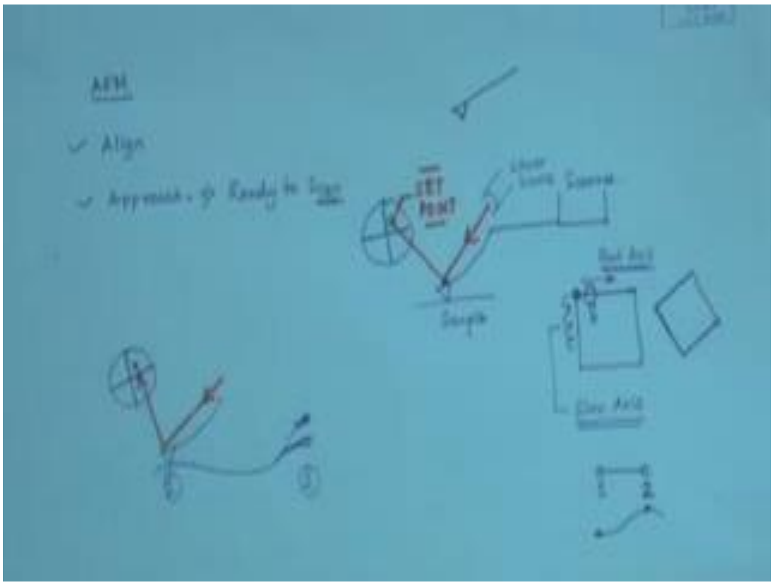
Soft Nano Technology
Prof. Rabibrata Mukherjee
Department of Chemical Engineering
Indian Institute of Technology, Kharagpur

Lecture – 28
Atomic Force Microscope – 5

Welcome back, now we actually have an AFM in that is ready to scan and let us now see how you can generate those awesome data's using Atomic Force Microscope awesome images, using an Atomic Force Microscope. Please try to appreciate this statement that I made that the discovery of the AFM, infact change the perception of vision in many ways.

Because as a part of this course, you have already seen several Atomic Force Microscope images, but a none of them are actually photographs, they are data rendered images and we will see how this data gets generated in somewhat more detail now.

(Refer Slide Time: 01:10)

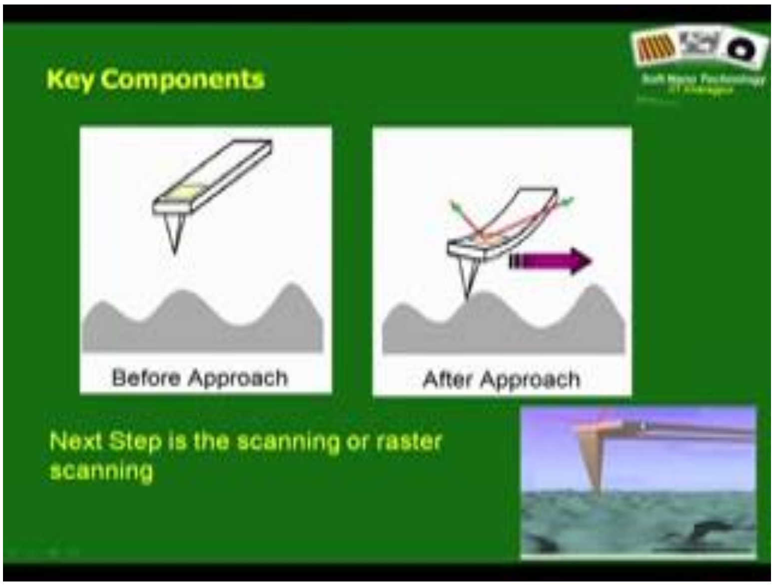


So what we have we now understand the basic components of an AFM. You have a tip a cantilever, you have a laser source, you have a QPD, you have a fit back loop and you have a scanner. So, the AFM is now aligned, it has approached and it is therefore, ready to scan. So now, if we tried to draw here for our own understanding. So, sample is now in place, you have the QPD because the laser source is there.

So, I mention that approach can be achieve by either moving the sample from the bottom or tip from the top. So, which would mean that in that case the laser source, the QPD and the tip moves simultaneously. These 3 always remain cooperate. That is deflection therefore the location, where the reflected laser spot is falling can change. So, from this particular image very simple looking image was it is reflecting from the back side of the cantilever tip, anything else you can comment this is in fact, the set point.

So now, this cantilever which is mounted to the scanner is ready to scan. So, if you look identify the area where it once to scan, which has approached at this point you can choose that point, it can be the top left corner right left right top corner whatever any of them, but it one of the extremes.

(Refer Slide Time: 03:04)



Key Components

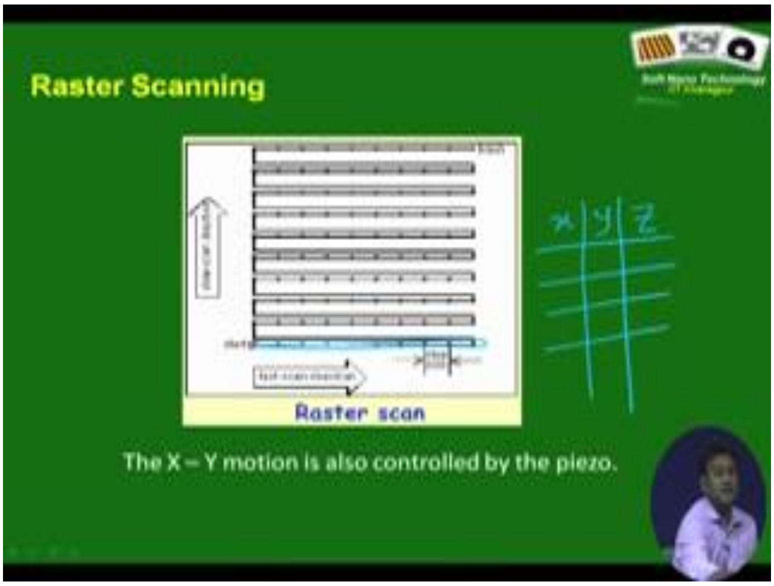
Before Approach

After Approach

Next Step is the scanning or raster scanning

So, Now what it is going to do? It is going to scan. So, it has to move first along let say this line typically what it does goes on collecting data at all the points over here as it is let say shown in this graph it goes on collecting.

(Refer Slide Time: 03:19)



Raster Scanning

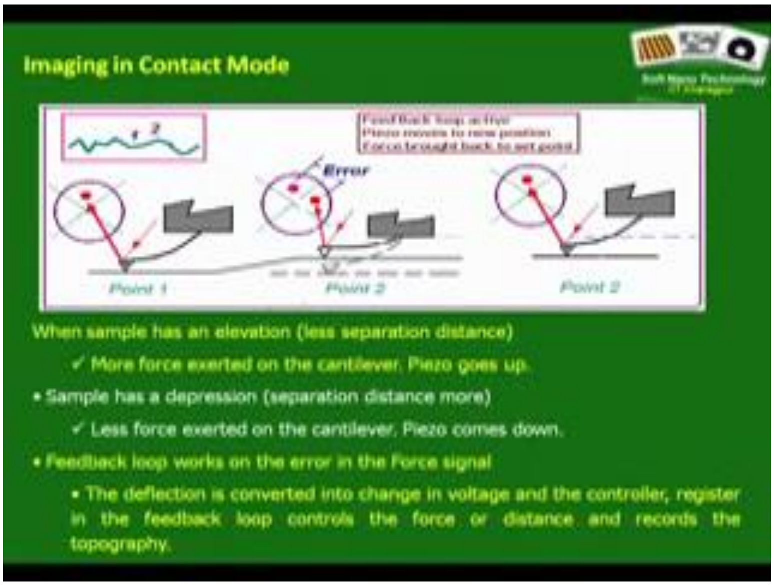
Raster scan

The X – Y motion is also controlled by the piezo.

So, here it shows that as it if is starting from this point it is all same it goes collecting data at all these points here, then it comes back goes to the next level collects all the point. So, it is a simple a double do loop and you have the option of choosing which way it will go. So, it can generate all the values of X is equal to 0,1,2,3,4,5 for Y equal to 0, then Y equal to 1, Y equal to 2 like that. Then your X becomes the fast axis and then why becomes the slow axis. So, if the tip is moving like this and then slowly hopping from this location to this then this is your fast axis, this is your slow axis right.

You can choose the motion to be like this, in that case this becomes your fast axis and this becomes your slow axis. Modern AFM’s in fact, allows you to tilled the area you want to scan like this and that is quite becomes possible because most of the modern some of the modern Atomic Force Microscope use as a cylindrical piezo a single piezo, but this was not possible or this is still not possible where you have d coupled or separate piezo for the X Y and thus it can be something I will discussing bit better detail.

(Refer Slide Time: 04:54)



Imaging in Contact Mode

When sample has an elevation (less separation distance)

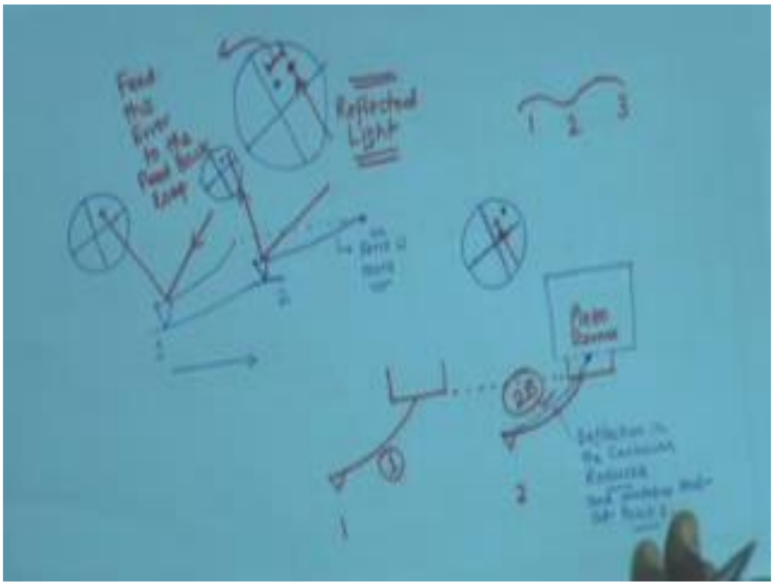
  - ✓ More force exerted on the cantilever. Piezo goes up.

- Sample has a depression (separation distance more)
  - ✓ Less force exerted on the cantilever. Piezo comes down.
- Feedback loop works on the error in the Force signal
  - The deflection is converted into change in voltage and the controller, register in the feedback loop controls the force or distance and records the topography.

So, anyway now as the scan take place, let say we just exaggerate this view and examine very carefully as to what happens as the cantilever reaches from point 1 to point 2 and let us assume that the topography of the surface is something like this. So, what it means then the surface is rough and point 2 is at a higher elevation then point 1. It is shown in this particular figure in the transparency, but there is a bit of a mistake made in the location of the reflected light. So, I would request you to follow the once that are here, these are all these of all been made by me some years of back for my course, but I made some mistake while making the sketches.

So this is let say the configuration of the cantilever at point 1 and this is let say the point 2 we have just exaggerated the gap. So this is the set point and as you start to scan the reflected light falls at the set point. Now as the so set picture has become a bit too complicated. As the cantilever moves from point 1 and also it for I will just read drawn it. We have a surface like this, this is your point 1, this is your point 2, this is the deflection at point 1, you have the QPD this is the set point. So, you reflected light fall set the set point.

(Refer Slide Time: 06:21)



Now as you raster as you move from the this point to this point, your tip reaches here. The end of the tip remains at the same elevation and therefore, what is the consequence the tip is as now more deflection. In fact, anyway it has more deflection, the force is more, figure is a bit wrong. I have drawn it a bit wrong anyway. So, what is the consequence? Again the sample can move or the tip can move, but if the tip move please remember it moves with this centre in the laser source and the QPD.

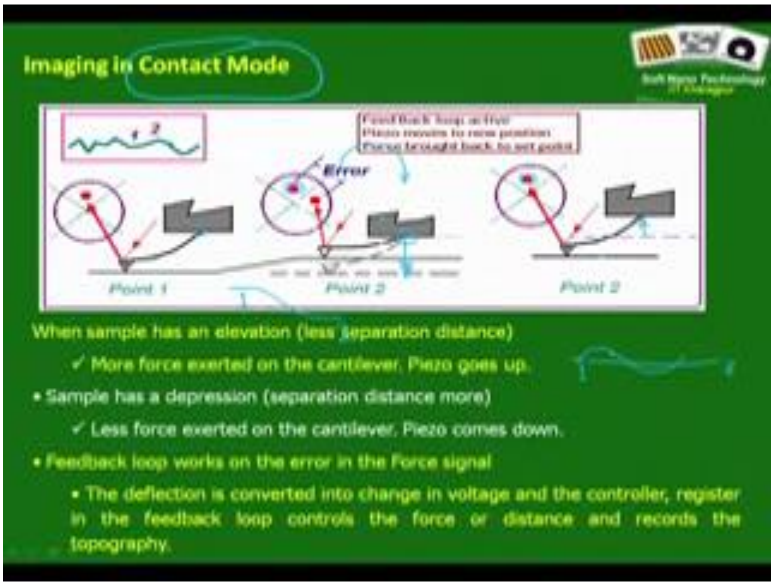
So, since the deflection has changed, now the reflected light is not falling at the set point it is falling somewhere else. I will exaggerate this, this was my set point and this is where reflected light is falling. So, what do you have? You in fact have an error. What is the error? The difference in the voltages between these 2 points. Now what you do you actually feed this error to the feedback loop and what does that do? Suppose this was the configuration of the cantilever at point 1, as the cantilever has gone to point 2 it is deflection has changed, this is 1, this is 2. Please note that these 2 are at the same level.

So, only the deflection has changed and now as a consequence of this change in deflection there is in fact, an error that gets generated in the QPD. This error is fade to the feedback loop, which now inputs this error in voltage to the scanner which is a piezo scanner and what does this scanner now do? The piezo now becomes short and wide in such a way that the point at which the tip that the cantilever is mounted goes up.

So, that the deflection now reduces and matches that at point 1. So, what would be the consequence on the QPD? The consequence on the QPD will be as the piezo, relax piezo sought of as or as the deflection reduces, light which was falling at this point, the laser again start to fall at this point because the deflection now let us star meters 2b matches with the deflection of 1,

Therefore, it is again falling at the set point the reflection is again as that corresponded to the set point and again now with this new reflection it is now ready move from point 1 to point 2 then to point 3 and at every point it goes like this. What do you have learned in the process we will have a look here in the PPT. Though the quadrants are wrong, but the basic essence is same.

(Refer Slide Time: 11:04)



Imaging in Contact Mode

When sample has an elevation (less separation distance)

- ✓ More force exerted on the cantilever. Piezo goes up.

- Sample has a depression (separation distance more)
  - ✓ Less force exerted on the cantilever. Piezo comes down.
- Feedback loop works on the error in the Force signal
  - The deflection is converted into change in voltage and the controller, register in the feedback loop controls the force or distance and records the topography.

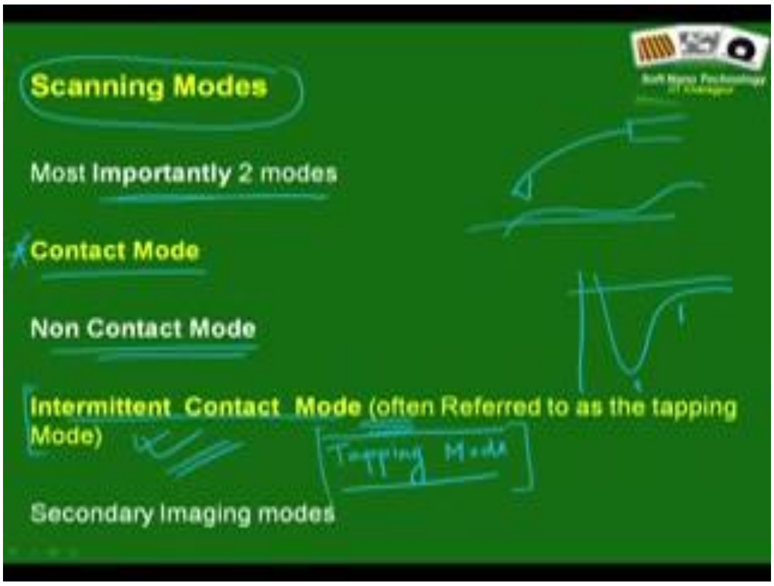
So, as the cantilever moves from point 1 to point 2 the deflection changes and therefore, the lacer light falls at a different location and not at the set point. This is the set point. In fact, I will use a different colour of the ink that will help. So this is the set point, but as the deflection changes it does not fall on the set point it falls somewhere else. So, there is an error, this error is fade to the feedback loop to the piezo and the piezo in fact, becomes in this particular case becomes short and wide. So, that the deflection of the cantilever force of the cantilever reduces and the reflected light again falls back at the location of the set point.

At the surface at the point 2 been at a lower elevation than point 1, then the error would have been such that piezo would have deflected in a manner that it becomes long and slim. So, that the bottom point of the bottom point where the where the cantilever is mounted to the piezo would have gone down and all you do is you track the this movement upward and downward movement of the this particular point at every X and Y and remember this will have negative and positive values, the values will be with respect to this particular point where the cantilever approached and that is the point where the elevation the height will be considered as 0. Then this point will have some plus Z value point which has lower elevation you will have some minus Z value, but if this is the point this is the first point, where the cantilever had approached this will maintained to be some sort of Z equal to 0 ok.

So, this is in fact, what do you have learned is contact mode imaging of the AFM the most basic mode. if has it is own problem because you are essentially dragging the cantilever while you are rastering. So, it is bad for both the tip and the sample particularly for soft samples contact mode tends to spoil up the surface it makes that to be very blunt those problems are there, but those are secondary thing.

So, we now understand the contact mode, but we also need to understand what are the other modes. So, this picture now should makes sense to you this is the rastering option it is in fact, a nested loop nothing more than that it is a nested d loop. So, you just go on gathering the data and now you understand that after your complete scan is over, you are simply going to generate a data file like this right. I will come back to this, but before that I will should tell you something that deliberately skip at the point and that is the scanning modes.

(Refer Slide Time: 14:10)



Scanning Modes

Most Importantly 2 modes

Contact Mode

Non Contact Mode

Intermittent Contact Mode (often Referred to as the tapping Mode)

Secondary Imaging modes

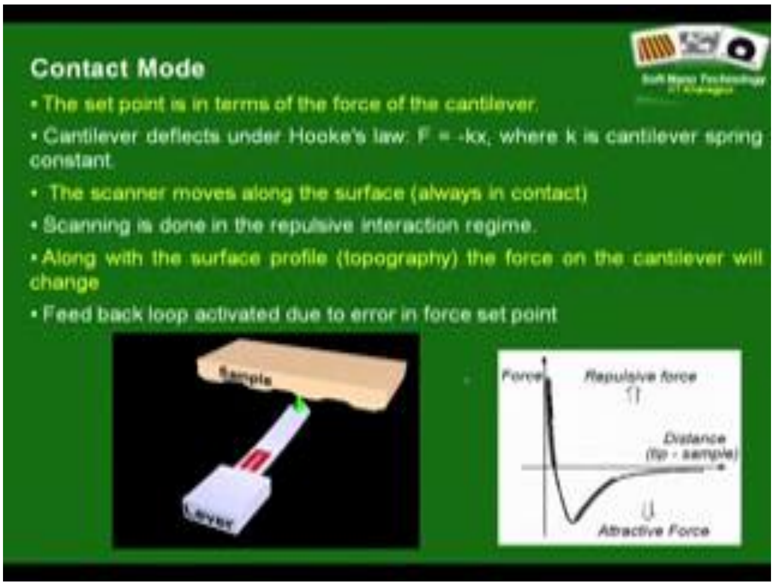
So, primarily there are 2 scanning modes. The contact mode what which you already know now, but there can be other modes like noncontact mode. In fact the noncontact mode the cantilever operates in this particular configuration. So, you are somewhere over here in the force curve because idea is same now as the cantilever moves as the points as the surface goes further away or becomes closer to the cantilever it can still change the deflection.

It is scientifically very sound rovers and very exciting also because it does not touch the surface, it is really relying on the interaction forces because if you look at the approach sequence of the contact mode cantilever, you are not exactly relying on Van Der Waals forces any more you are actually relying on root force repulsions, but see in noncontact mode imaging in principle realize completely on Van Der Waals forces, but in reality the resolution is extremely poor and noncontact mode imaging is used, but in conjugation with contact mode typically for certain, for extracting certain additional interactions, like electrical force microscope your magnetic force microscope, where let say in electrical force microscope, the scaling or the decade characteristic of the columbic force and the Van Der Waals forces are known to be different.

Therefore you generate different types of topographies from contact mode and noncontact mode and you subtract them to identify the electrically active or magnetically active domains of course, MFM requires a magnetically a cantilever coated with the magnetic material. More important features become extremely popular these days particularly because it gives you very robust data and it is very useful for polymer and soft materials and biological samples is what is known as Intermittent Contact Mode.

This is also even in many top journals this is often referred to as tapping mode, but I would prefer you not to use the word tapping mode the world honestly realizes this mode as the tapping mode, the tapping mode is actually a copyrighted term of a particular company and scientifically this mode is called Intermittent contact. That is something that we will take up in the next class this is very exciting and I mean most of the samples people look these days soft samples ,even hard sample tapping mode these out preferred because of many advantages which I will talk, but one thing we have not talk in detailed a. So, this is some cartoon that shows the systematic of the contact mode is about the scanner itself.

(Refer Slide Time: 17:01)



Contact Mode

- The set point is in terms of the force of the cantilever.
- Cantilever deflects under Hooke's law: $F = -kx$, where k is cantilever spring constant.
- The scanner moves along the surface (always in contact)
- Scanning is done in the repulsive interaction regime.
- Along with the surface profile (topography) the force on the cantilever will change
- Feed back loop activated due to error in force set point

(Refer Slide Time: 17:05)

Piezoelectric Scanner

Most modern scanning probe microscopes uses a single piezo with tube geometry

Each of the four indicated sections can be made longer or shorter individually. If all four sections are made longer or shorter by the same amount, the tip moves in the z-direction. If the X+ side is made longer, and at the same time the X- side is made shorter by the same amount, the tube deforms a little bit, as indicated. For small deformations, this makes the tip move primarily in the X-direction. The same can be done in the Y-direction

X – Y motion is required for Rustering

So it is a piezoelectric material you can in principle have 2 configurations. You can have so not only the scanner controls the vertical height or movement of the tip of the cantilever, but it also controls the lateral movement of the tip during rastering because as I mentioned in the context of SDM may be this entire area is 1 micron and the you want to generate data at 512 intermediate point. So, you can calculate that roughly you are seeking data every 20 nanometre. Now which motor in the world is going to give you this type of precision? None of them are going to give. So in fact, this X,Y motion is also controlled by the piezo as well as the Z motion.

There had been derived there are still designs of AFM, by the where the extra emotion controlled by 2 sets of piezos and the Z motion is controlled by a third separate piezo, but there are designs and which are becoming more popular that everything is achieved by one single cylindrical piezo. I will not going to the details of this thing, but except for the fact that I just highlight that this is roughly cylindrical piezo a what is used in many of the high and microscopes this thing uses the single piezo with tube geometry.

So, what happens if so this has in fact 4 parts. You can identify that there are 4 quarter circular parts right, which sort of constitute this 2 and each 4 sections can be made longer or shorter individually right. So, you can feed the voltage. So, feedback loop can feed the voltage individually with these four components. Now you can understand if all these four component simultaneously shorten or elongate it then you actually have a movement in the Z direction.

However, if let say Y one of this components let say the Y plus components elongates and the Y minus component shortens you actually have a motion in Y direction. Similarly with these 2, with the help of these 2 you can sort of control the motion in the X direction and that is precisely what is done this is something that if you want to understanding detail you can read a little bit, but even if you do not understand much is perfectly fine, accepting the fact that there is only one piezo in most of the in many of the instruments now which uses the single tube light circular piezo element and the which has different sections which can be sort of activated separately or which can be address separately and the voltage can be given separately.

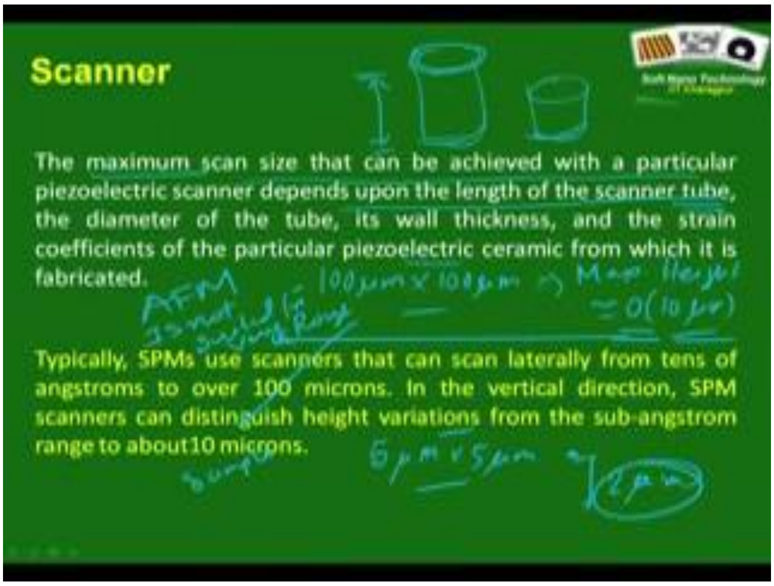
So when you want to sort of move in the X,Y direction during the rustering right. So, you have two sort of if you want to move in the X direction you simply feed to X plus address the X plus and X minus they sort of change the dimension and tip moves in the X direction, if you want to move in the Y direction you do the same thing Y plus and Y minus, if you want to sort of adjust the height of the piezo every 2B like when you realize that the new point where your cantilever has reached as a different elevation as compare to the earlier point you sort of feed it in feed the voltage to the piezo in such a way that all the four sections expand or contract by the same amount and therefore, you have a vertical movement or a either upward or downward to readjust the location of the reflected point to the set point value.

And you can in fact as I mention somewhere that modern the instruments it is in fact, possible to choose the direction of the X and Y the fast and slow axis which may not be the actual orthogonal direction, initial orthogonal direction that is simply because of the fact that you can you have the option of rotating the orientation of the whole assembly.

So, if you now rotate the whole thing. So, let say initially these were the four sections, which was responsible for movement in this and this direction and now what you have let say is something like this. So, this will be responsible for movement in this direction. So, depending there can be some interesting features for which you may want to change the direction of the scan and that can be easily done using a cylindrical piezo element.

There r models in which you have decoupled piezos for the X Y and Z motion they also have their own advantages you can have sort of individual motions, but a it also comes with certain problems. For example, one of the major problems is if you have linear piezos for X and Y movement, you cannot rotate this orientation of your fast and slow axis. Scan will always be your fast axis will be either be in this direction or in this direction you do not have a any handled to rotate it the way you want.

(Refer Slide Time: 22:29)



Scanner

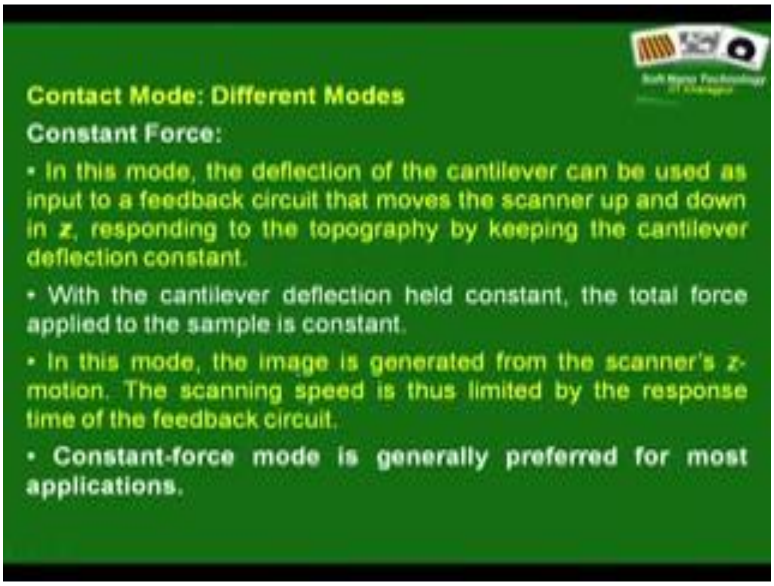
The maximum scan size that can be achieved with a particular piezoelectric scanner depends upon the length of the scanner tube, the diameter of the tube, its wall thickness, and the strain coefficients of the particular piezoelectric ceramic from which it is fabricated.

Typically, SPMs use scanners that can scan laterally from tens of angstroms to over 100 microns. In the vertical direction, SPM scanners can distinguish height variations from the sub-angstrom range to about10 microns.

There is also another important thing, that is the maximum scan size. The maximum scan size depends upon the length of the scanner tube. So, if it is longer the scan range is big if it is shorter, the scan range is small, same thing is a the length also determines the maximum height of the features that you can handled and typically it is possible now to sort of scan areas as large as 100 micron by 100 micron in certain instruments, with the maximum height of the order of I would say of the order of in micron, but you can.

And initially these numbers are very large compare to what was available initially where sort of people look maximum into 5 micron square areas with the maximum height and let say two microns.

(Refer Slide Time: 23:58)



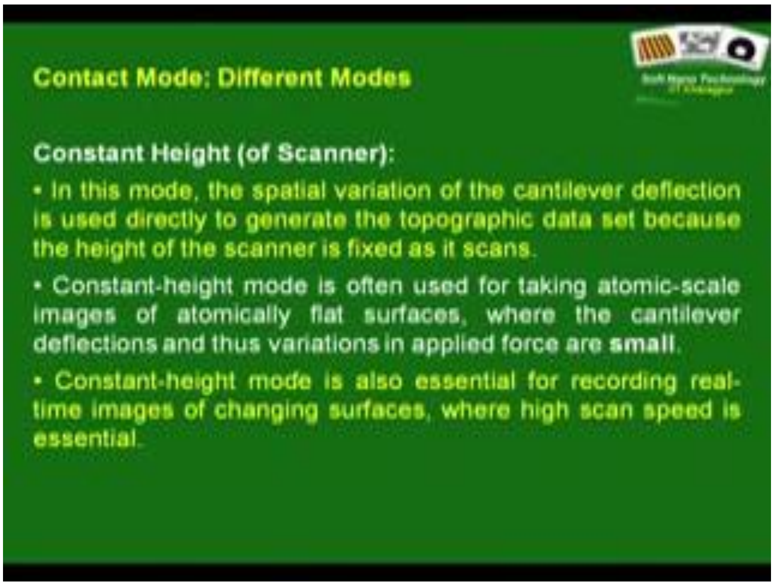
Contact Mode: Different Modes

Constant Force:

- In this mode, the deflection of the cantilever can be used as input to a feedback circuit that moves the scanner up and down in **z**, responding to the topography by keeping the cantilever deflection constant.
- With the cantilever deflection held constant, the total force applied to the sample is constant.
- In this mode, the image is generated from the scanner's z-motion. The scanning speed is thus limited by the response time of the feedback circuit.
- **Constant-force mode is generally preferred for most applications.**

So that also tells that AFM is not suited for very rough samples. So, once the scanning is done. So, this is something is I mean probably skip the different modes the constant force and the constant height very similar to what we have learned the constant current, constant height modes in a SDM.

(Refer Slide Time: 24:02)



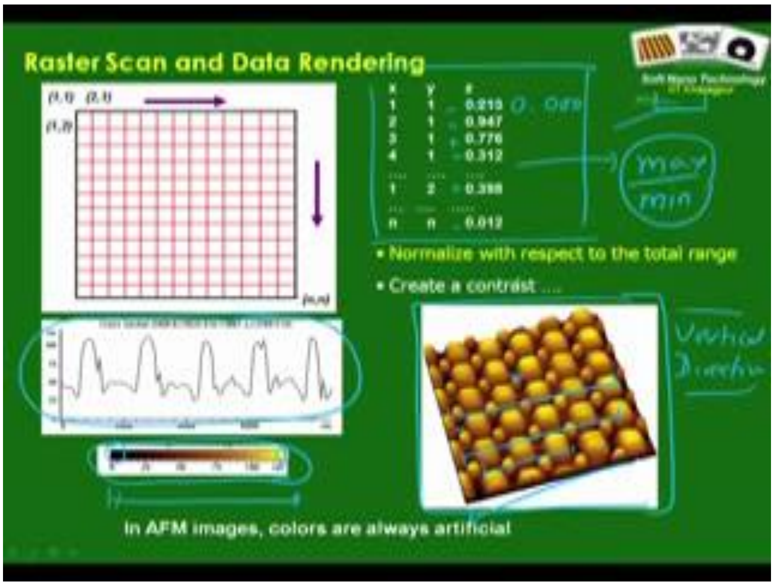
Contact Mode: Different Modes

Constant Height (of Scanner):

- In this mode, the spatial variation of the cantilever deflection is used directly to generate the topographic data set because the height of the scanner is fixed as it scans.
- Constant-height mode is often used for taking atomic-scale images of atomically flat surfaces, where the cantilever deflections and thus variations in applied force are **small**.
- Constant-height mode is also essential for recording real-time images of changing surfaces, where high scan speed is essential.

Every sort of almost all contact imaging mode is done in constant mode force I mean nobody does it constant height mode anymore because a constant height mode you can in principle run it without the (Refer Time: 24:36) which is not done.

(Refer Slide Time: 24:3)



Raster Scan and Data Rendering

x	y	z
1	1	0.215
2	1	0.947
3	1	0.776
4	1	0.312
....	....	....
1	2	0.398
....	....	....
n	n	0.012

- Normalize with respect to the total range
- Create a contrast ....

In AFM images, colors are always artificial

So, this is the one more thing that will highlight before I end and break for today this is the type of data you typically generate there will be certain minus values some will be plus, some will be minus, whatever again something I will missed out and 1, 1 should not have any value, 1, 1 will be 1, 1, 0, 0, 0 right.

So, this is how you sort of split up your zone of interest and you would like to sort of pick up the as I have mentioned you go on tracking how much the cantilever the scanner is moving up and down to if the cantilever is mounted, you generate this data file once the data generation is complete all you do is to run a search algorithm on the Z column, find out the maximum value and the minimum value. You normalize the data with respect to that and that that normalize data you simply place into some sort of a gray scale.

And therefore you see images like this, but this images are all digital rendered and this image in fact has no meaning in absence of this vertical scale, but because the colour code is simply corresponding to the scale you have used it is not a gray scale it is with this type of colour typically you see, but see here the colour corresponds to the darkest area corresponds to the deepest area in the samples.

So, these are deep areas and the brightest once are the highest areas and the maximum difference in the high according to this images of the order of 125 nanometre. Since you have data for all the lights it is possible that you go to any line, you just ask for the section and you can get sectional all the lines it is possible that you go to any line you just ask for the section and you can get the section image sectional information like sectional profile like this. So, what you have got? You have recreated the contours of the surface and you now have absolutely 2 information in the vertical direction.

So, this is an outstanding capability that only your Atomic Force Microscope can offered and it can offer because it sort of does not image or take a picture of the surface, it actually visit is the probe actually visit is every point and picks up information, how much elevated or depleted that point is with respect to the point where the tip head initially approached.

So, I will stop here, please go through these lectures very carefully and next class we will start discussing the intermittent contact mode or the trapping mode or revise some of the concepts we have discussed today.

Thank you very much.