VLSI Technology
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Lecture - 3
MOSFET Fabrication for IC

In the two previous lectures we have discussed the basic processing steps to realize a bipolar junction transistor and a MOSFET. You have seen so many steps go into that - oxidation, photolithography, diffusion, epitaxy, etc, etc. But, the starting point is always the same. That is in order to fabricate any device, you must first have a single crystal silicon wafer, right. So, that is the first unit step - how does one realize a single crystal silicon. Not only that, if you look at it more closely, for bipolar junction transistor we mentioned that the single crystal wafer is 1 1 1 oriented. On the other hand, if you are going for a MOSFET fabrication, universally the starting wafer will be 1 0 0 oriented.

Why is this difference? Is it just an arbitrary choice? No, let me assure that this is not an arbitrary choice. The properties of the material are influenced by the crystal orientation that is to say different crystal planes have, may have different properties and which will influence the device performance. That is why, while bipolar junction transistors can be fabricated on 1 1 1 substrate, for MOSFET fabrication you would prefer a 1 0 0 wafer. So, in today’s class, let us take a look at the silicon crystal.

Now, the simplest crystal structure that you can think of is called a cubic lattice.

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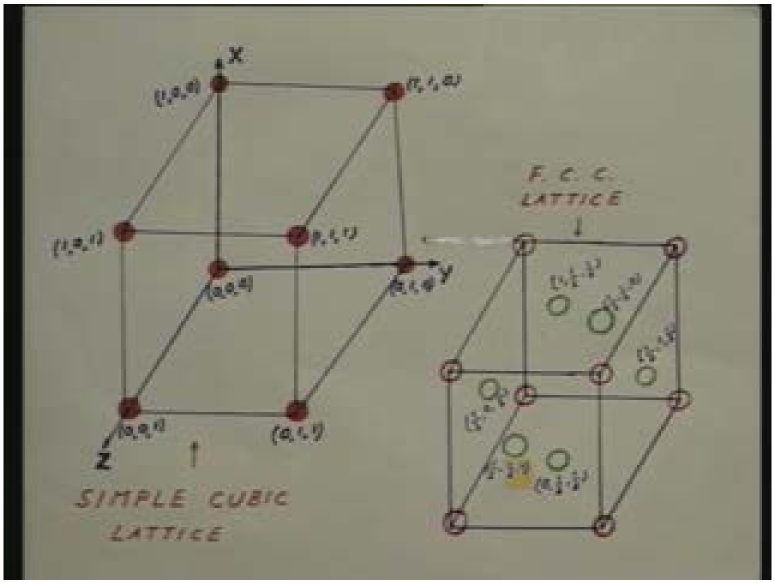

If you look at the card we have here, where the picture of a simple cubic lattice is there, to the left of the picture you can see the simple cubic lattice. What is it? It is nothing but a simple cube with atoms placed at each corner of the cube and if I think of a three dimensional co-ordinate system, three axis x, y and z and if I consider that the dimensions of this cube is unity that is it is an unit cell, then the co-ordinates of each of this corner atoms will be given like 0 0 0, 0 1 0, 0 0 1, etc, etc. So, this is the simplest structure that one can think of - a simple cubic lattice.

Let us take it one step further in complexity. You know, a cube will have 6 faces - front and back, top and bottom, left and right. Now, in addition to the corner atoms, 8 corner atoms placed in the corners of the cube, if we think of atoms in the middle, in the center of each of the faces, then what we get is a face centered cubic lattice and that is the picture you can see towards the right of the card. In addition to the 8 corner atoms, you also see 6 extra atoms placed in the center of each face and their co-ordinates are given by half half 0, half half 1, 0 half half, 1 half half, half 0 half and half 1 half. Right, very simple, is it not?

Silicon however is neither a cubic lattice nor a face centered cubic lattice. We have to take one further step in complexity. You have seen the face centered cubic lattice, fcc lattice. Now, think of two fcc lattice, two fcc sub lattice rather, one pushed inside the other along a major diagonal by a distance of one fourth. That is we have two face centered cubic sub lattice; two interpenetrating f centered cubic sub lattice, one is pushed inside the other along a major diagonal and displaced by one fourth in all the direction. What we have is this model here.

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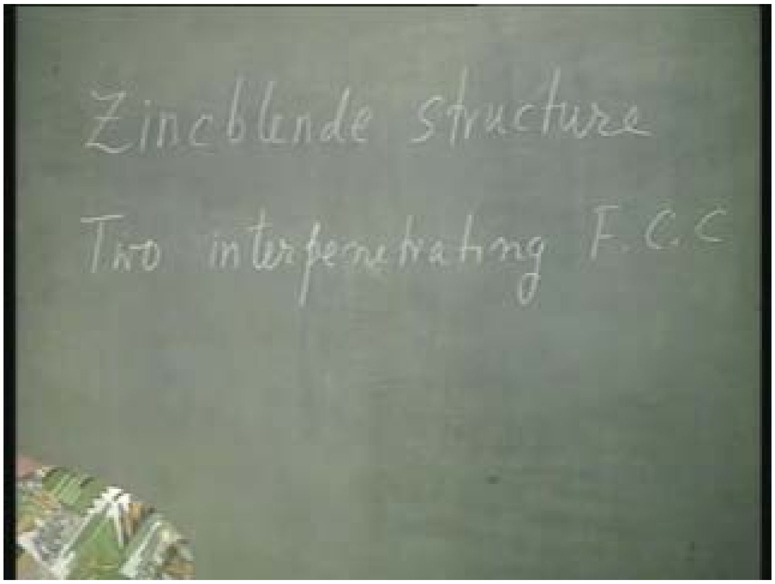

Zincblende structure

Two interpenetrating F.C.C

This is called a zinc blende structure, two interpenetrating fcc sub lattice. Look carefully at this model.

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For the time being, forget about the blue balls and concentrate only on the yellow balls or part of the balls. What do you see? This is nothing but an fcc lattice. I have atoms at the corner of the cube and also at the center of the each of the face. In addition to this, now see that I have 4 blue balls, the blue balls, to distinguish between the first sub lattice and the second sub lattice and what are the co- ordinates of these blue balls? Let us consider that this point is the origin. This is the x- axis, this is the y-axis, this is the z-axis. Then, this blue ball here, it has the co-ordinates of one fourth one fourth one fourth. It is displaced from the origin in all directions by one fourth.

What about this one? It is displaced in x and in z direction by three fourth and in y direction by one fourth. That means its co-ordinate is three fourth one fourth three fourth. What about this one? This is displaced by three fourth in x and y direction and one fourth in z direction. Accordingly you have three fourth one fourth three fourth, three fourth three fourth one fourth and one fourth three fourth three fourth. So, the coordinates of this 4 blue balls are actually they belong to the second fcc sub lattice and it has been pushed inside the first fcc sub lattice and it is, it has these following co-ordinates. That is the co-ordinates will be ......

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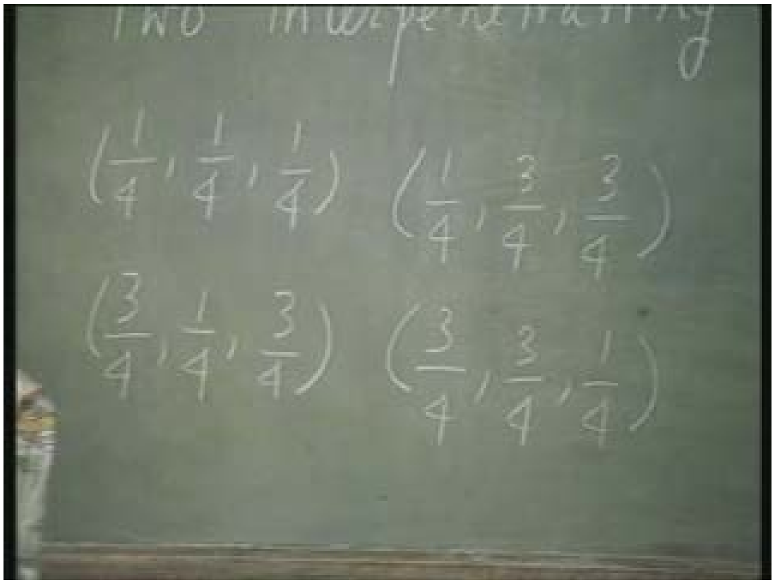

Two interpenetrating

$\left(\frac{1}{4}, \frac{1}{4}, \frac{1}{4}\right)$ $\left(\frac{1}{4}, \frac{3}{4}, \frac{3}{4}\right)$

$\left(\frac{3}{4}, \frac{1}{4}, \frac{3}{4}\right)$ $\left(\frac{3}{4}, \frac{3}{4}, \frac{1}{4}\right)$

Now, when I say it is a zinc blende structure, what I mean is that the two sub lattices they are made of different atoms. For example, gallium arsenide. Gallium arsenide is a zinc blende crystal.

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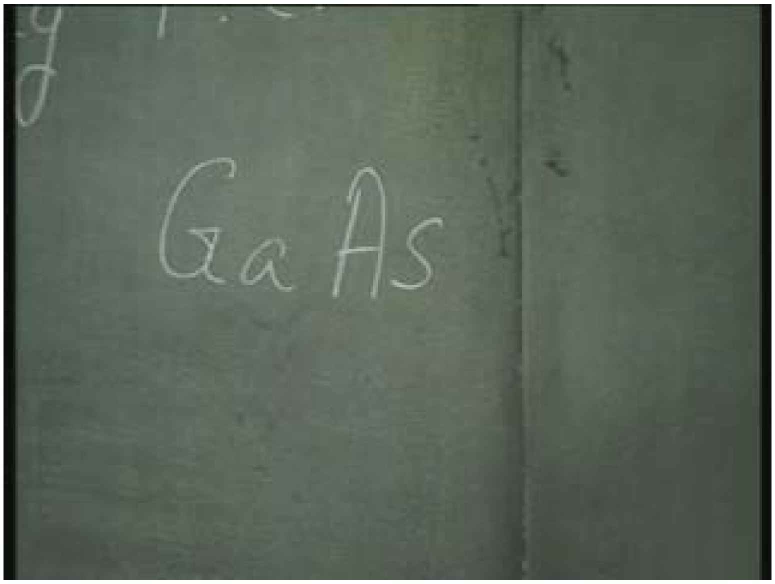

GaAs

That is in this model you can consider that this yellow balls refer to gallium atoms and blue balls refer to arsenic atoms. Inside the gallium sub lattice you have pushed an arsenic sub lattice or the other way round. You could also think that the yellow atoms are arsenic atoms and the blue atoms are gallium atoms, makes no difference. All I am trying to say is that each zinc blende lattice is comprised of two interpenetrating fcc lattice; one lattice, two interpenetrating fcc sub lattice, let us say. One sub lattice is comprised of gallium atoms, the other sub lattice is comprised of arsenic atoms. Now silicon is a degenerate form of zinc blende structure. This is called a diamond lattice.

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When I say it is a diamond lattice, what I mean is that there is no difference between the two sub lattices. They are made of identical elements. In this particular case, both the sub lattices are comprised of silicon. So, silicon is a degenerate form of zinc blende structure which is called the diamond crystal structure. Now that you know what the crystal structure of silicon look like, let us look a bit closer to the zinc blende or the diamond structure and see what information we get from here. First of all, let me tell you that in the unit cell we have considered that the cube is of unit dimensions. Now, if the unit of this dimension is called a, a is called the lattice constant of the particular material. That is each side of the cube is a, it has a length a. So, a is called the lattice constant.

For a zinc blende structure, what is the distance between two neighboring atoms? That is can you think what is going to be the distance between the two neighboring atoms in a zinc blende structure like this? Let us take the case of the atom which is placed at one fourth one fourth one fourth.

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That is here, the blue ball, one fourth one fourth one fourth shifted in all directions from the origin. What are its nearest neighbour? One nearest neighbour is of course the atom at the origin 0 0 0. What are the other nearest neighbours? One is this face centered atom, the other one is this face centered atom and the other one is the bottom faced centered atom. Is it not? So, the distance between two nearest neighbors can be calculated by simply calculating the distance of this one fourth one fourth one fourth atom from the origin and what is that distance?

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That distance is going to be and if I consider that this cell, it has a lattice constant of a, then this distance will be root 3 by 4 times a. Is it not? So, each atom of the second sub lattice, it forms a tetrahedron with the atoms of the first sub lattice that is with its four nearest neighbour. If you look at this blue ball, it has these 4 nearest neighbours and it forms a tetrahedral structure. What is a tetrahedral structure? It is like this.

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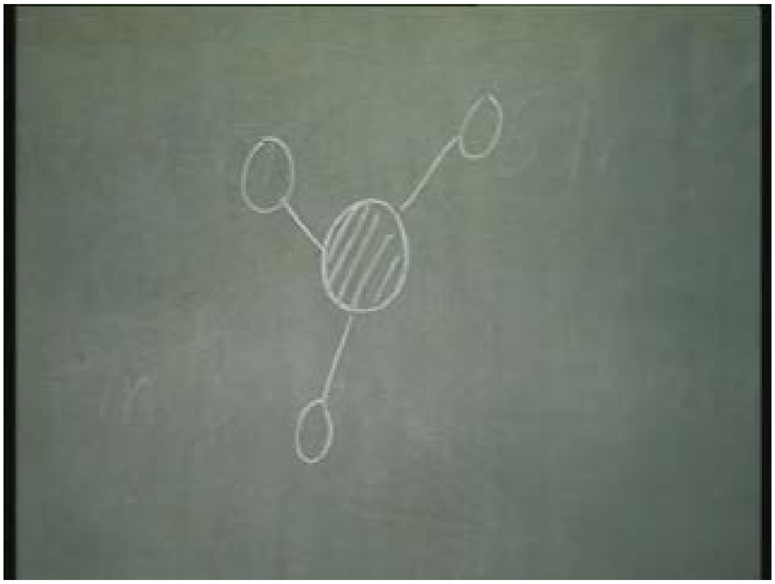

You have this blue ball here and the other one going inside the board. Yes? Now, if I consider that this atoms are nothing but hard spheres that is called the hard sphere model; just as you are seeing here, hard sphere model, then what can be their maximum radius? How close can they be spaced when they are touching each other? Is it not? Very like in this model; you can see here that the blue ball is touching its nearest neighbours on all four sides and you know that the distance between them is root 3 by 4 a.

Essentially I have a situation, this is my blue ball, this is one of the nearest neighbours. How close can we place them when they are touching each other? Right, maximum closest possible positioning will be when they are touching each other. So, when they are touching each other, let us forget about all the other neighboring atoms and concentrate on only one.

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So, then it is like this and the distance between them is this and this is root 3 by 4 a. Therefore, each atom can have a radius maximum half of this distance that is root 3 by 8 a. This is called the tetrahedral radius.

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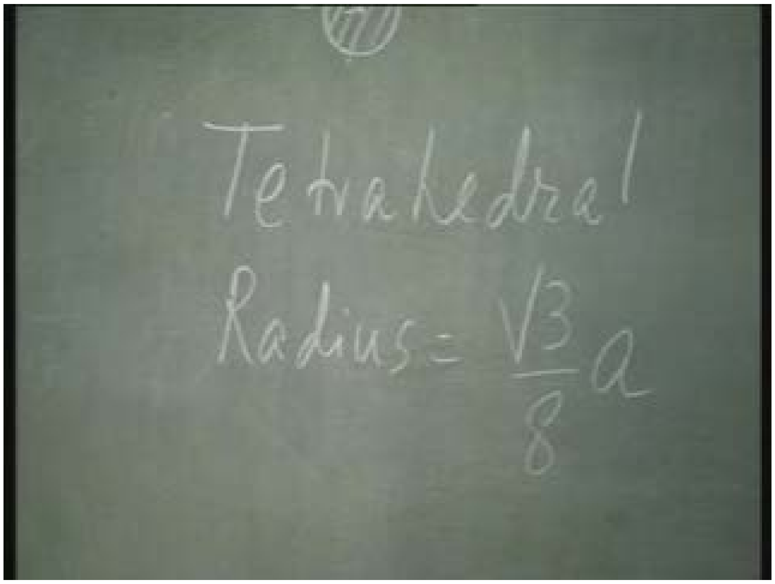

Tetrahedral

$$\text{Radius} = \frac{\sqrt{3}}{8} a$$

This is, if we assume hard sphere models and each atom its sphere is touching the other, then the tetrahedral radius is root 3 by 8 a.

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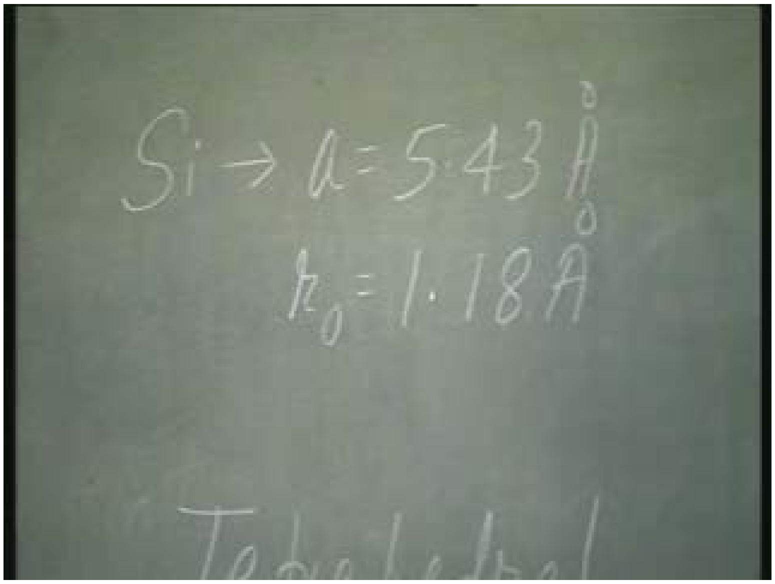

$$Si \rightarrow a = 5.43\ \text{Å}$$

$$r_0 = 1.18\ \text{Å}$$

Tetrahedral

For example, silicon has a lattice constant that is a for silicon is 5.43 angstrom and therefore its tetrahedral radius root 3 by 8 a that is 1.18 angstrom.

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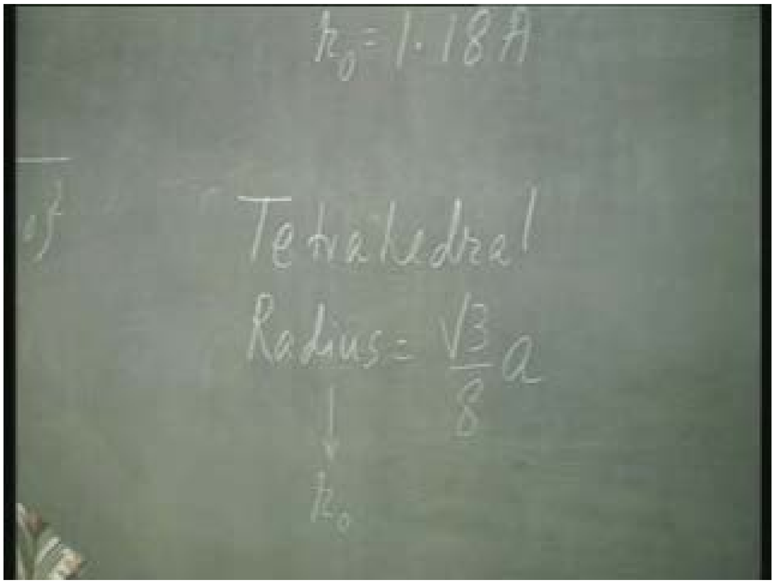

Tetrahedral radius is, usually the symbol that is used is r 0. Now, let us look at the packing density of this zinc blende structure.

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You can see in this model itself that not the entire space is taken up by the atoms. It cannot be, right? How does one calculate the packing density of a particular crystal structure? First of all we must see how many atoms are there in a particular unit cell. So, this is my zinc blende unit cell. How many atoms are there? Let us look at the corner atoms first. Take this corner for example. This corner atom does not belong exclusively to this unit cell. Yes, it is shared by many others. How many others? That is I can think of placing another unit cell here, another unit cell here, another unit cell here, that makes it 4 and then I can place another set of 4 such unit cells on top of this. See, this is the top corner. I can think of another set of 4 unit cell for which this atom will be the, at the bottom corner. Each corner atom is shared by 8 unit cells, so each of their contribution to one unit cell is actually one eighth.

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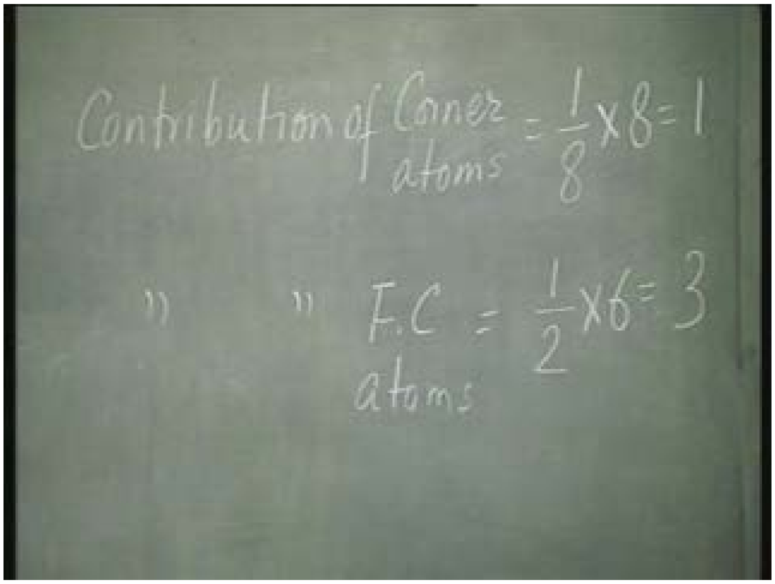

Contribution of Corner atoms $= \frac{1}{8} \times 8 = 1$

" " F.C atoms $= \frac{1}{2} \times 6 = 3$

One eighth for each corner atom and how many corner atoms I have? 8. Therefore, the total contribution is one eighth into eight that is equal to 1. Next, let us consider the face centered atoms. So, the contribution of each face centered atom to 1 unit cell is half. It is shared by two, one here and the other on top of this. 2310So, contribution of face centered atoms and how many such face centered atoms I have? 6, because there are 6 faces. So, half into 6 that is 3 and now, for the zinc blende structure, I have 4 atoms of the second sub lattice and they are not shared by anybody, they are present there in full.

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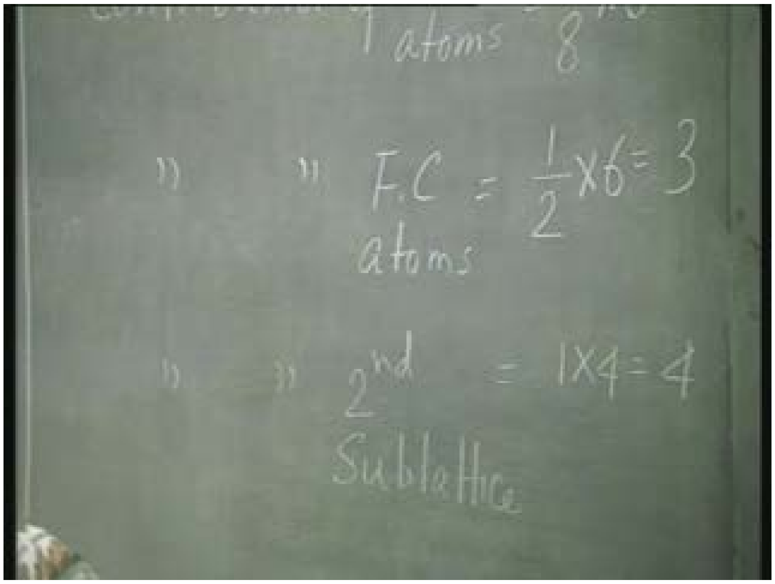

atoms 8

" " F.C atoms $= \frac{1}{2} \times 6 = 3$

" " 2^{nd} Sublattice $= 1 \times 4 = 4$

Therefore the contribution of the second sub lattice atom is actually 1 into 4. So, I have a total of 8 atoms in the unit cell. Agreed? I have a total of 8 atoms that is 8 full spheres. Considering hard sphere model, I have 8 full spheres inside the unit cell and each atom can have a maximum radius of root 3 by 8 a. So, what is the total volume occupied by these atoms inside the sub lattice? What is the volume of a sphere?

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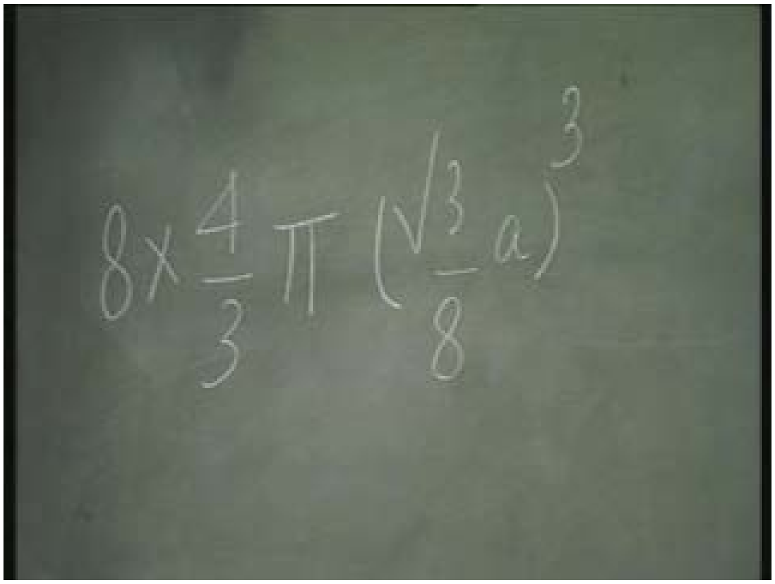

$$8 \times \frac{4}{3} \pi \left(\frac{\sqrt{3}}{8} a\right)^3$$

You know, it is 4 by 3 pi r cube. r is actually root 3 by 8 a and there are eight such spheres.

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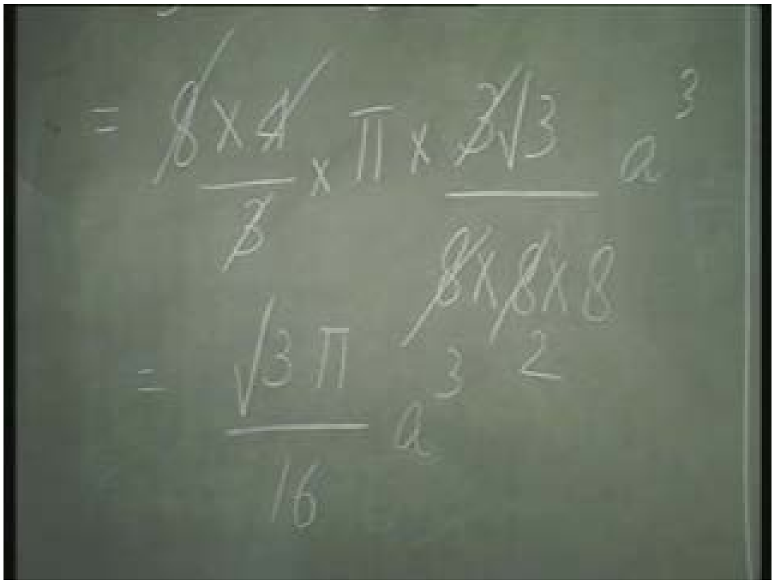

$$= \frac{\cancel{8}\times\cancel{4}}{\cancel{3}}\times\pi\times\frac{\cancel{3}\sqrt{3}}{\cancel{8}\times\underset{2}{\cancel{8}}\times 8}a^3$$

$$= \frac{\sqrt{3}\,\pi}{16}a^3$$

So, it works out to be root 3 pi by 16 a cube. This is the volume occupied by the atoms inside the unit cell and what is the volume of unit cell? a cube.

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$$\frac{\sqrt{3}\,\pi}{16} \simeq 34\%$$

So, the area, the volume that is occupied by the atoms inside the crystal with respect to the total crystal volume is simply root 3 pi by 16, which is about 34%; root 3 pi by 16 works out to be about 34%. Let us for a moment think about a simple fcc lattice, face centered cubic lattice. We have seen that for a zinc blende structure, the packing density is 34%. That is 34% of the total unit cell volume is occupied by the atoms. Now, if you compare it with a face centered cubic lattice, is this packing density more or less? Think about a face centered cubic lattice. You can have it here, just ignore the blue balls.

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We will have a face centered lattice. So, the nearest neighbour is this with this.

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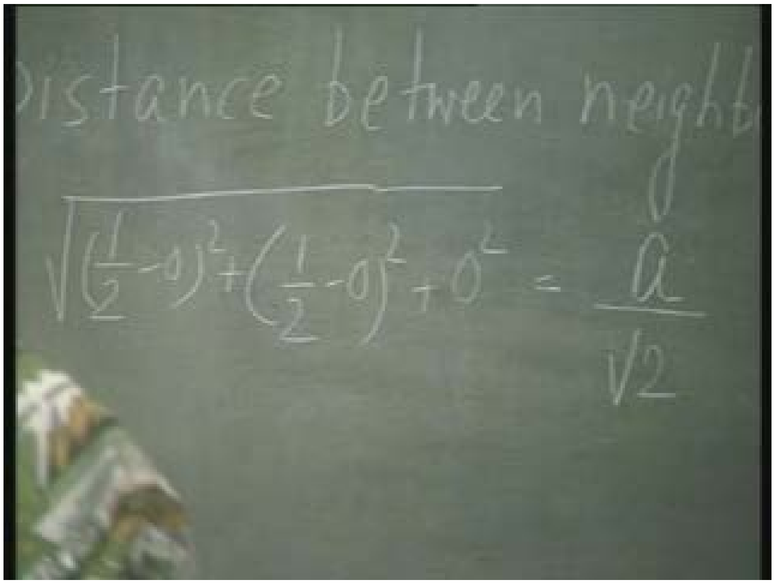

Distance between neighb

$$\sqrt{\left(\frac{1}{2}-0\right)^2+\left(\frac{1}{2}-0\right)^2+0^2} = \frac{a}{\sqrt{2}}$$

So, the distance between the nearest neighbours can be calculated to be .... It is actually .... Right? So, this works out to be and if I consider the crystal lattice to be a, then this is actually a by root 2 and in the fcc lattice, you do not have this interpenetrating second sub lattice atoms. Therefore the total number of atoms present inside is only 4. So, the volume that is occupied will be .....

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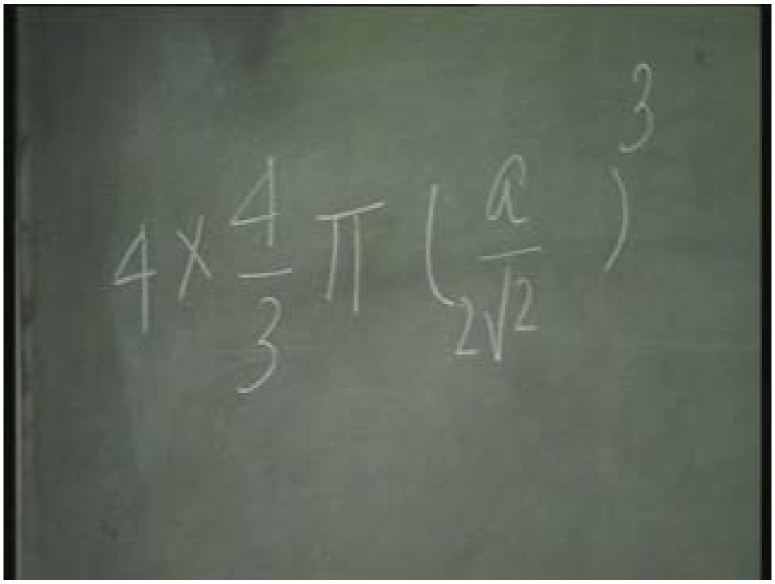

$$4\times\frac{4}{3}\pi\left(\frac{a}{2\sqrt{2}}\right)^3$$

The distance between the nearest neighbors is a by root 2. Therefore the tetrahedral radius can be a by 2 root 2 and I have only 4 spheres, 4 such spheres. Therefore, the total volume that is occupied is only this much; 4 into 4 by 3 into pi into a by 2 root 2 cube.

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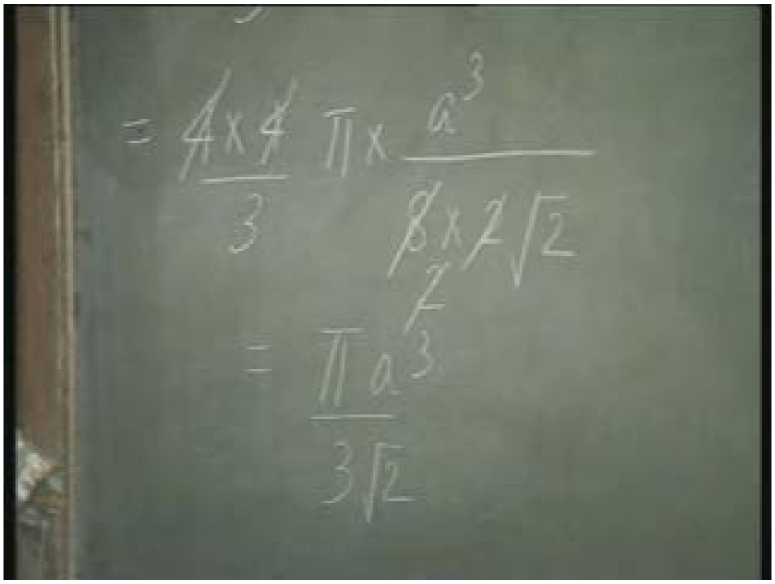

$$= \frac{\cancel{4}\times\cancel{4}}{3}\pi\times\frac{a^3}{\underset{\cancel{2}}{\cancel{8}}\times\cancel{2}\sqrt{2}}$$

$$= \frac{\pi a^3}{3\sqrt{2}}$$

So, this works out to be or the percentage of volume that is occupied that is going to be simply pi by 3 root 2.

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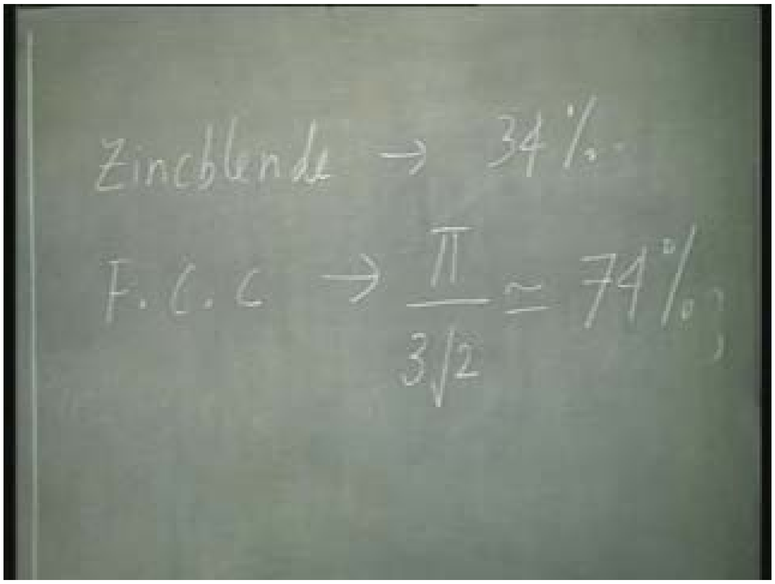

Zincblende → 34%

$$\text{F.C.C} \rightarrow \frac{\pi}{3\sqrt{2}} \simeq 74\%$$

This actually works out to be more than 70%. So, you see, compared to a zinc blende structure, an fcc lattice is much more densely packed. The packing density is much higher for a face centered cubic lattice compared to a zinc blende structure. Now, when you try to dope silicon that is we would like to introduce impurity atoms inside the silicon crystal and these impurity atoms, you know, should replace the silicon atoms. So, one of this positions, one or many of this positions should be taken off by the impurity atoms. It should push the silicon atoms out and take that position instead, right. Incidentally, this is called a substitutional kind of introduction, that one impurity atom it goes and substitutes one silicon atom.

Now, silicon has a particular tetrahedral radius. Just now we have said that it has a lattice constant of 5.43 and therefore its tetrahedral radius works out to be 1.18 angstrom. The impurity atom may or may not have the same tetrahedral radius. Yes? So, what will happen? If it does not have the same tetrahedral radius, then you can introduce strain in the lattice. The lattice will be strained. This is a very important consideration. If the tetrahedral radius of the impurity atom differs considerably from that of silicon, then the lattice will be under a lot of strain and this will eventually dictate the amount of electronic activity.

Now, what do I mean by electronic activity? Suppose you are introducing impurity atoms inside silicon. They will be electronically active only when they have occupied the proper positions in the lattice that is when they have substituted for silicon. Otherwise most likely they will not be electronically active. They might be precipitated, they might stay in the interstitial points. So, they will not be electronically active. So, you can keep on putting a lot of impurity. You can try to put a lot of impurity inside the silicon, but finally the carrier concentration that will not be at par with the amount of impurity that you have introduced. This is what we mean by electronic activity. All the impurity atoms you have put inside the silicon may not be electronically active and the difference in the tetrahedral radius will dictate to a large extent as to how much electronically active a dopant material is going to be. I have the tetrahedral radii of a few common dopant impurities in silicon.

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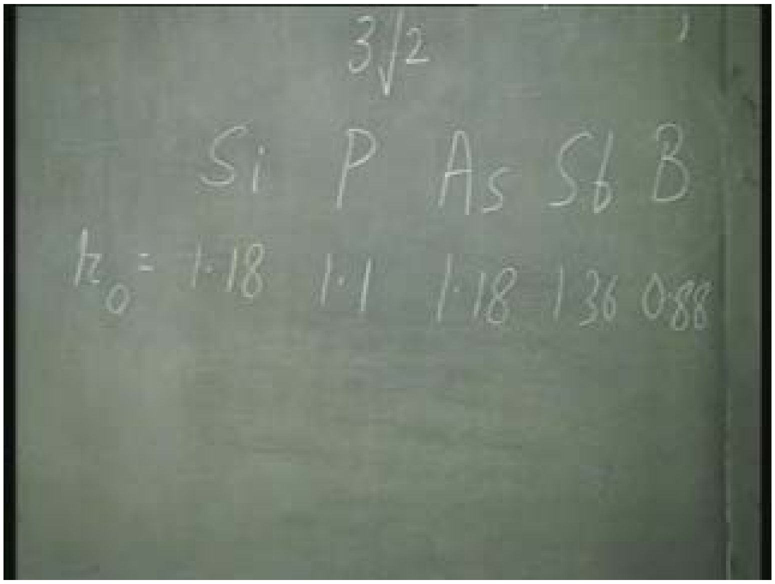

So, silicon, phosphorus, arsenic, antimony and boron. For silicon it is 1.18. For arsenic also this is 1.18. For phosphorus this is 1.1, for antimony this is 1.36 and for boron this is only 0.888. In this context, we also define a term called the misfit factor, which is denoted usually by the symbol epsilon. We define the radius, the tetrahedral radius of the impurity atom as r 0 into 1 plus epsilon.

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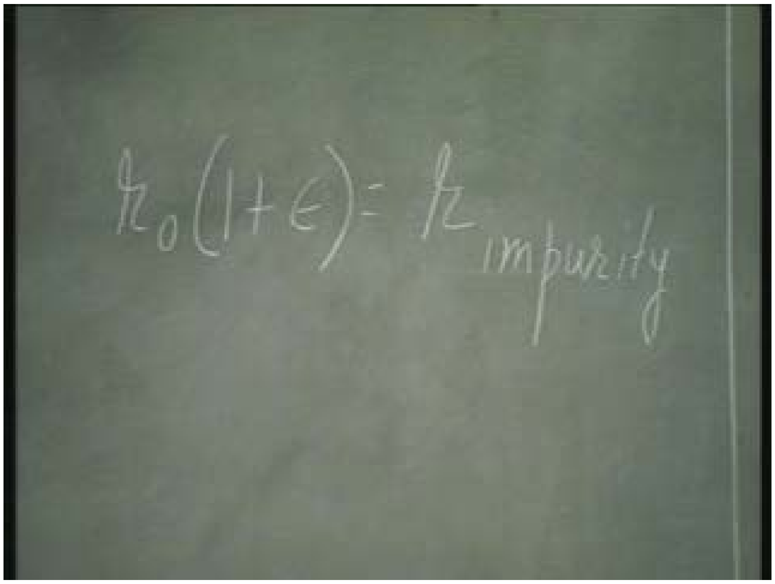

r 0 is the tetrahedral radius of silicon, epsilon is the misfit factor and r impurity is the tetrahedral radius of the impurity atom. So, we co-relate the two tetrahedral radii by the misfit factor and obviously from this, you can see that the misfit factor is going to be very large for boron, because the tetrahedral radius of boron differs maximum from that of silicon.

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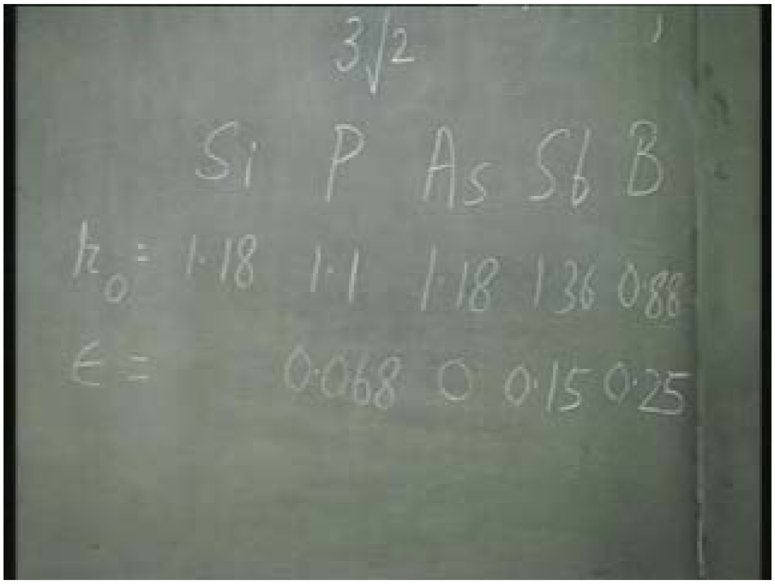

$3\sqrt{2}$

	Si	P	As	Sb	B
r_0 =	1·18	1·1	1·18	1·36	0·88
ϵ =		0·068	0	0·15	0·25

So, epsilon for boron is actually 0.25, for arsenic on the other hand it is zero. They have the identical tetrahedral radii. For phosphorus also it is pretty small and it is about 0.068, for antimony it is about 0.15. This brings us to a very interesting point. Boron is a Group III element. So, we need boron in order to dope the silicon, p-type. You see, unfortunately the tetrahedral radius of boron differs considerably from that of silicon, so that the misfit factor is actually the largest among all. On the other hand the Group V elements, particularly arsenic and phosphorus, they have zero or very small misfit factors. Think of what I said about electronic activity. The misfit factor is going to determine the electronic activity. The larger the misfit factor, the more difficult it is going to be to make the dopant electronically active. Yes?

So, you see, it is more difficult to heavily dope silicon p-type, because boron has such a large misfit factor. It is more difficult to have a heavily doped p-type region in silicon compared to an n plus region in silicon. Corollary - it is easier to fabricate an npn transistor than a pnp transistor. Why? Because in an pnp transistor, the emitter needs to be p-type. The emitter is the most heavily doped region, should be the most heavily doped region in the transistor and since we use boron for doping it p-type, it is going to be more difficult to have, to achieve very high doping concentration, very high carrier concentration, not just doping concentration, electronically active dopant that is high carrier concentration, if you are going to have a pnp transistor. This is one of the various reasons why, for integrated circuit we prefer to use npn transistor wherever possible rather than pnp transistor. There are various other reasons why you prefer npn transistor, but one of them is related to the lattice constant and misfit factor of silicon and boron. So, now you know about the crystal structure of silicon, about the packing density of the particular zinc blende structure and about the misfit factors.

Next, let us concentrate on the crystal planes that is the crystal orientation. We mentioned that for a certain particular applications, we prefer certain planes. Why is it so? Let us first look at some of the common crystal planes.

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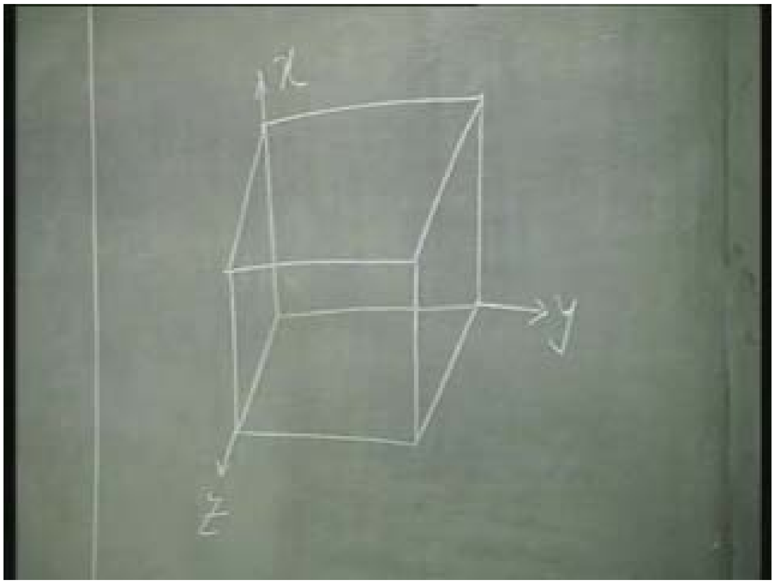

This is a crude sketch of the unit cell. I have just drawn the cubic structure, I have not drawn the atoms, okay. Now, a plane is actually, you know, defined by the intercepts on the three axis x, y and z axis. You have considered that this is the x-axis, this is the y-axis and this is the z-axis.

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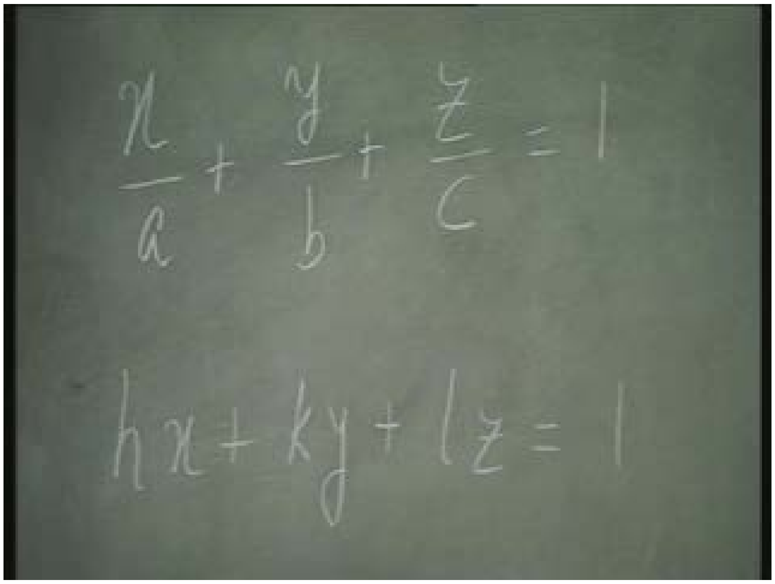

$$\frac{x}{a} + \frac{y}{b} + \frac{z}{c} = 1$$

$$hx + ky + lz = 1$$

So, a plane is actually defined by this equation that is where a, b, c are the intercepts made by the plane on x, y and z axis respectively. I can also define this plane as hx plus ky plus lz is equal to 1, where h, k, l are the reciprocal of the intercepts.

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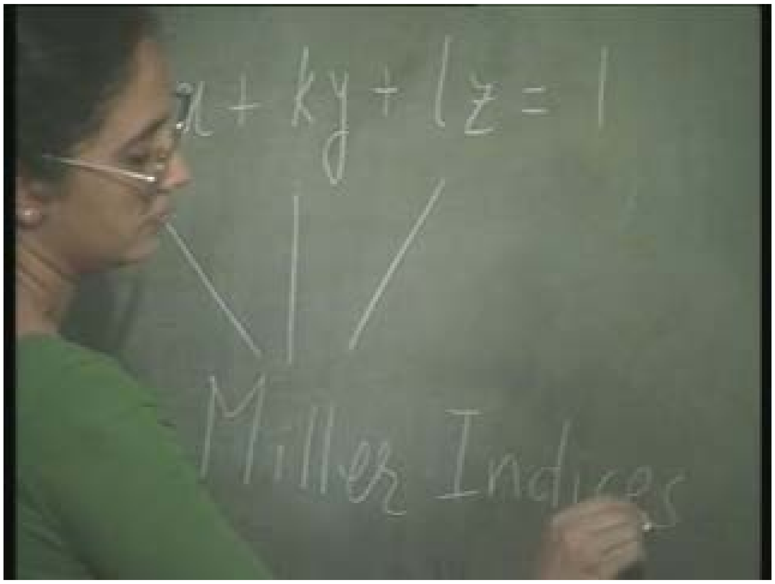

These h, k, l are referred to as the miller indices and the planes are commonly referred to by this miller indices; h, k, l values that actually defines the plane.

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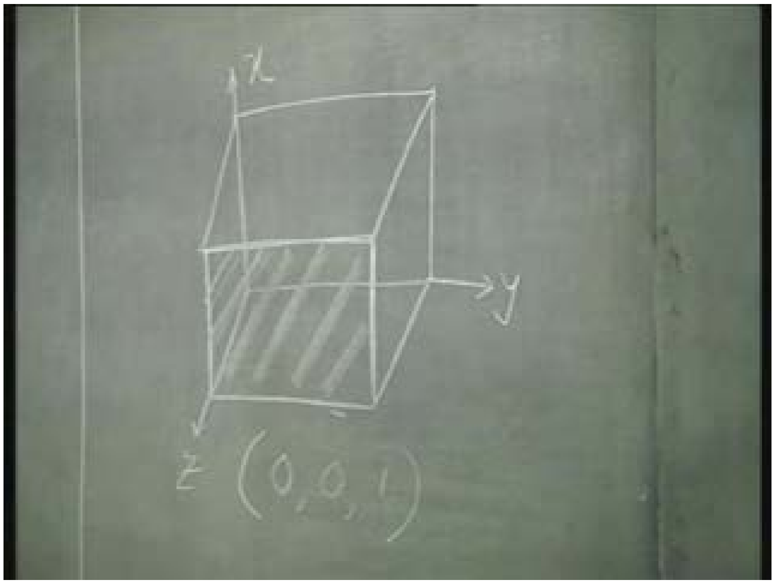

Coming back to this diagram, let us consider this plane, this plane or this plane, you could say. On the board you can see this is the plane. This makes an intercept on the z-axis and it is parallel to both x and y axis. That is its intercepts on the x and y axis will be infinite. What is this plane called? This plane is therefore called, its z- axis intercept is 1; the reciprocal of 1 is also 1. Its x- axis intercept is infinite, reciprocal of that is zero and its y-axis intercept is also infinite, the reciprocal of this is zero.

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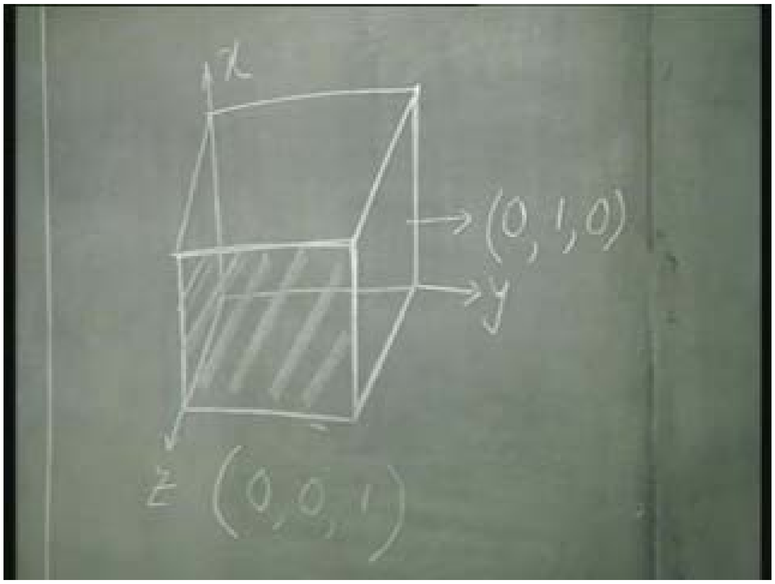

Let us take this plane. This makes an intercept on the y-axis alone. So, this plane will be called 0 1 0. Its y-axis intercept is 1, its x and z-axis intercepts are both infinite, therefore, this plane will be called 0 1 0. Similarly you can take the top plane and you can see that this is actually 1 0 0.

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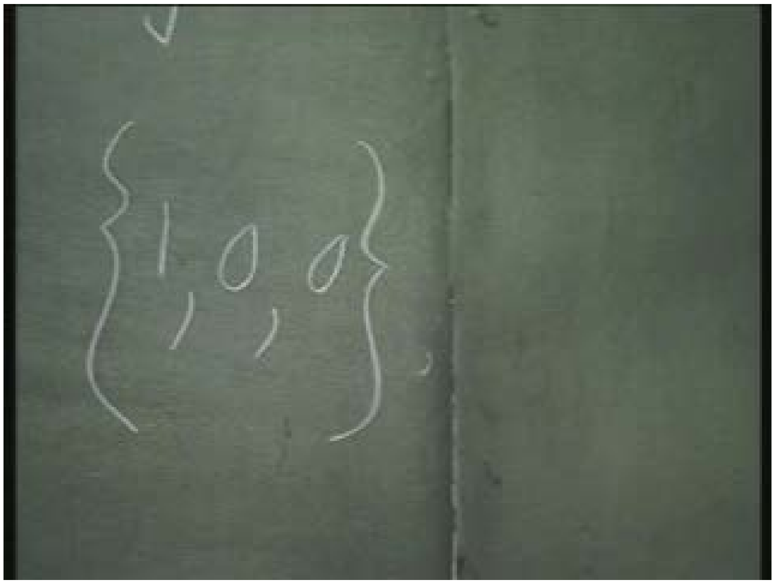

The entire family of such planes which makes intercept only on one axis and are parallel to other two axis will be given as, notice the difference. When I put them inside the first bracket, I am being specific. I am specifically telling what this particular plane is. When I am putting the miller indices inside the second bracket, I am referring not to one particular plane, but to a class of planes which makes collectively all those, make intercepts only on one axis and are parallel to the other two axis. They are referred to as 1 0 0 planes.

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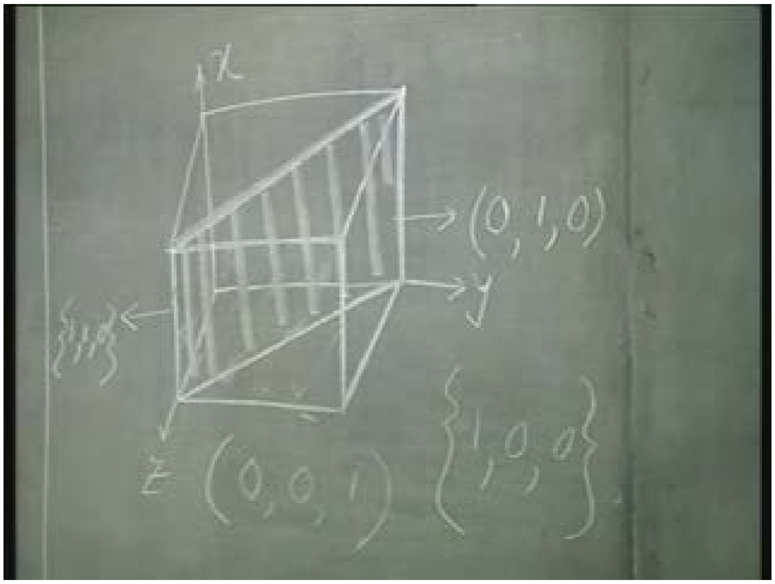

Similarly, I can think of a plane going like this and this plane will be one in the family of 1 1 0 planes, 1 1 0 planes. So, this plane will be belonging to the family of 1 1 0 planes.

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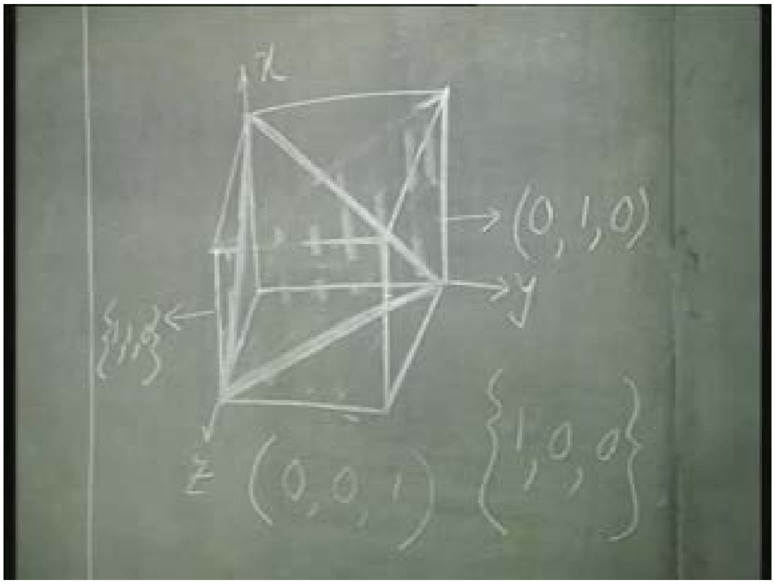

Similarly I can even think of another plane like this, a triangular shaped plane and this plane you can see makes intercepts all the three axis and therefore this belongs to the family of 1 1 1 planes. So, they are the three basic families of planes we need to discuss when discussing the crystal orientation of silicon. They are 1 0 0, 1 1 0 and 1 1 1. Depending on the particular plane, the properties of the material will differ and in the next class we will see how the properties of the material is going to depend on the particular crystal plane.