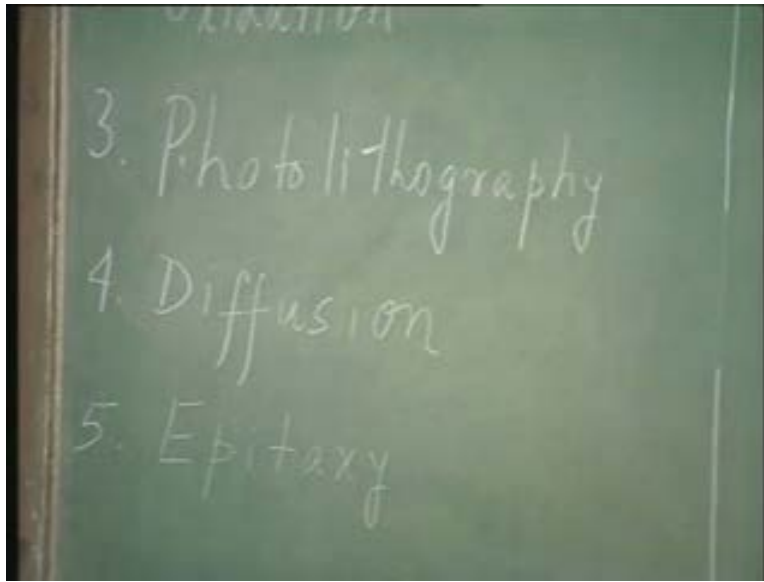
This particular diffusion incidentally is called buried layer diffusion. Why it is called buried layer diffusion will become clear in a few minutes. This n plus layer diffusion, usually the dopant used for this is antimony or arsenic.

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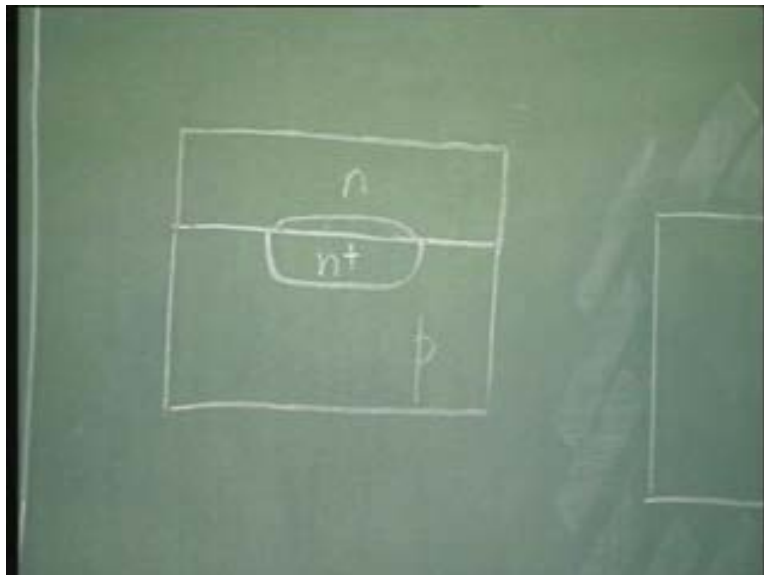
After the buried layer diffusion we remove the rest of the oxide, so that what we have, the structure is like this. You have again the bare silicon substrate. In the active region, it is doped n plus. The next step is called epitaxy. The next step is called epitaxy.

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Epitaxy literally means arranged upon, arranged upon. You already have a single crystal substrate. You are going to grow another single crystal layer on top of this substrate. This is epitaxy. Please realize that the single crystal substrate is a few hundred microns in thickness. In contrast, the epitaxial layer you are going to grow on this substrate is from a fraction of micron to a few microns thick. That is we are talking about a much thinner layer compared to the original bulk substrate.

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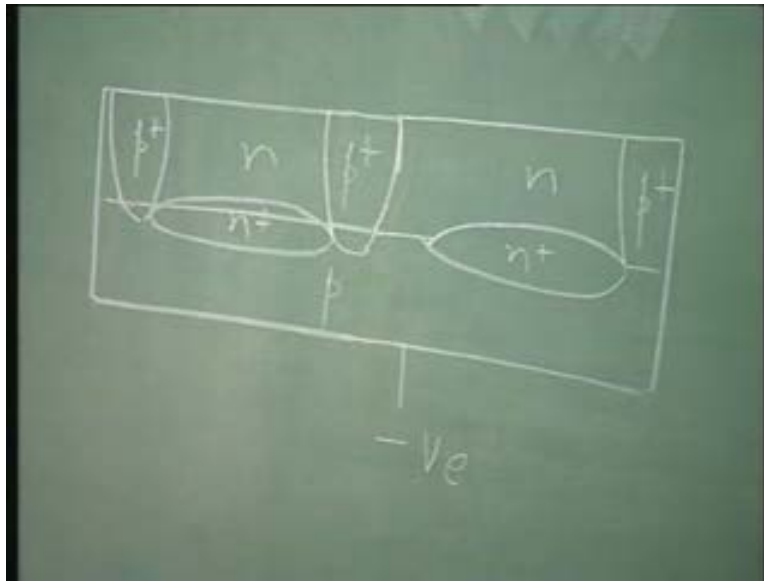


By this epitaxy, you grow an n layer on top of this and while growing this n layer, this n plus diffuses out a little bit and looks like this. Now, I suppose the term buried layer diffusion has become clear to you. This n plus layer is buried underneath the epitaxial layer. So, now we have originally the p-type substrate, then the n plus buried layer diffusion and then on top of that the n epitaxial layer. This n epitaxial layer is going to be the collector of the npn transistor and the n plus buried layer diffusion is done in order to reduce the collector resistance.

Now, think for a moment. This n epitaxial layer is going to be the collector of the bipolar junction transistor. Now obviously, I am not going to have just one transistor in this entire silicon chip. I am going to have thousands of transistors when I am talking about LSI or VLSI . What does that mean? That means all the collectors are shorted together, because all of them are housed in the same n epitaxial region. You do not want that, you cannot permit that. You do not know what kind of circuit you are going to make, but chances are that all the collectors cannot be shorted together, right. If you were making discrete transistors it would not have been problem, because you could cut individual transistors. You could scribe them in individual transistor pieces and use them. But, when I am talking about the integrated circuit that is not merely the transistor, the interconnections, the passive components, everything is housed in the same chip, then I cannot allow that all the collectors of the transistors get inadvertently shorted together.

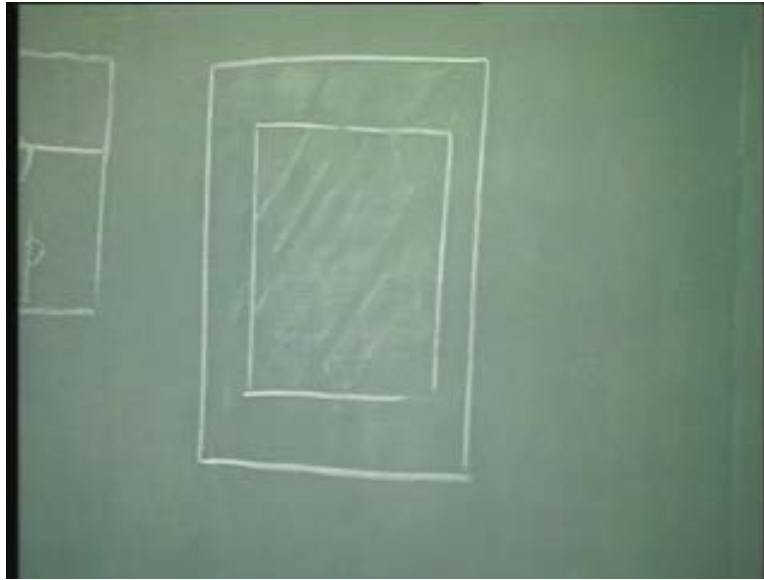
Remember this is one very important criteria of the integrated circuit technology that is to provide isolation between devices, provide isolation between adjacent devices. So, I must find a scheme in order to isolate the adjacent transistors. The oldest technology to realize this isolation between transistors uses a reverse biased pn junction. You know, a reverse biased pn junction is a blocking contact. It is not going to allow the flow of current between two transistors. So, what we do have is called a pn junction isolation and in order to have the pn junction isolation, what we do is something like this.

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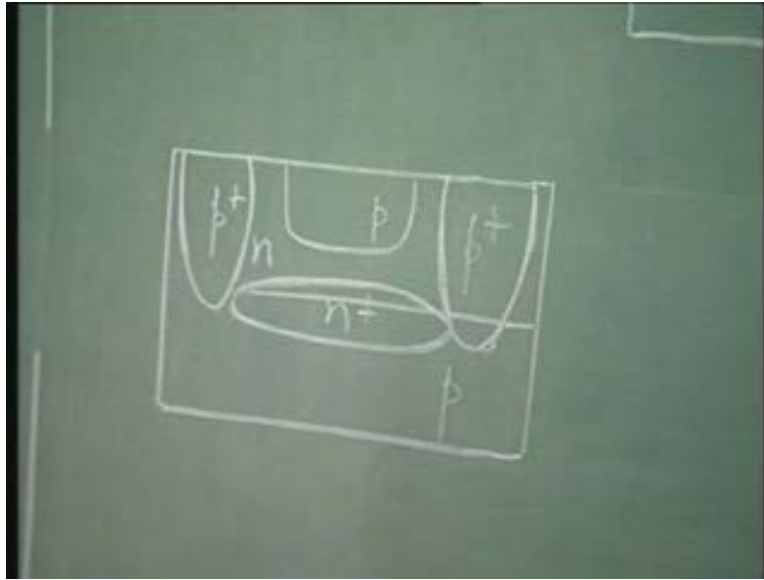
You have the n epitaxial region and the n plus region. This is for one transistor. Similarly, next to it you have another n plus buried layer diffusion and the continuous n epitaxial layer. What you have to do is protect the active region by means of an oxide and dope here all the way down to the p-type substrate by a p plus diffusion. It is very important that this doping comes all the way to the p-type substrate. Then you see your transistors are isolated from each other. If I just extend it on this side, you can see that these two transistors are isolated from each other, current cannot flow through this reverse biased p plus n junctions. All you have to do is you have to make sure that this substrate is connected to the most negative point of the supply. So, this is called pn junction isolation. I have of course drawn it very, very simply, but you probably appreciate by now that in order to selectively diffuse this p plus region, I must have oxidation, photolithography and diffusion and the mask for this is, a mask like this surrounding the active region.

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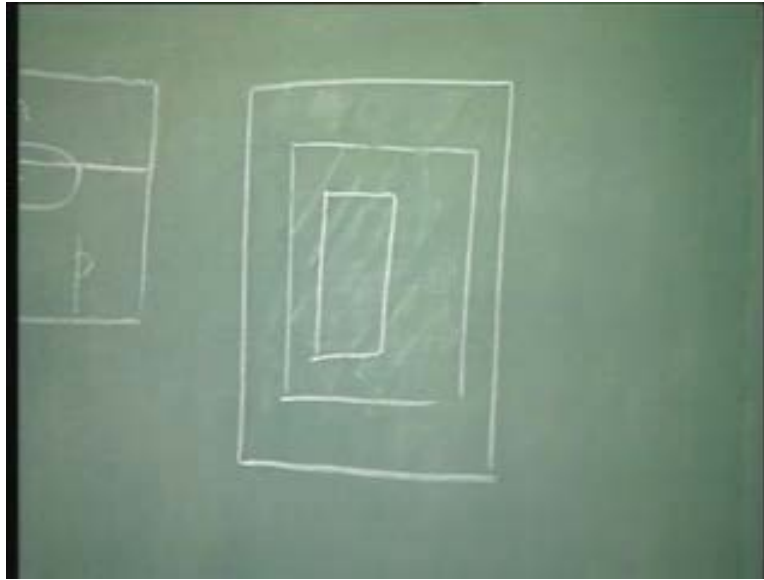
Now, this portion becomes dark. I have surrounding the active region, the diffusion window for isolation diffusion. That is the p plus dopant can enter only through this region surrounding the active region of your transistor. The active region is marked by this n plus buried layer diffusion. Now, my task is relatively simple. I have realized the collector, I have realized the isolation between the adjacent devices. All I have to do now is to realize the base and the emitter. Understand the first maxim of the doping process - the base is doped earlier than the emitter, because the emitter is more highly doped than the base. So, first I must have the base doping and only after that I have the emitter doping.

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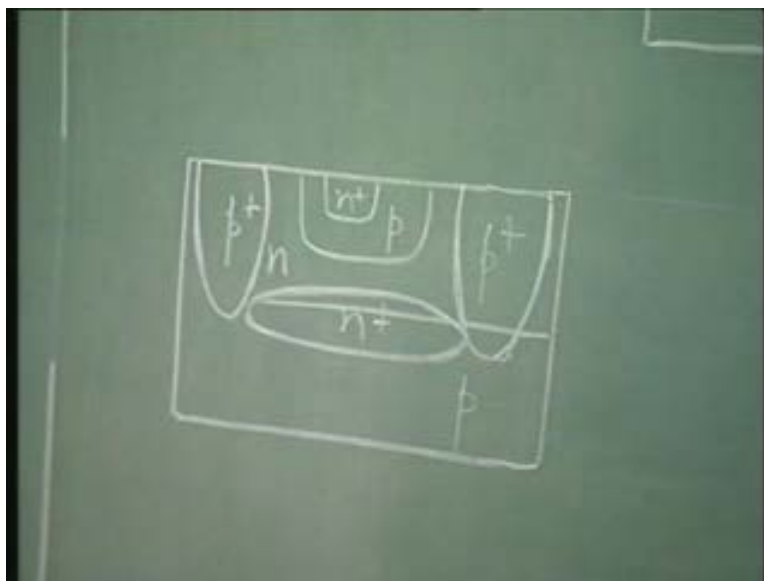
Focusing our attention back to the bipolar junction transistor, the single bipolar junction transistor for which we have realized the isolation and the collector region, all I have to do now is to have a p region, p region doped p for the base. Again I am drawing it very simply, but you know, in order to realize a p region, again I have to have oxidation, photolithography and diffusion. Therefore almost in every stage of processing these three steps have to be repeated - oxidation, photolithography and diffusion. You have realized your base region. Notice that this base p region is located within the active region mask.

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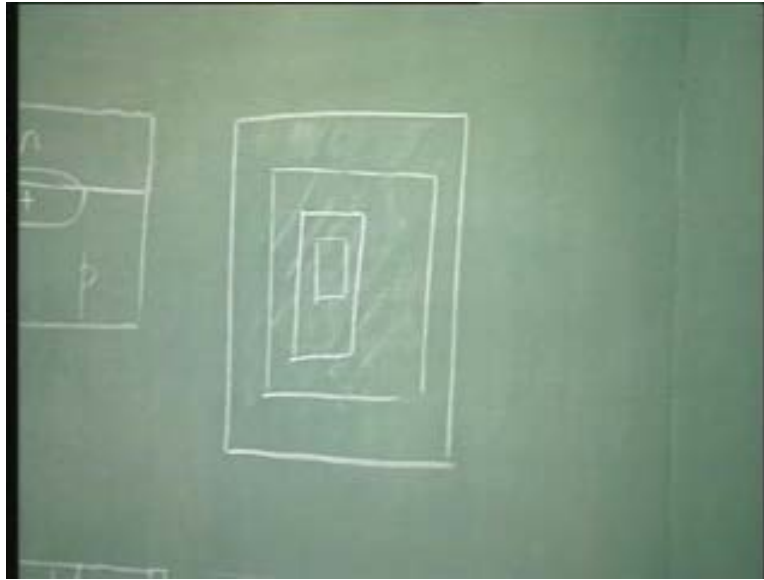


So, if you look at the top view, then your base is actually located within the active region mask. Only that portion is transparent when you are going to have the mask for the base. Its relative position is that it is within the active region mask. So, I have realized the base. Next what we want to realize? I want to realize the emitter. So, the emitter is here.

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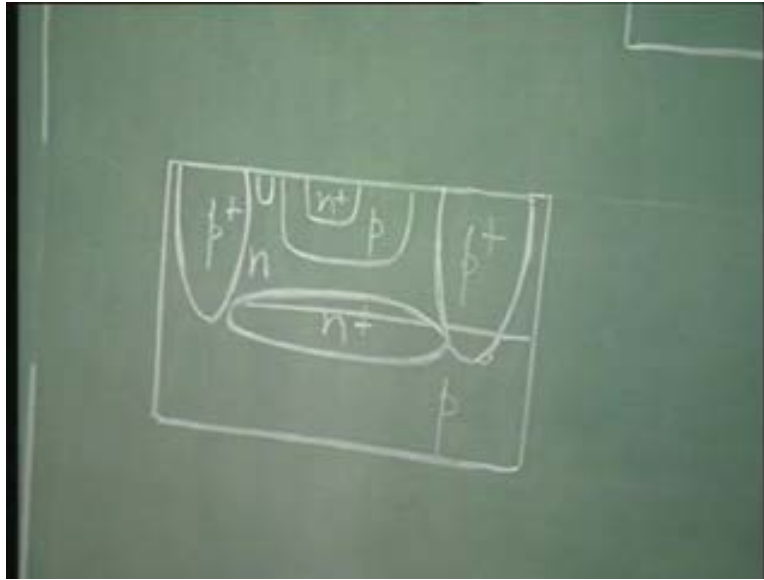


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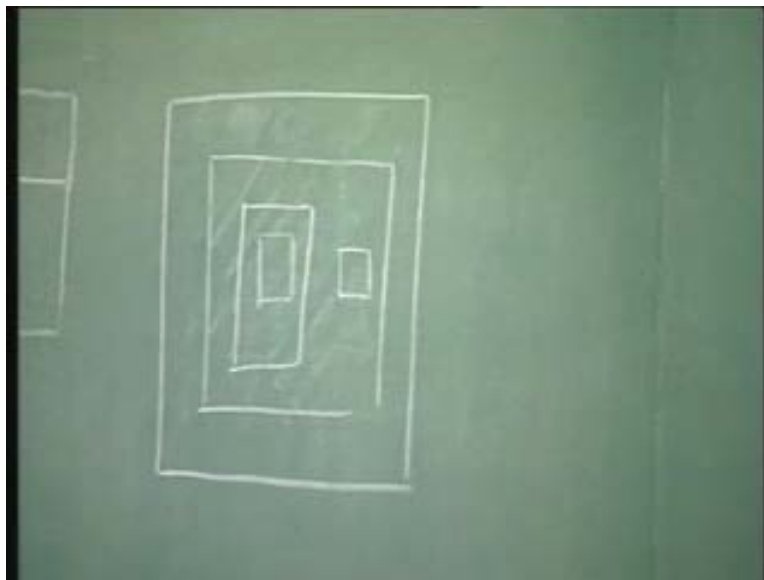
Within the base window I have the emitter region. Now, the usual practice is when you are having the emitter doping, n plus doping, you also have a small n region in order to facilitate taking contact from the collector region. You see your collector is n. This is an epitaxial n region. Remember, it is not n plus; it is not very heavily doped, it is lightly doped n region. In order to take contact from that lightly doped n region, you want to reduce the contact resistance. It is difficult to have a proper ohmic contact to a lightly doped n region. So, the usual practice is you have a small pocket of n plus diffusion for collector contact.

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You can have it here, small pocket for collector contact. This needs no extra step. This can be done along with the emitter diffusion.

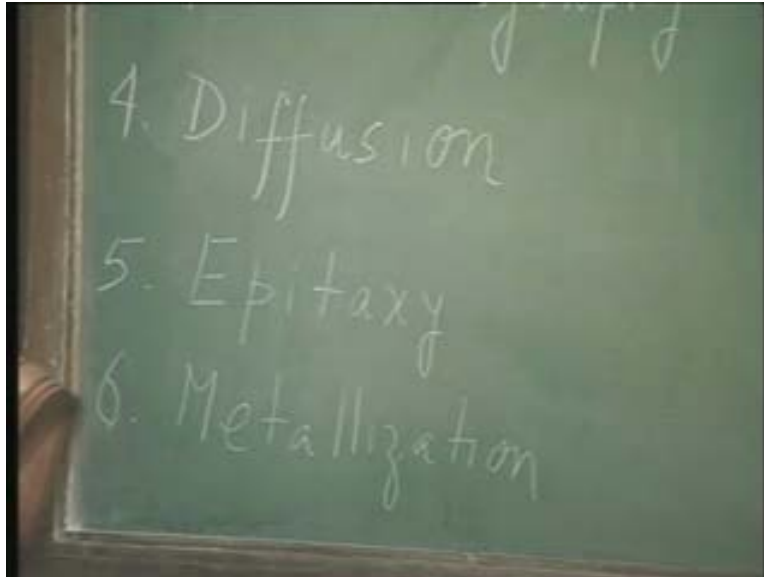
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Only thing is for that you need to have a small opening inside the active region. So, your transistor is almost ready. You have the emitter, you have the base, you have the collector, you have the isolation between adjacent devices as well. What is remaining? To

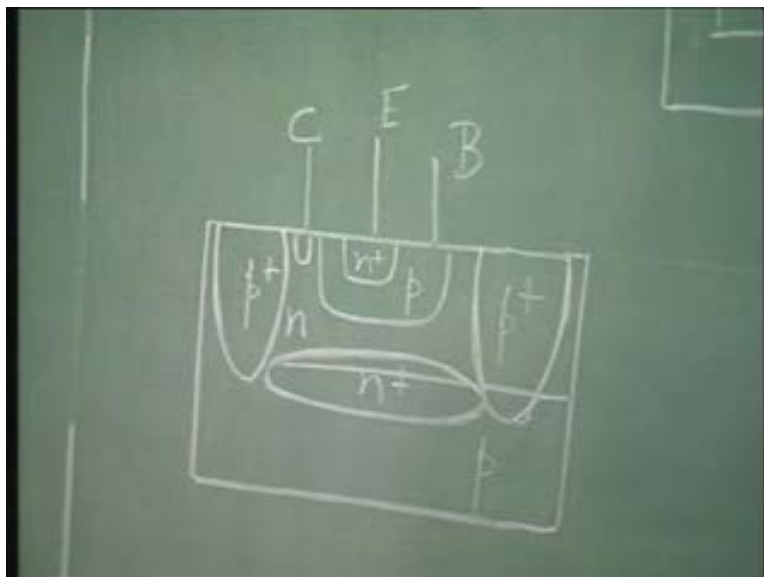
establish contact with the outside world and that is done by a technique called contact metallization. So, that brings us to the process step number 6.

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Remember, this metallization also needs selective deposition of metal over the base, emitter and collector region. That means whenever I use the term selective, I must have photolithography. I must have masks.

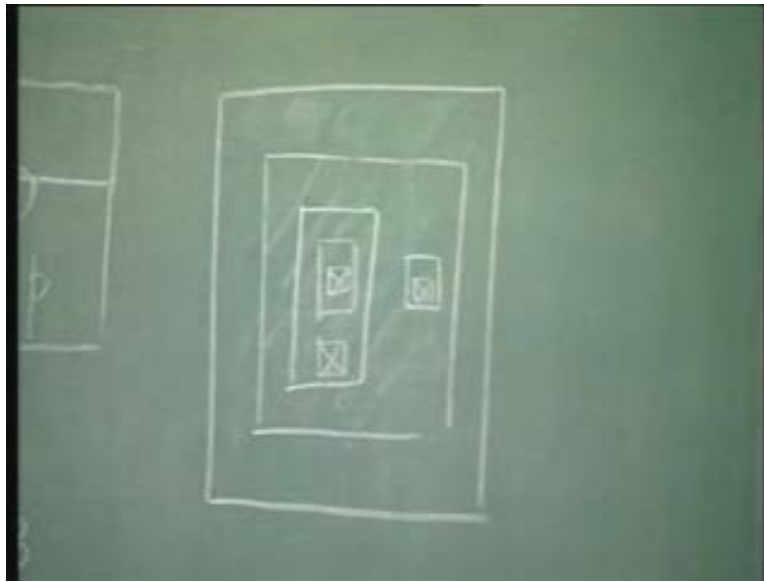
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So, I can take a contact from here. This is the collector, this is the emitter and this is the base. Usually the metal used for contacting in VLSI is aluminum. Yes, now aluminum is also a Group III element. That means aluminum would actually dope silicon p-type. You see, it is very easy to use the aluminum as a contact metal when you are contacting a p region. It is p and aluminum is going to make it as p plus. Therefore, the contact resistance is going to be very, very small. Situation is slightly more difficult when you have a n region. However, if you have a very heavily doped n plus region it is not a problem, because what you have is a p plus n plus. p plus n plus is going to be a very leaky diode, which is a good enough ohmic contact. So, to take contact from n plus region is not a problem. The only problem is to take contact from a lightly doped n region. That is why I said, in order to facilitate collector contacts we use a n plus pocket; in order to facilitate taking collector contacts.

Of course, aluminum has its own problems. We will discuss all this when we discuss the particular topic of metallization and the latest technology is to replace aluminum with copper. In fact, I think IBM and Motorola they have both started their latest chip using copper. That is because aluminum has some problems. The most important problem is called electromigration, which we will discuss later when we are going to discuss the topic of metallurgy.

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So you see, we have, for the metallization of course we need to have another set of masks. This is for the emitter contact, this is for the base contact and this is for the collector contact. In a nut shell, very simply speaking, these are the steps we need to realize a bipolar junction transistor.

Let us do a very quick recap. We have started with a single crystal substrate. That means we must have some means to grow this single crystal and then we have subjected it to oxidation, to photolithography - in order to selectively remove oxide from certain regions. We have subjected it to diffusion, to dope the particular region and we have seen that this process has to be repeated a number of times for base, for emitter, for pn junction isolation. We have also seen that we need to have an epitaxial region for the bipolar junction transistor fabrication. That is another state, the epitaxy and then finally we have the contact metallization.

Just one more word before we close the lecture for today - doping can be done either, as I have already said, by diffusion or there is a more sophisticated technique called ion implantation. That actually is our seventh process step which the ion implantation has now to quite a large extent replaced diffusion, because you have much more flexibility.

However, diffusion is still a very important doping technique. So, doping can be done either by diffusion or ion implantation which would be our seventh processing step. In the next class we are going to discuss how to realize a MOSFET.