Processing of Semiconducting Materials
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Lecture - 23
Molecular Beam Epitaxy- II

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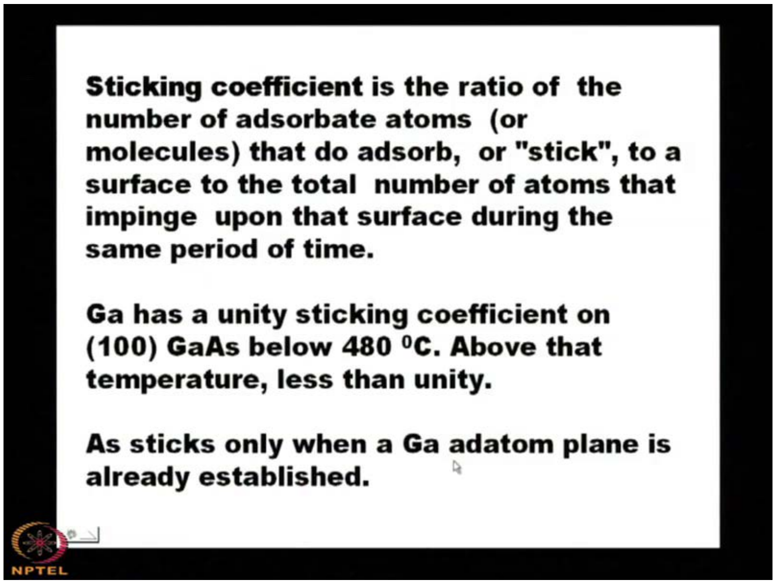

Sticking coefficient is the ratio of the number of adsorbate atoms (or molecules) that do adsorb, or "stick", to a surface to the total number of atoms that impinge upon that surface during the same period of time.

Ga has a unity sticking coefficient on (100) GaAs below 480 ^{0}C. Above that temperature, less than unity.

As sticks only when a Ga adatom plane is already established.

We are talking about the sticking coefficient and we find that for gallium arsenide growth, the sticking coefficient of gallium is unity below 480; that means if you grow at 480 degree centigrade or less then that the gallium arsenide sticking coefficient is 1.

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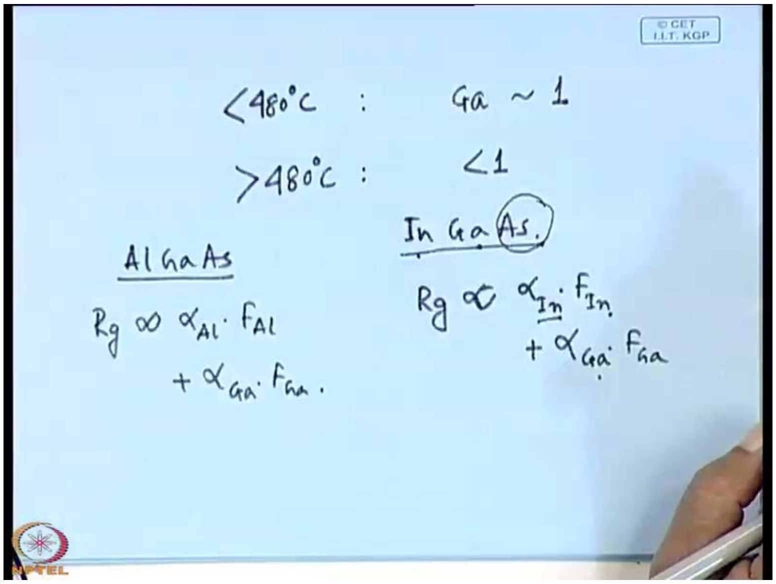

$< 480°C$: Ga ~ 1

$> 480°C$: < 1

AlGaAs

$R_g \infty \alpha_{Al} \cdot F_{Al} + \alpha_{Ga} \cdot F_{Ga}$.

InGaAs.

$R_g \propto \alpha_{In} \cdot F_{In} + \alpha_{Ga} \cdot F_{Ga}$

Now, if you grow above 480 degree centigrade you will find that it is less than 1; less than 1 means depending on the temperature it can be 0.5, 0.6, 0.7, 0.8, 0.9, etcetera. That means it has very good sticking coefficient and arsenic sticks only when a gallium adatom plane is already established.

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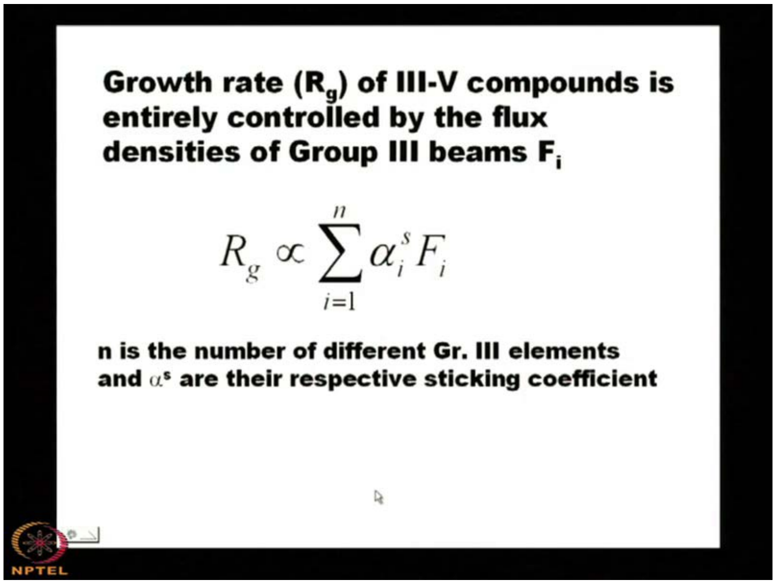

Growth rate (R_g) of III-V compounds is entirely controlled by the flux densities of Group III beams F_i

$$R_g \propto \sum_{i=1}^{n} \alpha_i^s F_i$$

n is the number of different Gr. III elements and α^s are their respective sticking coefficient

Now, the growth rate of 3-5 compounds is entirely controlled by the flux densities of group 3 beams F I; that means Gallium Arsenide, Indium Phosphate, Indium Arsenide, Indium Gallium Phosphate, all 3-5 compounds the growth rate R g you find that is a submission of alpha i s F i. What is i? i is the number of different group 3 elements and F is the flux. Flux that means which are coming out from the oven or the effusion cell that flux.

Now, growth rate is propositional to this means; suppose I want to grow Indium Gallium Arsenide, in that case R g will be propositional to what? R g will be proposition to the stepping sticking coefficient of indium multiplied by the flux of Indium plus sticking coefficient of Gallium multiplied by the flux of Gallium. So that, that is the meaning of this summation that is the meaning of the summation alpha is the sticking coefficient and F is the flux and they are basically the group 3 elements. So if I would like to grow Indium Gallium Arsenide, here group 3 elements are Indium and Gallium. So the sticking coefficient of Indium multiplied by the flux of Indium plus the sticking coefficient of Gallium multiplied by the flux of Gallium. So Arsenic has no role basically in the growth of Indium Gallium Arsenide. So far as the growth rate is concerned, arsenic cannot change the growth rate, growth rate will be governed by the 3 group elements.

Say let us take another example of Aluminum Gallium Arsenide, the growth rate will be propositional to sticking coefficient of Aluminum multiplied by the flux flux of Aluminum plus the sticking coefficient of Gallium multiplied by the flux of Gallium that is all. Arsenic or phosphorus or antimony has no role to determine the growth rate of the 3 5 compound growth rate remember. It is required otherwise no growth will take place but it has no role so far as the rate is concerned.

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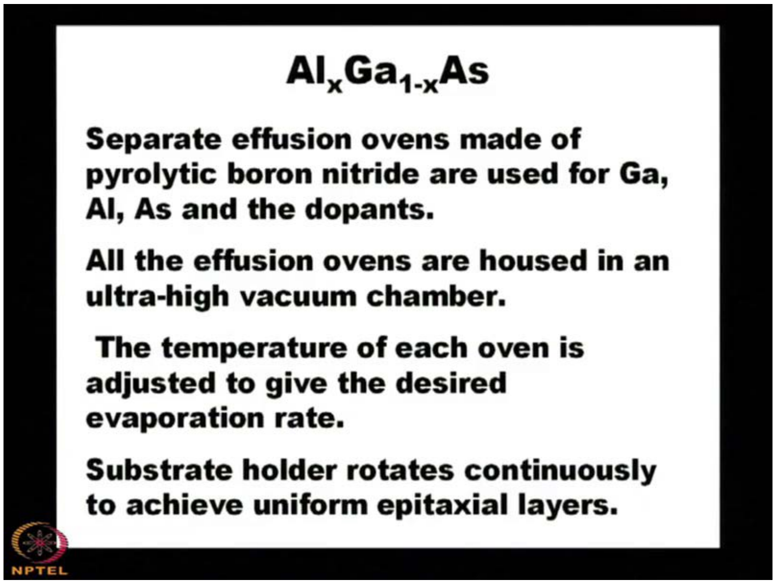

$Al_xGa_{1-x}As$

Separate effusion ovens made of pyrolytic boron nitride are used for Ga, Al, As and the dopants.

All the effusion ovens are housed in an ultra-high vacuum chamber.

The temperature of each oven is adjusted to give the desired evaporation rate.

Substrate holder rotates continuously to achieve uniform epitaxial layers.

For Aluminum Gallium Arsenide growth we have separate effusion ovens made of pyrolytic Boron nitride for Gallium Arsenic and the dopants. What are the dopants? The dopants are Silicon or Sulphur for n type and Zinc for p type or Beryllium for p type; all the effusion ovens are housed in an ultra-high vacuum chamber that we have seen. The temperature of each oven is adjusted to give the desired evaporation rate, because element to element there will be variations, so far as the evaporation rate is constant. You cannot evaporate gallium using the same temperature which you have used for indium or aluminum; if for aluminum it is T 1, then for indium it will be T 2 for gallium it will be T 3 and substrate holder rotates continuously to achieve uniform epitaxial layers. It is continuously rotated, so that the growth becomes uniform in all directions.

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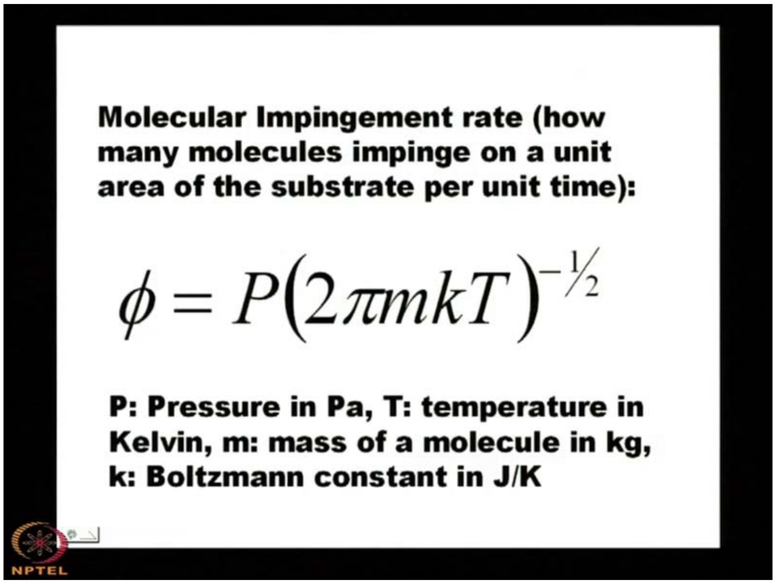

Molecular Impingement rate (how many molecules impinge on a unit area of the substrate per unit time):

$$\phi = P\left(2\pi mkT\right)^{-1/2}$$

P: Pressure in Pa, T: temperature in Kelvin, m: mass of a molecule in kg, k: Boltzmann constant in J/K

Now the most important thing in m b growth is the molecular impingement. What is impingement? Impingement rate is how many molecules impinge on a unit area of the substrate per unit time; remember that per unit area per unit time. How many molecules impinge? Impinge means fall, impinges means falling; it comes in contact with the substrate. So that is very important and that is given by phi equals to P 2 pi m k T to the power minus half; what is P? P is the pressure in Pascal, T is heat temperature in Kelvin, k is the Boltzmann constant joule per Kelvin and small m is the mass of a molecule in k g.

So this is the molecular impingement rate that means; how many molecules impinge on a unit area of the substrate per unit time. Now this impingement rate we can calculate obviously, then the rate if you change with the M that means; the molecular weight it is not the molecular weight. You see that it is a mass of molecule in k g that is m, that we want to converting into M that means; the molecular weight of the atom.

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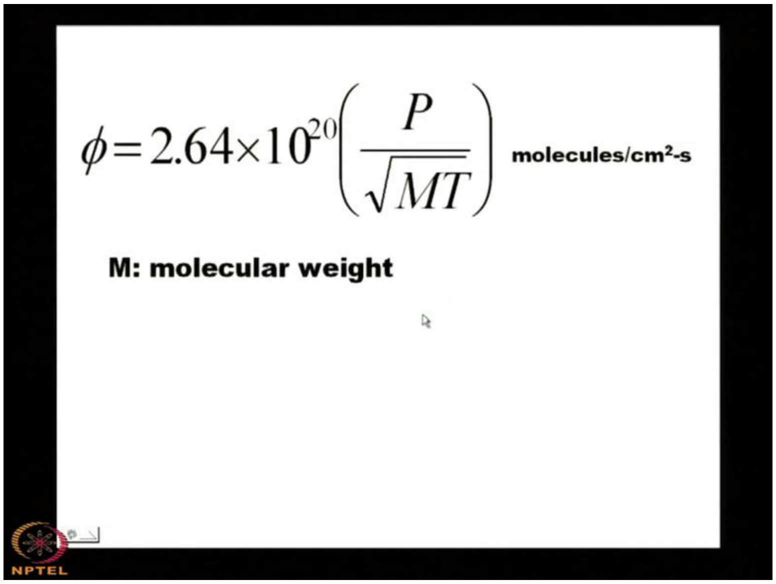

$$\phi = 2.64\times10^{20}\left(\frac{P}{\sqrt{MT}}\right)$$ molecules/cm^2-s

M: molecular weight

So it comes out to be P by root over of M T 2.64 into 10 to the power 20, how it comes? pi is there, k is there and you can convert it to if you put the value of the k etcetera, it comes to be 2.64 into 10 to the power 20 into P by root M T molecules per centimeter square second. That means; per unit area per unit time the number of molecules and M is the molecular weight, T is the temperature in Kelvin and P is the pressure in Pascal. So that is the molecular impingement rate which is very important.

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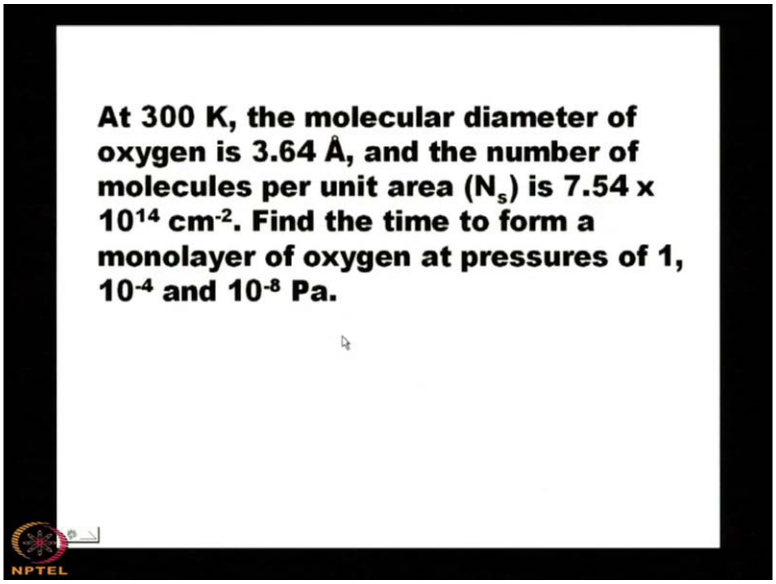

At 300 K, the molecular diameter of oxygen is 3.64 Å, and the number of molecules per unit area (N_s) is 7.54 x 10^{14} cm^{-2}. Find the time to form a monolayer of oxygen at pressures of 1, 10^{-4} and 10^{-8} Pa.

Now you calculate at 300 K the molecular diameter of oxygen is 3.64 angstrom and the number of molecules per unit area is 7.54 into 10 to the power 14 centimeter square inverse. Find the time to form a monolayer of oxygen at pressures of 1 10 to the power minus 4 and 10 to the power minus 8 Pascal. What we want to know? The time to form a monolayer of oxygen and for monolayer it is given that 7.54 into 10 to the power 14 per centimeter square molecules are required and diameter of the molecule is given. Remember that the diameter we need not to use, because if you use this expression, what is required? You require the temperature and m molecular weight and temperature.

Since it is 300 K that is the temperature phase molecular weight; it is oxygen you know, because the pressure is varied past of pressure is 1 Pascal, then 10 to the power minus 4 Pascal, then 10 to the power minus 8 Pascal. So you try to solve this numerical problem, that is very important problem to understand that how the pressure determines the growth. Phi is 2.64 into 10 to the power 20 P by root M T, what is m for oxygen? 32 and temperature T is 300 K. So you put 32 multiplied by 300 root over of keep P as it is because then with that expression; you have to put P 1 10 to the power 4 and 10 to the power minus 8 then what should be the result? You will find that so far as these is concerned I can show you the result.

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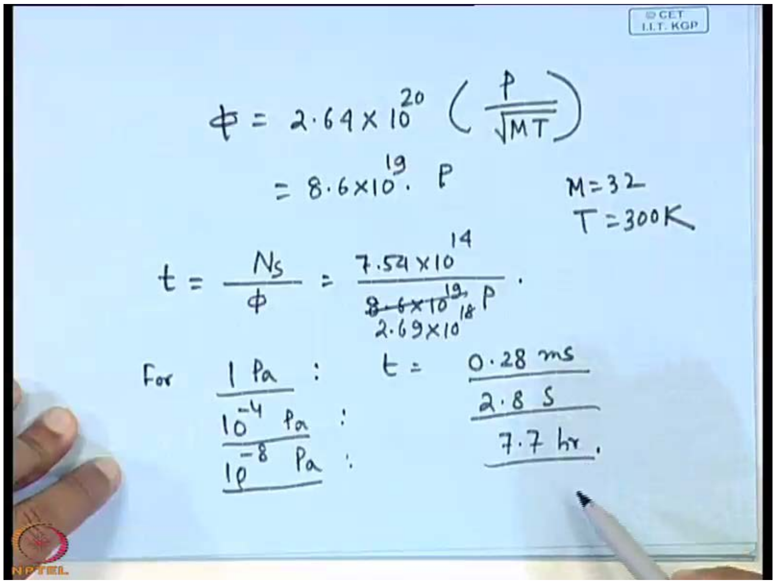

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$$\phi = 2.64 \times 10^{20} \left(\frac{P}{\sqrt{MT}} \right)$$

$$= 8.6 \times 10^{19} \cdot P$$

M = 32
T = 300 K

$$t = \frac{N_s}{\phi} = \frac{7.54 \times 10^{14}}{\cancel{8.6 \times 10^{19}}\, P} \cdot$$

$$2.69 \times 10^{18}$$

For 1 Pa : t = 0.28 ms
10^{-4} Pa : 2.8 s
10^{-8} Pa : 7.7 hr.

Say phi is equals to how much? 2.64 into 10 to the power 20 P by root over of M T. So now you put M and T then tell me what is the value? You just put M and T and tell me what is the value? If M is 32 and T is 300 K then what is the value? What is 8. 8.6 into 10 to the power 19 multiplied by P multiplied by P, then time because in this example you need you see that find the time to form a monolayer, find the time to form a monolayer. So time is t equals to N s by phi N s is given number of molecules per unit area 7.54 into 10 to the power 14.

So if you take this value N s is 7.54 into 10 to the power 14 by phi is 8.6 into 10 to the power 19 P. For 1 Pascal of pressure t will be 0.28millisecond, you can calculate in your home and you will find that t is 0.28millisecond. For 10 to the power minus 4 Pascal it is 2.8 second and for 10 to the power minus 8 Pascal it is 7.7 hour, so what we find? We find that as the pressure increases since the time is inversely propositional to the pressure, time goes out that means; from 0.28millisecond to 7.7 hour. So you find that the growth rate is very, very slow, growth rate is very, very less 7.7 hour from 0.28millisecond, but do not try to grow the epitaxial layer using 1 Pascal of pressure. In m b minimum 10 to the power minus 8 Pascal is required because; ultra-high vacuum conditions must be achieved.

So even that here the 0.28 millisecond dot 2.8 second is required for that kind of a growth, but the growth will not be a good one because you are not achieving the ultra-high vacuum condition. What? 2 point (( )) it is a material because you can always check the absolute value is not important for us. For us the important factor is that, as we go on increasing the back warm the time increases, that is the main theme; that you can check from in your home that is not a major problem.

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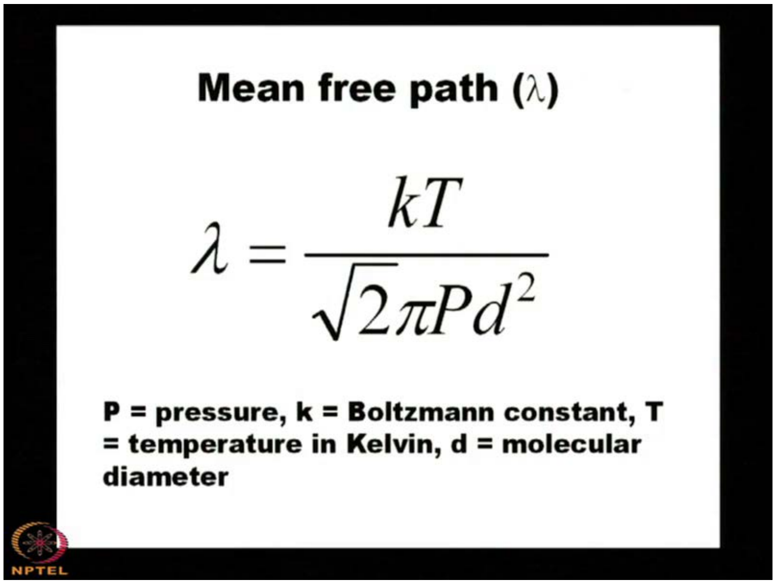

Mean free path (λ)

$$\lambda = \frac{kT}{\sqrt{2}\pi P d^2}$$

P = pressure, k = Boltzmann constant, T = temperature in Kelvin, d = molecular diameter

Now the second important factor is the mean free path that is very important. That the mean free path problem is very important and you see that this so far as the mean free path is concerned.

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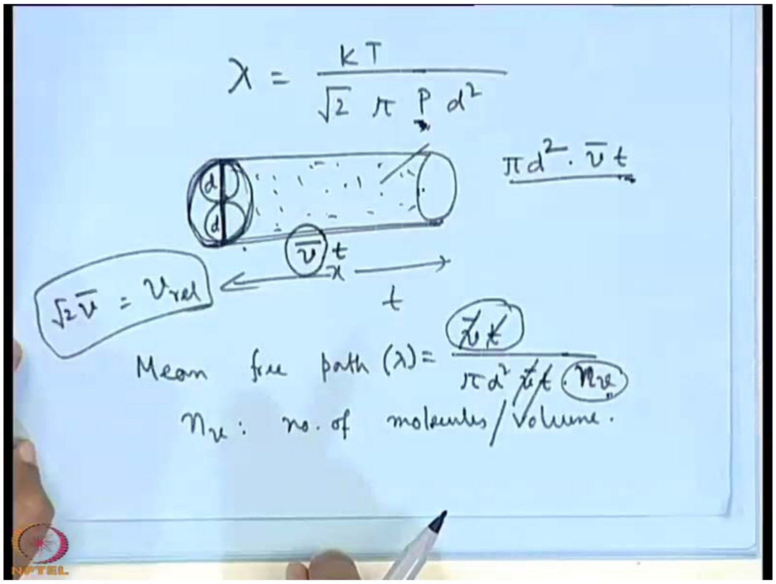

Lambda is the mean free path; it is given by k T by root 2 pi P d square what is K? K is Boltzmann constant, T is the temperature in Kelvin, P is the pressure in pascal and d is the molecular diameter, d is the molecular diameter. This is very important parameter for m b growth, that the mean free path must be as large as possible to avoid any collision from the effusion oven to the substrate, because from the orpheus of the effusion oven to the substrate; the molecules must traverse a distance, finite distance that is a finite distance and it must not be suffering from any collision. Here also you see that, so far as the mean free path expression is concerned, this P is in the denominator. P is in the denominator means to increase lambda P must be small means 10 to the power minus 8, minus 9, minus 7, that type of theme from 1 2. P is 1 say atmospheric, say it must be 10 to the power minus 8; so that will increase manifold.

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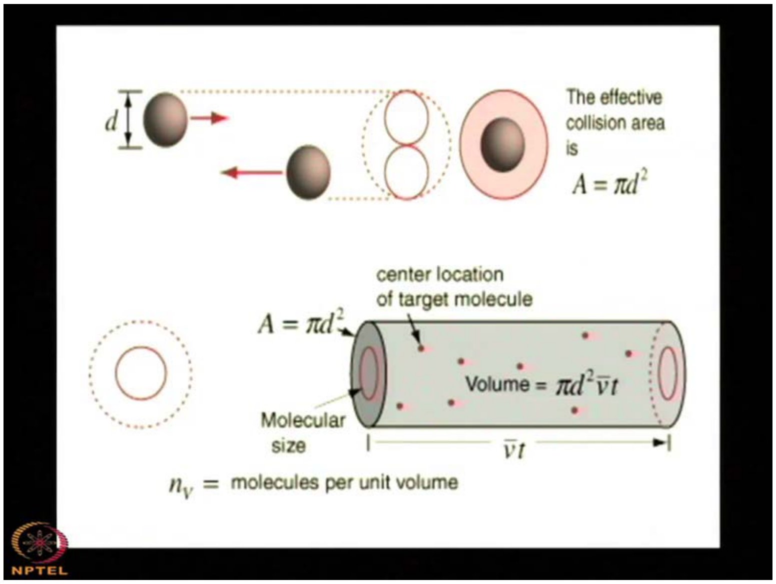

The effective collision area is $A = \pi d^2$

n_V = molecules per unit volume

Now how this mean free path is calculated? How this mean free path is calculated? This mean free path is calculated using the concept of this kind of a modeling. You see that there is a atom of diameter d, so it will collide with another atom, because say these two atoms are there; so any atom which are coming within this range of 2 d diameter will be scattered. This is one atom of diameter d and this is another atom of diameter d, so the total diameter of the system is 2 d. So these 2 d is the new diameter of a theoretical sphere which will moves a up to the distance of x in time t, this will this can move.

So any atom or any species within that area will be scattered by this molecules or atoms. So that is the model that means; these area will be pi d square, this area will be pi d squared and if this is the if the velocity is v bar and time is t. So the distance is v bar into t, so multiplied by v bar t, so that is the volume. So mean free path will be, will be this distance by pi d square v bar t multiplied by n n v; n v is number of molecules per unit volume, n v is the number of molecules per unit volume. Say it is consider the kinetic theory of gas, consider the kinetic theory of gas the all molecules are moving and they are colliding with each other.

So if I consider a time t and the molecules move with a velocity of v bar then at time t it will cross a distance of v bar into t. So that is the distance and number of scattering will be n v is the total number of molecules per volume, what is the volume? Volume is this, volume is this. So if you multiply this volume with the number of molecules per volume. So within that volume, the total number of molecules will be pi d square v bar t multiplied by n v and if you divide v bar t with these thing, you will get what is the value?

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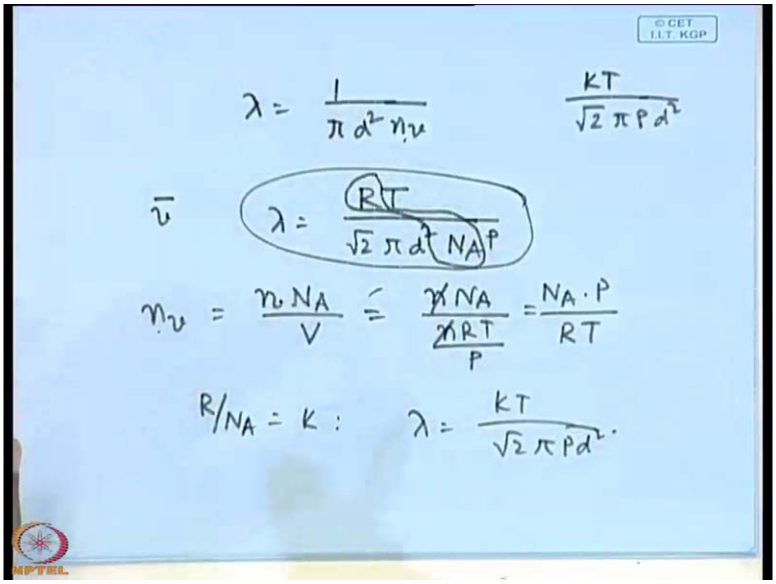

$$\lambda = \frac{1}{\pi d^2 n_v} \qquad \frac{KT}{\sqrt{2}\pi P d^2}$$

$$\bar{v} \qquad \lambda = \frac{RT}{\sqrt{2}\pi d^2 N_A P}$$

$$n_v = \frac{n N_A}{V} = \frac{\cancel{n} N_A}{\frac{\cancel{n} RT}{P}} = \frac{N_A \cdot P}{RT}$$

$$R/N_A = K : \quad \lambda = \frac{KT}{\sqrt{2}\pi P d^2}.$$

The value is obviously; volume of lambda will be 1 by pi d square into n v, 1 by pie d square into n v because you see that this is v bar t v bar t cancels out, so1 by pi d square into n v. But you see that, here we have used a different kind of expression which is given by k T by root 2 pi P d square; so from this expression we have to come to that expression.

Here you see that the mean free path is related to the molecular movement, now what is this v? This v bar is basically you must take the relative velocity of the molecules, why? Because, no molecule is in stationary state, all the molecules are moving. So when i talk about this v bar t, that v bar t is not the actual v bar t it is basically the relative velocity we have to consider and their relative velocity is basically root 2 of v. v bar root 2 will be the relative velocity r e l that you can prove in the text book you have already proved in your b s c classes, the relative velocity is basically root 2 v.

So now the lambda becomes 1 by root 2 pi d square N A p multiplied by R T how? Because, what is n v? n v is equals to n into N A by v, how? From Avogadro hypothesis; n v is small n multiplied by N A by v and that is equals to n into N A by v equals to n R T by P P v equals to n R T, this is equals to N A p by R T. So if you put n v here, you will get this expression, (( )) R by (( )) yes R by N A equals to K. So this R by N A equals to K, so lambda is equals to K T by root 2 pi p d square. I will not ask you in the exam to deduce it, just I am giving you the confidence that the expression are true is not very complicated thing; it comes from mainly the kinetic theory of gas using some Avogadro hypothesis and related equations that you can consider.

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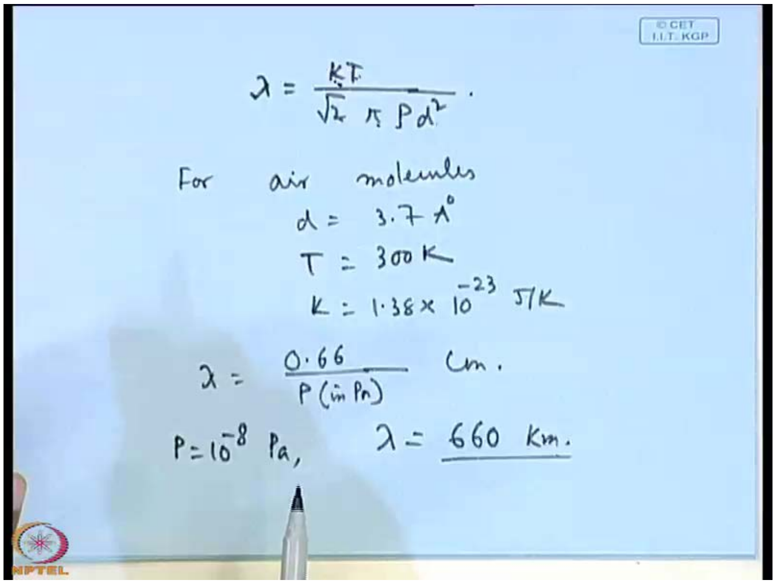

$$\lambda = \frac{KT}{\sqrt{2}\,\pi\,P d^2}.$$

For air molecules

$d = 3.7$ Å

$T = 300$ K

$K = 1.38 \times 10^{-23}$ J/K

$$\lambda = \frac{0.66}{P\ (\text{in Pa})}\ \text{cm}.$$

$P = 10^{-8}$ Pa, $\lambda = 660$ Km.

So that is the thing and you find that lambda is K T by root 2 pi p d square for air molecules, what is d? d is 3.7 angstrom, it is 3.7 angstroms. Then what should be the value of lambda, if you put the values K T d T is 300 k, k is 1.38 into 10 to the power minus 23 Joule per Kelvin. So if you put you will find that, lambda equals to 0.66 by p in Pascal that much Centimeter that means; in this expression I have put the value of k, then T, then root 2 pi, then d square, d is 3.7angstroms this for air molecules then lambda become this Pascal.

So when p equals to 10 to the power minus 8 Pascal what is the lambda? What is the value tell me in kilometer tell me the value in kilometer what is the value of lambda in kilometer? (( )) Yes around 660 Kilometer. So that means what you find? That the mean free path for air molecule at room temperature with a pressure of 10 to the power minus 8 Pascal is very, very high that means; 660 kilometer, what it means? What is the physical implication of this? (( )) Yes 2 air molecules will collide after 660 kilometer not before 660 kilometer. So that means 660 kilometer is free space, free from any collision, it is free space from any collision; so that is very important thing, that the pressure must be very, very high. Under such a situation not that you will avoid the collision at the same time, you will avoid contamination all other remainant gases which are in the gaseous form in the wafer form they will leave. The most of the problem is created by oxygen; it forms oxide, so oxygen is evacuated. So you see that this high lambda, because of the high lambda to achieve 10 to the power minus 8 Pascal of evacuation is required.

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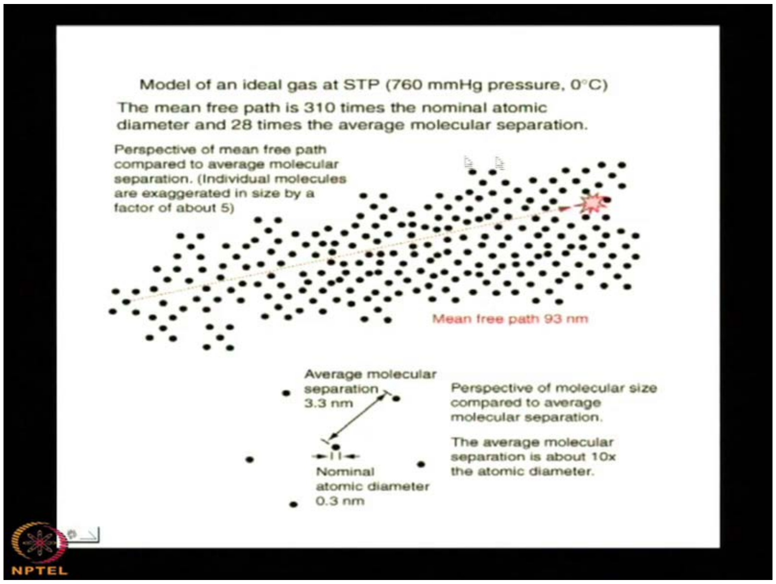

Model of an ideal gas at STP (760 mmHg pressure, 0°C)

The mean free path is 310 times the nominal atomic diameter and 28 times the average molecular separation.

Perspective of mean free path compared to average molecular separation. (Individual molecules are exaggerated in size by a factor of about 5)

Perspective of molecular size compared to average molecular separation.

The average molecular separation is about 10x the atomic diameter.

Here this is one example of an ideal gas at STP that means at 0 degree Centigrade and 760 millimeter of marker pressure. The values are you see that is an example only, this is a molecule of an ideal gas. Its diameter is 0.3 nanometer diameter and average molecular separation is 3.3nanometer; its mean free path you see 93nanometer. 93 nanometer means, its 28 times the average molecular separation and 310 times the nominal atomic diameter is very high basically.

Mean free path is the free space travel by the molecule before successive collisions between 2 collisions, how much it can move without any collision and you see that so far as the atomic dimension of the atoms and molecules are concerned. It is very high, because if the atomic diameter is 0.3nanometer and if it is 93nanometer the mean free path then mean free path is very, very high then the atomic diameter and it is you see there is 310 times in this case not a matter of joke, 310 times. The red line shows that, this atom will collide with this atom after 93nanometer. So this is a model basically with some specific values and this is very important concept in MB growth.

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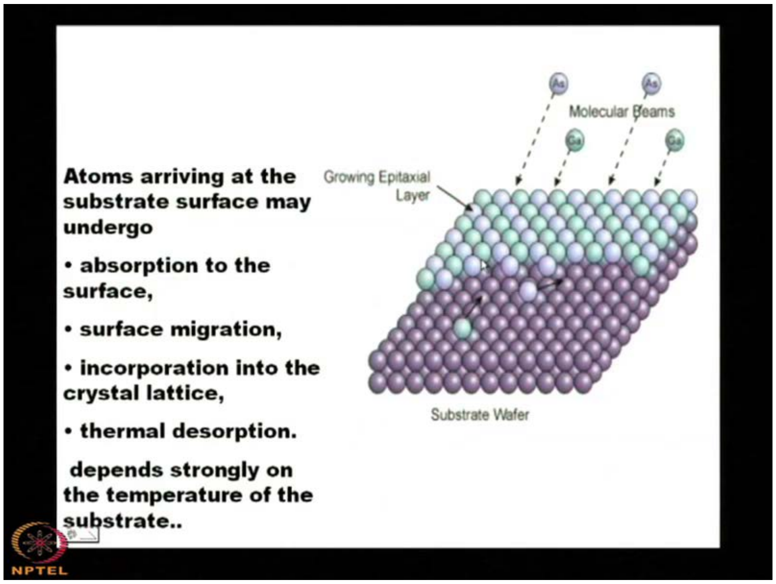

Atoms arriving at the substrate surface may undergo

- **absorption to the surface,**
- **surface migration,**
- **incorporation into the crystal lattice,**
- **thermal desorption.**

depends strongly on the temperature of the substrate..

Here you see that the atoms this blue are the Arsenic atoms, then green are the Gallium atoms and this is layer by layer growth you see this is one layer, this is second layer, then the third layer is being grown. So this is one mono layer, this is second mono layer, this is third mono layer, but it is not complete; so such type of thing is going to happen in m b. First the atoms arriving at the substrate surface will undergo absorption to the surface that means; they will accumulate on the surface.

Then there will be surface migration, say from point a to point b or point b to point c. Incorporation into the crystal lattice, crystal lattice means on the substrate. Then there will be thermal desorption and depends strongly on the temperature of the substrate, one thing is missing with the back warm of the system also it depends strongly, because we have seen that the growth rate is 7.7 hours was required for 10 to the power minus 8 Pascal. Whereas, for 10 to the power minus 4 Pascal the time required was 2.8 second, so it the difference is very, very high.

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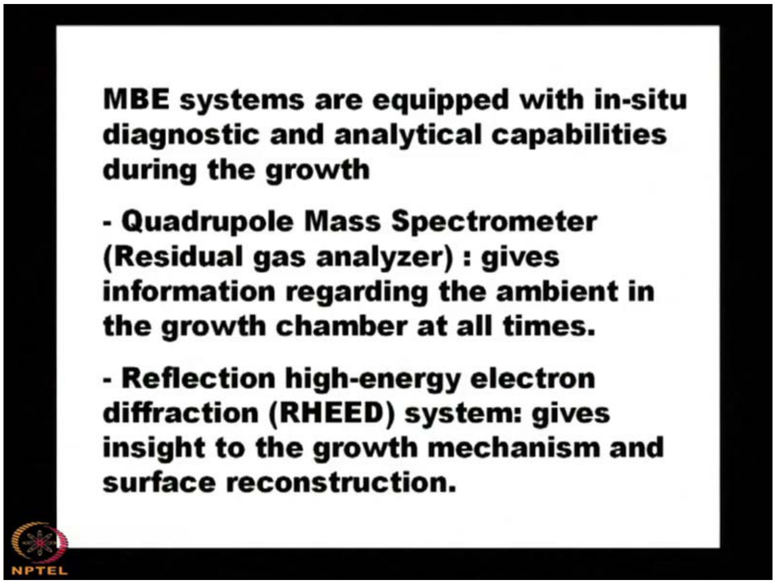

MBE systems are equipped with in-situ diagnostic and analytical capabilities during the growth

- Quadrupole Mass Spectrometer (Residual gas analyzer) : gives information regarding the ambient in the growth chamber at all times.

- Reflection high-energy electron diffraction (RHEED) system: gives insight to the growth mechanism and surface reconstruction.

Now we shall come into that thing that MBE systems are equipped with in-situ diagnostic and analytical capabilities during the growth.

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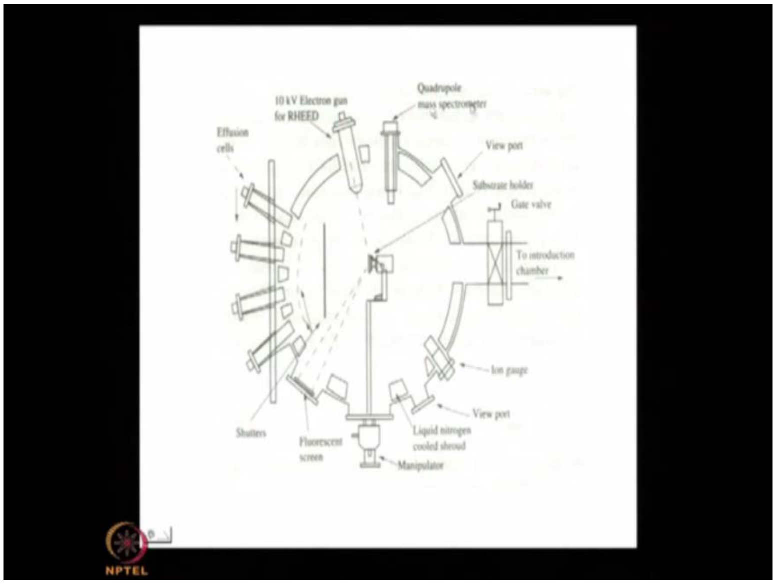

You see that in this figure, I have shown you that mass spectrometer is there and RHEED is there, you see this is mass spectrometer and that is RHEED.

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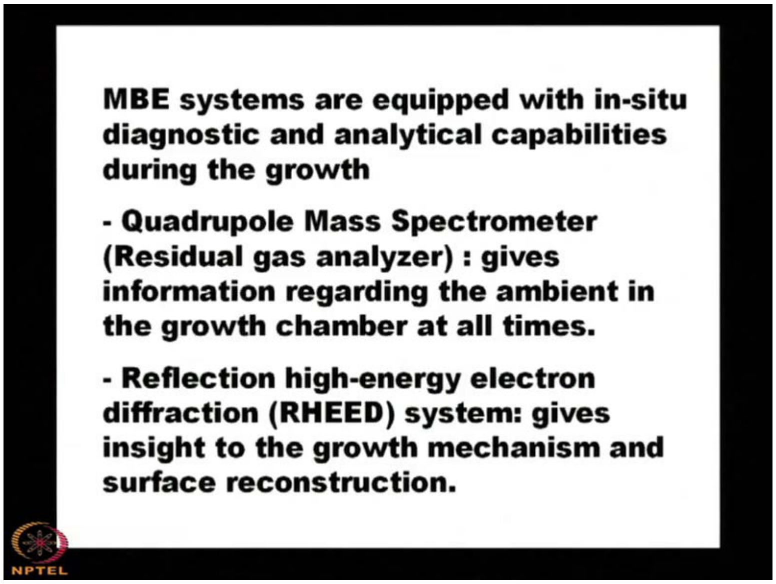

MBE systems are equipped with in-situ diagnostic and analytical capabilities during the growth

- Quadrupole Mass Spectrometer (Residual gas analyzer) : gives information regarding the ambient in the growth chamber at all times.

- Reflection high-energy electron diffraction (RHEED) system: gives insight to the growth mechanism and surface reconstruction.

So now we shall come into those accepts of the MBE growth that, two important equipments are or accessories are there in the MBE system attached attachments are there; one attachment is the quadrupole mass spectrometer or residual gas analyzer: gives information regarding the ambient in the growth chamber at all times. Ambient in the growth chamber means; the chemical composition gasses inside the growth chambers. So that means if you want to know the carrier concentration, if you want to know the chemical composition weather it will be aluminum 0.3 or 0.38 that I have mentioned. It will be analyzed by the mass spectrometer or the gas analyzer it is in-situ. Another is the reflection high-energy electron diffraction or in short it is known as RHEED R h double e d reflection high-energy electron diffraction system: it gives insight to the growth mechanism and surface reconstruction; it is basically related to the surface morphology.

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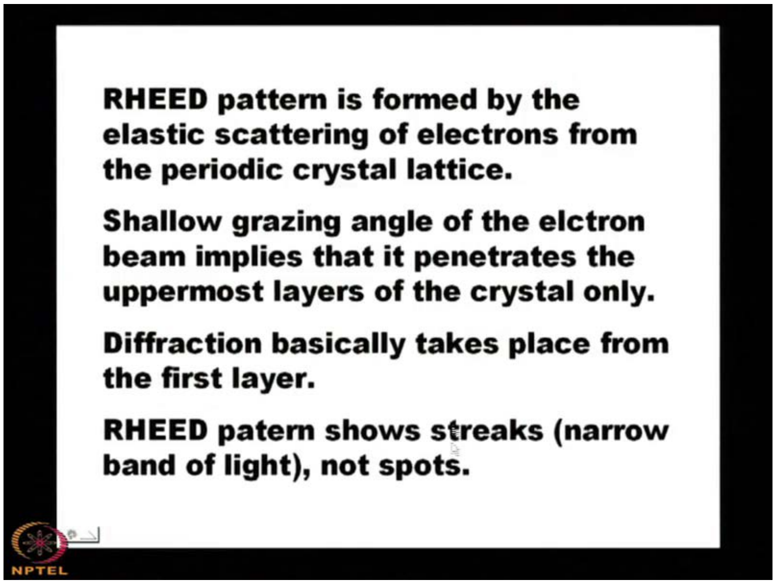

RHEED pattern is formed by the elastic scattering of electrons from the periodic crystal lattice.

Shallow grazing angle of the elctron beam implies that it penetrates the uppermost layers of the crystal only.

Diffraction basically takes place from the first layer.

RHEED patern shows streaks (narrow band of light), not spots.

RHEED pattern is formed by the elastic scattering of electrons from the periodic crystal lattice; when the epitaxial layer is grown it is single crystal layer, if it is epitaxy. So from the periodic potential if it is a crystalline structure then what should be the potential of the crystal structure? Periodic potential, it will be periodic potential, because periodicity is maintained in the single crystal. So the electrons are scattered from the periodic potential so that that elastic scattering of electrons from the periodic crystal lattice that pattern is given by the RHEED.

The grazing angle of the electron beam is shallow very small some theta degree 2 degree, 5 degree, 10 degree grazing angle of the electron beam. It implies that it penetrates the uppermost layer of the crystal only, it is not the normal incidence; normal incidence means it is 90 degree. So if it is a normal incidence it penetrates deep inside the bulk, but grazing angle means; it is confine to the top most layer or the surface layer only that is the grazing angle and it penetrates only the upper most layers of the crystal. Diffraction basically takes place from the first layer because of the grazing incidence; it will not penetrate deep inside the material only 1 or 2 layers will be scanned. RHEED pattern shows streaks not spots, streaks means; narrow band of light streaks, this type of streaks will be there not spot.

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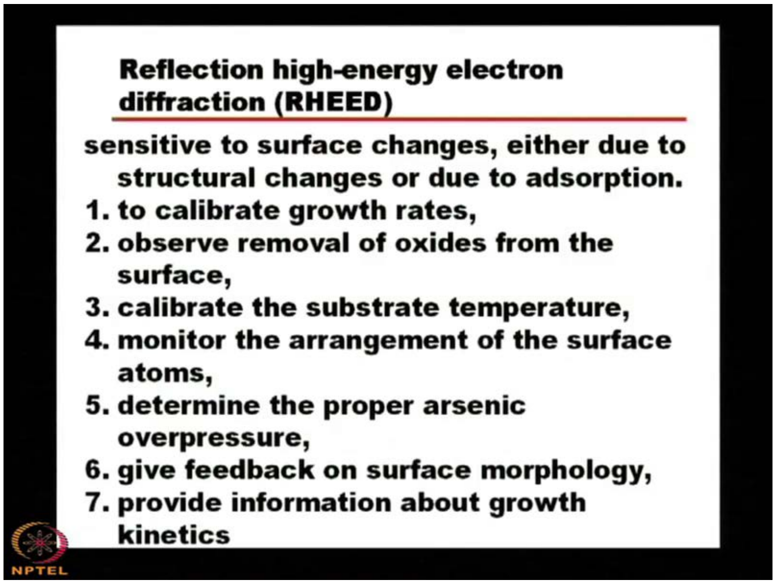

Reflection high-energy electron diffraction (RHEED)

sensitive to surface changes, either due to structural changes or due to adsorption.

1. to calibrate growth rates,
2. observe removal of oxides from the surface,
3. calibrate the substrate temperature,
4. monitor the arrangement of the surface atoms,
5. determine the proper arsenic overpressure,
6. give feedback on surface morphology,
7. provide information about growth kinetics

From the RHEED many things you can learn, many things you can understand of the growth. Sensitive to surface changes, either due to structural changes or due to adsorption; when there is a change in adsorption pattern that means the chemical composition will be changed. To calibrate growth rates you can calibrates growth rates, observe removal of oxides from the surface; calibrate the surface temperature, monitor the arrangement of the surface atoms. Determine the proper arsenic over pressure because when gallium arsenide grow arsenic well pressure must be there because even at 480 degree centigrade growth temperature arsenic will evaporate from the substrate surface so it must be grown using arsenic over pressure. Give feedback on surface morphology, provide information about growth kinetics.

So all these seven important aspects of the growth; can be monitored using this RHEED spectroscopy that is very important. You see that number point number 2 is observe removal of oxides from the surface, what is this? Observe removal of oxides from the surface, what is this? What is that removal of oxide? Because you see, that when we grow something; when we take the substrate or the wafer. Obviously there must be an oxide layers on it that I have mention and why there is an oxide layer? Because of the dangling bonds unsaturated bonds are there because of the abrupt termination of the crystal because when we talk about an wafer of a substrate basically it is a piece from the bulk crystal. So when you cut a portion of it, that bond is terminated.

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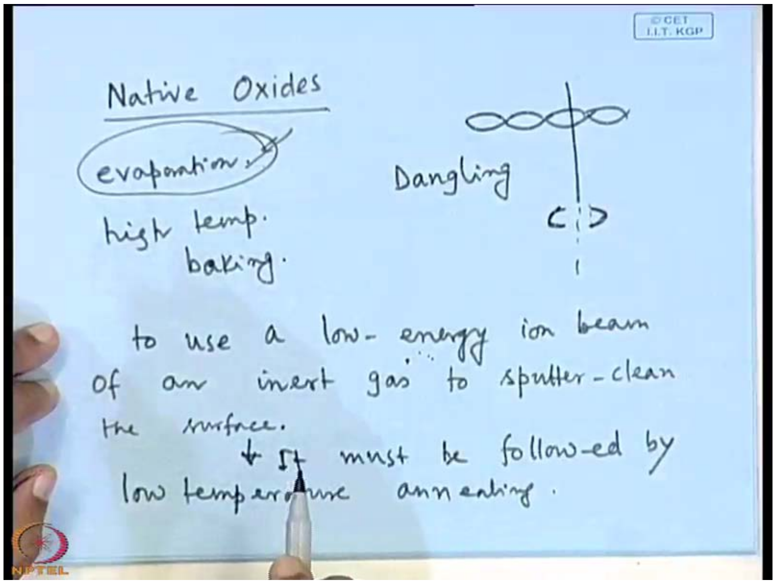

Native Oxides

evaporation

high temp. baking.

Dangling

to use a low-energy ion beam of an inert gas to sputter-clean the surface.

It must be follow-ed by low temperature annealing.

Say this is this as a bond you break here, so it is terminated; so it becomes like this. So this surface this is unsaturated bond on the surface there is unsaturated bond. So there on the both the pieces there will be unsaturated bonds, that is known as the dangling bonds, dangling bonds and dangling bond are varies prom to oxygen. Even trace amount of oxygen if it gets (( )) yes, the surface becomes oxidized, because of the dangling bonds. So that that oxygen or the oxide layer from the substrate be its Silicon or Gallium Arsenide or Indium Phosphate. That oxygen layer or oxide layers can be removed before the growth it must be removed, before the growth it must be removed. You can remove it by aching that is chemical that is chemical aching, some acid treatment you can use to ache the oxide layer but there can be dry aching also.

Using m b e dry aching can be possible, dry aching can be possible means high temperature baking what is baking? What is baking? Where the baking is used (( )) yes for for the preparation of cakes not fabrication cake cannot be fabricated. So so at high temperature baking, you can bake the substrate at high temperature to remove the oxide or you can use some inert gas ions; because you see it is a high back warm system. So you can use argon or that type of inert gas make it ion and then bombardment of the substrate. So due to the bombardment of the substrate by the chemically inert ions, oxides will be removed or aged. So that removal of oxides from the surface.

So now how to remove the oxide you see that native oxides can be decomposed and it can remove the other one is evaporation high temperature baking, one is high temperature baking. So that the native oxide or the other things can be evaporated, it is by h method of evaporation. If you bake it will evaporate and pressure is very ultra high vacuum is there, so it will go away as soon as it will be evaporated it will go away; so one is the high temperature backing.

Another approach is to use a low energy ion beam of an inert gas to sputter-clean the surface. To use a low energy ion beam of an inert gas to sputter clean the surface, remember that when we sputter something whatever be the energy I am I have written that it is a low energy. So there will be deformation of the surface, so that means you have to make some low temperature annenling; that we have mention during our discussion on diffusion an ion implantation.

You can remember the during our discussion on diffusion an ion implantation we have use the term it must be followed by, it must be followed by low temperature annenling. What is the job of this annenling? To re arrange, to reconstruct the crystal lattice disorder, because when there will be some sputtering or implantation. So the substrate will be deformed, some crystal damage will be there to make it order there will be some low temperature annenling.

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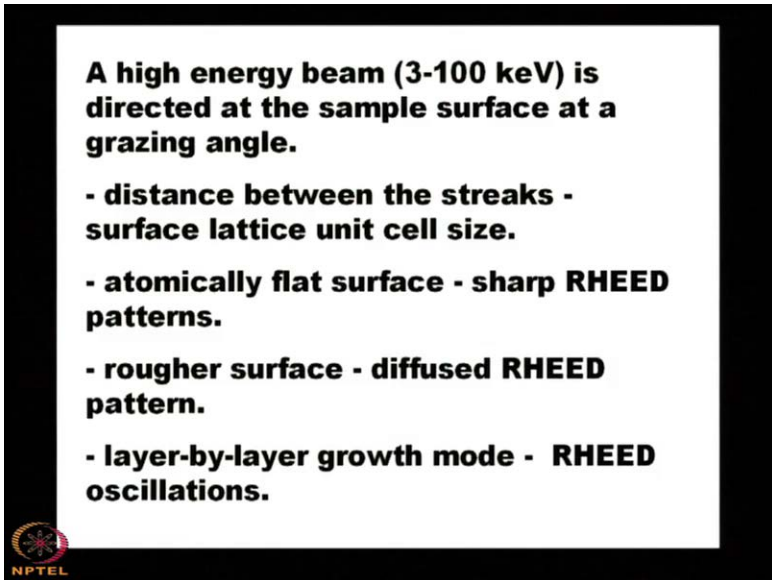

A high energy beam (3-100 keV) is directed at the sample surface at a grazing angle.

- **distance between the streaks - surface lattice unit cell size.**
- **atomically flat surface - sharp RHEED patterns.**
- **rougher surface - diffused RHEED pattern.**
- **layer-by-layer growth mode - RHEED oscillations.**

That is very important thing and generally for RHEED R H double E D 3 to 100 k e V high energy beam, electron beam is directed with a small angle grazing angle to the substrate surface; you see this is the incident electron beam, this is the sample. So it is grazing angle diffraction and this is that you see, that the screen phosphorus screen where the sticks are obtained. This is the streaks 1, 2, 3, 4, 5 this streaks are obtained; so that is the monitor or a screen which is attach to the MBE system to see the screen, to see the structure or the surface of the sample and you see that sharp RHEED patterns are obtained when atomically flat surface is there, if your substrate, if your epitaxial layer is atomically flat then sharp RHEED patterns will be there.

If rougher surface is there then diffused RHEED pattern will be there and layer by layer growth mode, if there more than one layer; say super lattice many layers are there quantum in many multi quantum in many layers are there, layer by layer growth; then you will get RHEED oscillations and from the frequency of the oscillations you will you can determine the thickness of the layers.

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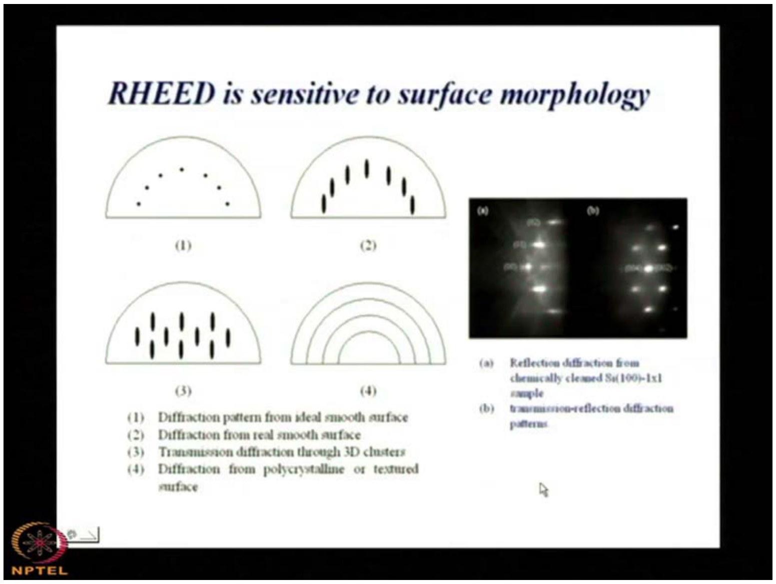

RHEED is sensitive to surface morphology

(1) Diffraction pattern from ideal smooth surface
(2) Diffraction from real smooth surface
(3) Transmission diffraction through 3D clusters
(4) Diffraction from polycrystalline or textured surface

(a) Reflection diffraction from chemically cleaned Si(100)-1x1 sample
(b) transmission-reflection diffraction patterns

You see these are the streak patterns number 1; this is diffraction pattern from ideal smooth surface. Here you see real smooth surface this is some bordering is there, it is all all almost spotted dot like of things, the spots here it is a streak type of spots and if it is a 3 d plaster not layer only plasters are formed; then the sticks will fallow this type of a pattern and if it is a polycrystalline not a single crystal substrate a substance or epitaxial growth, then this pattern will be like this. So from the pattern of this RHEED you can inform that how your subs how your epitaxial layer looks like yes, (( )) one streaks is (( )) basically it is the grazing angle is, so you see that the angle is so low that the streaks are from the layer only.

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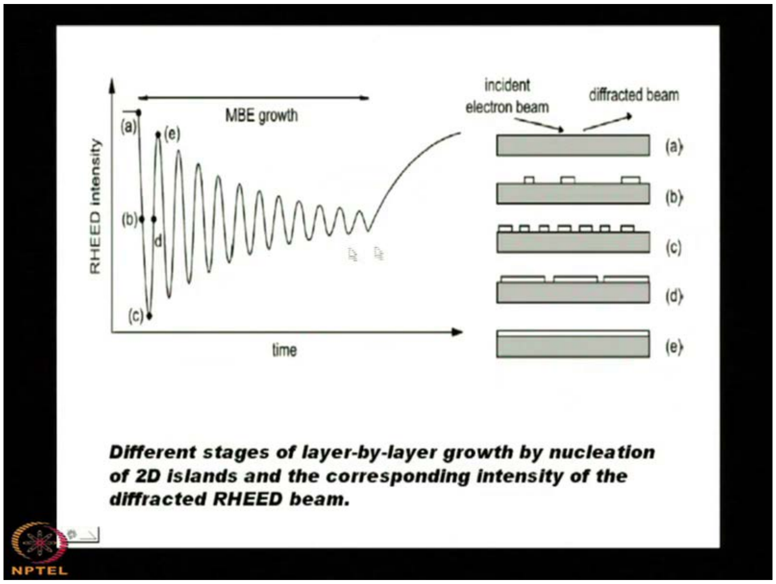

Different stages of layer-by-layer growth by nucleation of 2D islands and the corresponding intensity of the diffracted RHEED beam.

Then if you can consider different kinds of layer say in this case you see that, oscillations will be there. This is layer a, layer b, layer c, layer d, layer e, so first in a layer there is nothing it is basically the substrate so at this point you see the point a. Then from island types of growths are there b the nucleation, then this is the point b. Then more nucleation sites are there it is point c; then some of the nucleation sites formed a layer type of growth d then a full layer is formed e. So from the oscillations of the RHEED pattern you can conclude the different layers, how many layers are there? You can infer about the layer composition the layer thickness. So there is simulation software which can be read with this RHEED intensity oscillation.

So different types of at difference stages you can evaluate the condition of your subs (( )) no no it is not very easy process, but everything is computer control. So basically computer takes this data and they give you on the screen, that the surface is smooth. Now if you, if you investigate something very theoretically or say very radically, that is a separate story, but for normal cases these are basically used for optimization. When a process is optimized then you need not to see those pattern or any kind of thing it is for the optimization only; as soon as it is optimized everything is redundant you need not to fallow those things.

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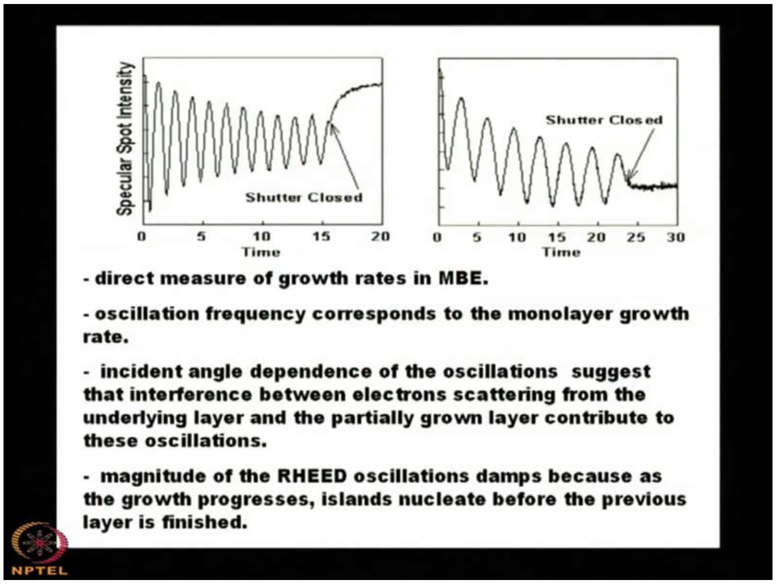

- direct measure of growth rates in MBE.
- oscillation frequency corresponds to the monolayer growth rate.
- incident angle dependence of the oscillations suggest that interference between electrons scattering from the underlying layer and the partially grown layer contribute to these oscillations.
- magnitude of the RHEED oscillations damps because as the growth progresses, islands nucleate before the previous layer is finished.

So there are many oscillations type of thing and using this oscillation type, you can oscillation frequency corresponds to the monolayer growth rate. So, from the frequency you can see how many monolayers are grown, etcetera.

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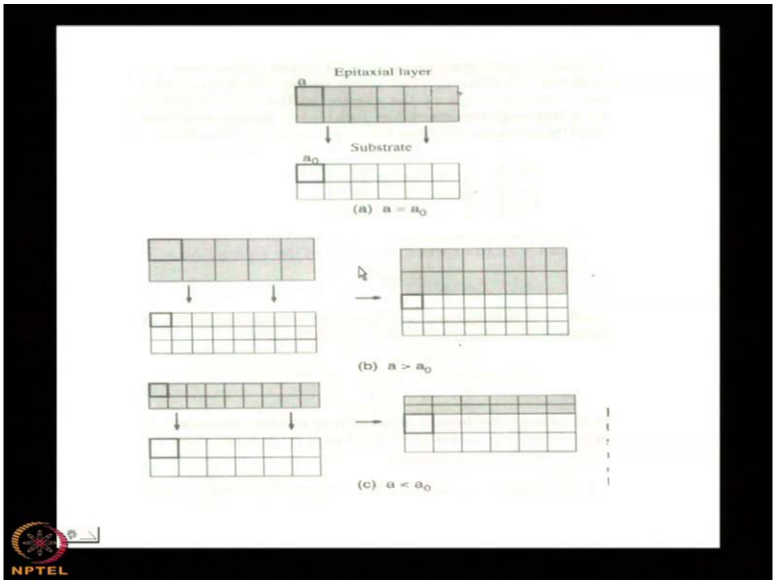

So that is not very easy process obviously, but for optimization you have to fallow that path.

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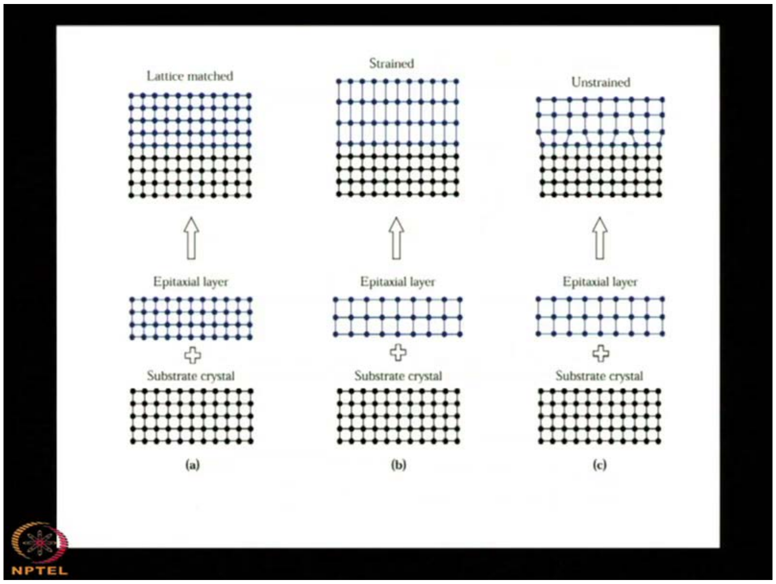

Here you see, that when we talk about the substrate and the layer. So there is no guarantee that all the time your epitaxial layer will have the same lattice constant like your substrate, because not available always.

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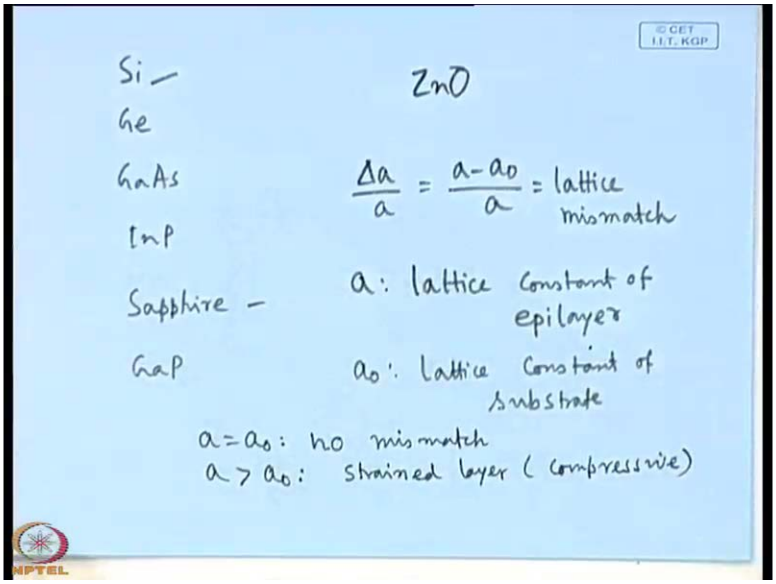

Si –
Ge
GaAs
InP
Sapphire –
GaP

ZnO

$\frac{\Delta a}{a} = \frac{a - a_0}{a}$ = lattice mismatch

a : lattice constant of epilayer

a_0 : lattice constant of substrate

$a = a_0$: no mismatch
$a > a_0$: strained layer (compressive)

Say Zinc oxide is one material for which the substrate is not available. The lattice constant of Zinc oxide does not matches with any other normal semiconductor substrate because substrate is available only in the form of Silicon, Germanium, Gallium Arsenide, Indium Phosphate, Sapphire, Gallium Phosphate etcetera. Only these types of substrates are available commercially with good, with good chemical composition and free from any defects this location etcetera. For Zinc oxide you cannot use any of them because one thing is that zinc oxide it is an (( )) structure these are or cubic or Zinc blend structure accepts the sapphire.

Sapphire you can use but the lattice constant sapphire is not exactly matching with zinc oxide, but how you can grow? You have to use the substrate. So people use either silicon or sapphire type of thing and there will be lattice mismatch. You see that the lattice match is given by delta a by a it is equals to a minus a 0 by a. What is a? a is lattice constant of epilayer, that mans epitaxial layer and A 0 is lattice constant of substrate. It is a 0 is lattice constant of substrate and a is lattice constant of epitaxial layer. So a minus A 0 by a is given by the it gives the lattice mismatch, it is a parameter to describe the lattice mismatch. Ok? Lattice mismatch.

Now if a equals to a 0, a and a 0 are same then there is no mismatch, no mismatch perfectly matching, no mismatch. When a greater then a 0, when a greater then a 0, see this is the case in this case you see that this is substrate; so substrate is a 0 and this is epitaxial layer it is a a greater then a 0 then what will happen? You see that it is basically so far as the parallel constants are concerned they are force to shrink. Here it is you see that laterally they are larger than the substrate, but as you grow the layer you find that laterally the epitaxial layer is shrinked; there is a shrinkage laterally. Ok? Perpendicularly it has increased, but laterally it is shrinked that means; it is strained, it is a strained layer and this strained layer is basically the compressive strain because the strain can be compressive, it can be tensile. The strain can be compressive, the strain can be tensile; so this is you see that in this case it is a strain layer.

Here also you see that the substrate crystal has lattice constant less than the epitaxial layer here, here you see what happen? Here vertically they have what you see? You see that at the boundary between the substrate and the epitaxial layer there is a dislocation type of thing or disorder type of thing, but on the rest of the cases, it is perfectly matching you see that the top layers are matching. So that is unstrained layer that layer is known as the pseudomorphic layer. As the layer starts growing, there will be a competition between the strain energy and the chemical energy. Strain energy because of the elasticity, the strain energy comes from the elasticity, because they are difference lattice constant; so there will be elastic strain energy. So there will a competition between the elastic strain energy and the chemical energy.

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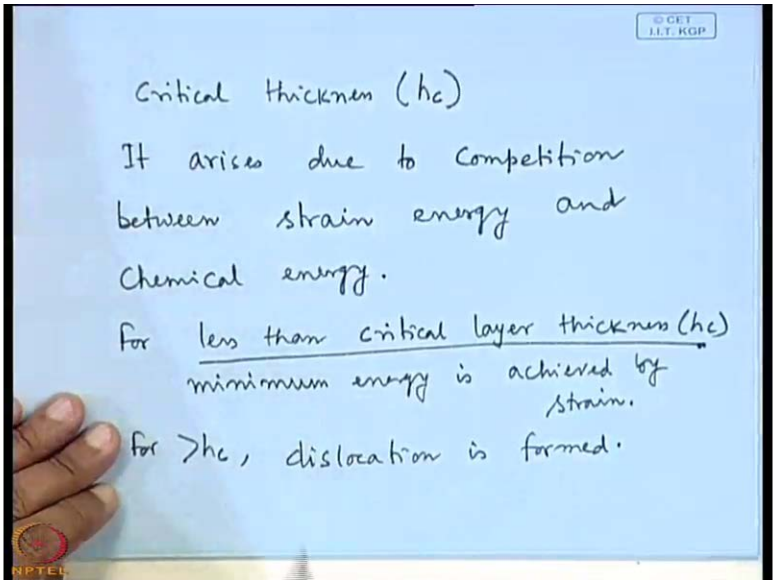

Critical thickness (h_c)

It arises due to competition between strain energy and Chemical energy.

For <u>less than critical layer thickness</u> (h_c) minimum energy is achieved by strain.

for $> h_c$, dislocation is formed.

And there will be one concept which is known as the critical thickness which is determine by h c critical layer thickness; critical layer thickness of whom? Critical layer thickness of the epitaxial layer. This critical layer thickness it arises due to competition between strain energy and chemical energy, it arises due to competition between strain energy and chemical energy. For less than critical layer thickness, for less than critical layer thickness that means; less then h c, for less than h c minimum energy is achieved by strain, for less than critical layer thickness minimum energy achieved by strain. For greater then h c that means if it is larger than the critical layer thickness dislocation is formed, dislocation is formed. So we can say that less than the critical layer thickness, less than the critical layer thickness there will be no strain ok? There will be no dislocation and it is very small.

It may be some order of nanometer 4nanometer, 3nanometer and growing that nanometer is very difficult in any system. So that is very important concept that, if he lattice matching is not there then there will be two possibility; one is that if the thickness of the epitaxial layer may be greater than or less then the critical layer thickness. There is formula called critical layer thickness, I am not going into those details critical layer thickness, if the grown epitaxial layer is higher than the critical layer thickness.

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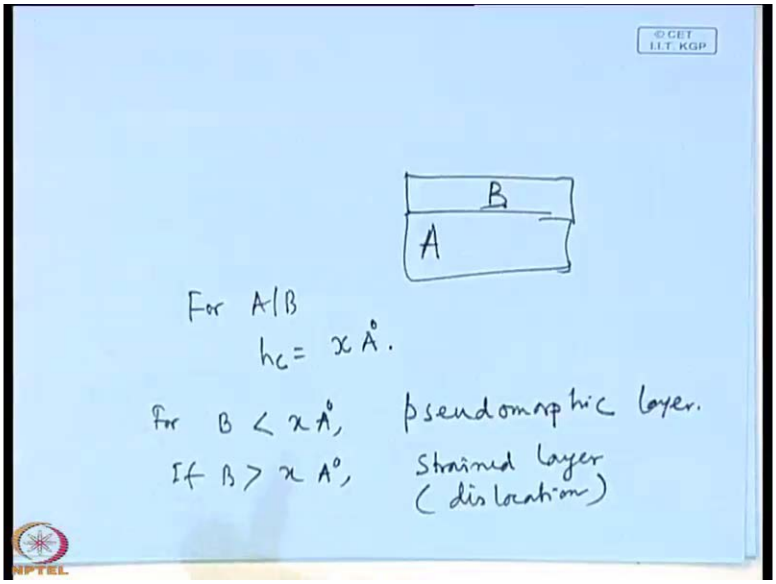

For A/B
$h_c = x$ Å.

For $B < x$ Å, pseudomorphic layer.

If $B > x$ A°, Strained layer
(dislocation)

Suppose I am considering one case of say A is one substrate and I want to grow B on it ok? For A and B system say critical layer thickness is say x angstrom for A B system the critical layer thickness is x angstrom. Then if the thickness of B is less then x angstrom, it is free from any defect or dislocation. That is known as pseudomorphic layer; for B less then x angstrom it is pseudomorphic pseudomorphic layer. That means unstrained, there will be no strain, there will be no dislocation good device you can built over that. If b greater then x angstrom strain layer will be there that means; dislocation will be there.

So for any system A B system A is one material, B is another material. You have to consider what is the critical layer thickness if, the lattice matching is not there. If it is matched you need not bother about, but if it is not matching, then try to keep it below the critical layer thickness or if it is larger than the critical layer thickness think that, there will be dislocation and strain layer. It is known as strain layer and the pseudomorphic layer is not a strain layer it is unstrained layer.

Thank you.