Advanced machining processes
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Lecture 34
Focused Ion Beam Machining

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Welcome to the course on advanced machining processes. I'm going to discuss briefly focused ion beam machining. Here I will also explain some of the things related to the setup in applications other than machining.

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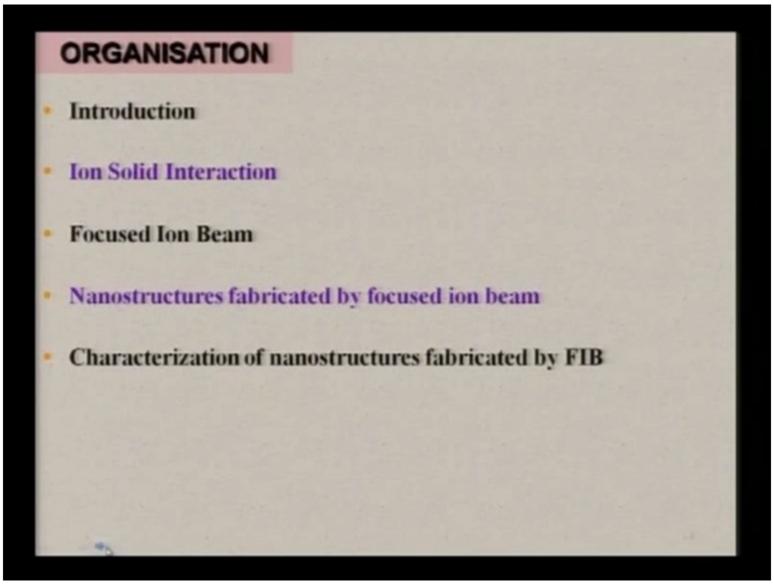

Organization of the talk is like this, introduction ion solid interaction. Focused ion beam, nanostructures fabricated by the focused ion beam. Characterization of nano structure fabricated by FIB, I'm not going to discuss much related to the characterization of these microstructures.

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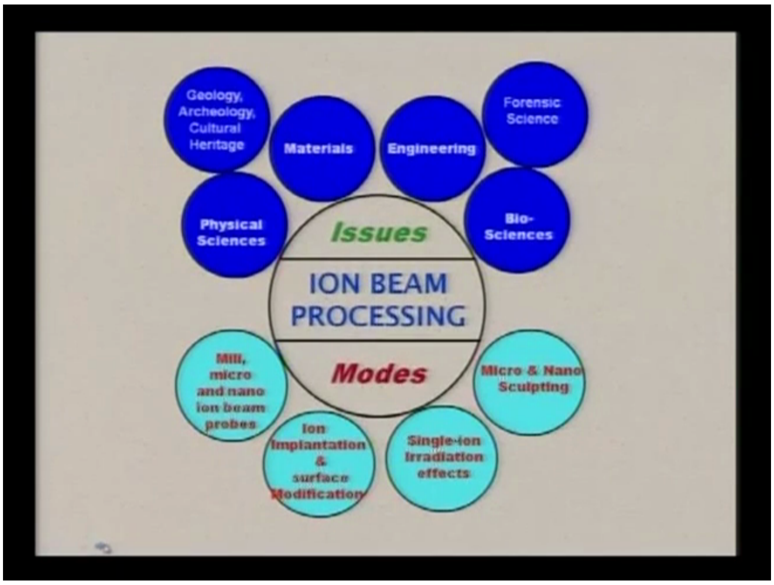

There are various issues related to ion beam processing it can be used in various modes and it is very commonly used in physical sciences as I will show you later on also, for processing of materials, characterization of materials, various in applications in engineering than biosciences, it is very useful for biosciences because there are hardly any forces acting on the components being analyzed. Hence it is very much suitable for the application biosciences.

Geologic, archaeology, cultural Heritage etc have some applications of this and then forensic science is another area where it has applications. Now Milli, Micro and Nano ion beam probes are used and I'm not going to discuss this issue in this one. This we are going to discuss ion implantation and surface modification specifically during the ion beam machining and deposition of the materials with the help of the ion beam.

Single iron radiation effects and am not going to discuss this and Micro Nano sculpting there are lot of applications in this area as well but my talk will be very limited to certain applications related to engineering only and that too specifically machining and little bit deposition.

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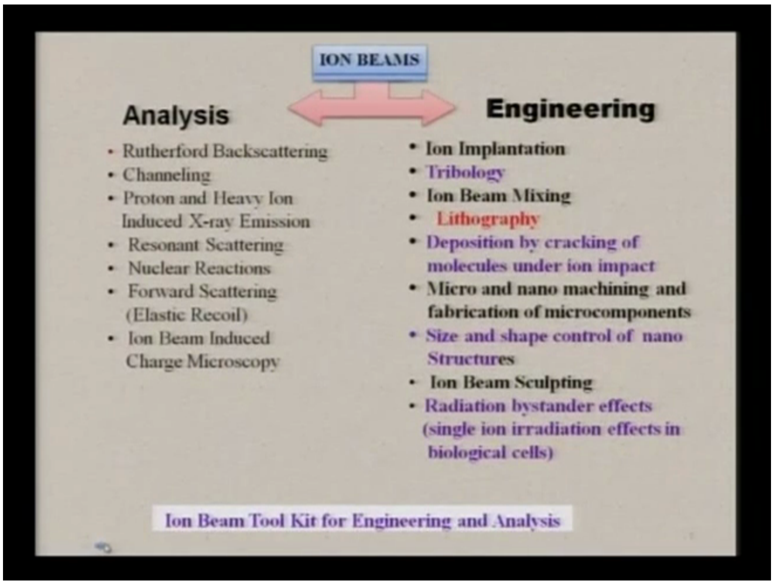

As I mentioned ion beam has 2 types of applications, one is the analysis which is mode related to the physics or chemistry people like Rutherford Backscattering, channelling, proton and heavy ion analysis. Induced x-ray emission, resonant scattering, nuclear reactions, forward scattering elastic recoil, ion beam induced charge morphology these are the various applications which have lot of importance in the physics and related areas.

And there are some applications which have importance in engineering as well as I mentioned in the earlier slide either in the form of machining or in the form of deposition, so that you can prepare Micro nanostructures applicable to the various devices used in engineering biomedical and other areas. One of them is ion implantation, tribology, ion beam mixing, lithography, deposition by cracking of molecules under ion impact.

Micro-and nano machining and fabrication of Micro components using focused ion beam. Size and shape control of nanostructures. Ion beam sculpting. Radiation bystander effects. Single ion irradiation effects in biological cells these are some of the applications related to engineering. You can involve many other applications once you know the capabilities and limitations of ion beam setup. Now these capabilities, limitations and other details of ion beam setup will be discussed in the later part of the lecture by Mr Neeraj Shukla.

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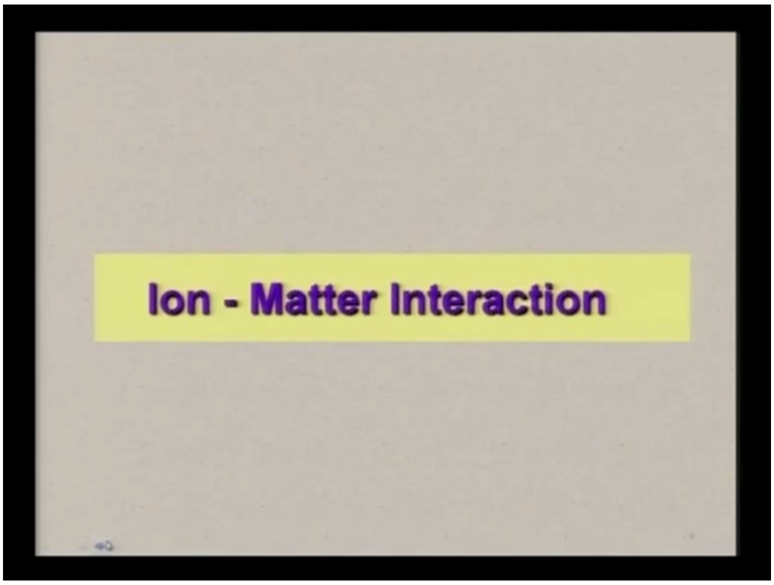

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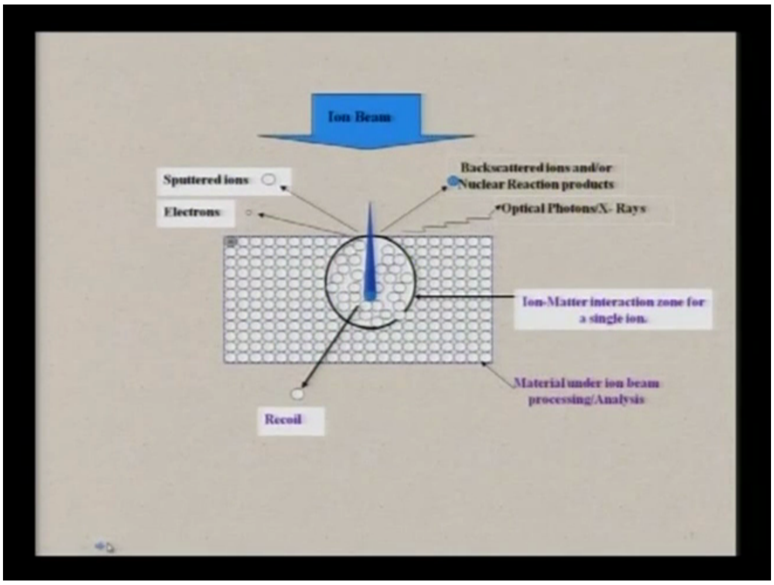

Ion matter interaction, as you can see here ion beam is there, ion are hitting the top surface of the work piece and as a result of that sputtered ions as a can see over here, electrons then recoil ion is there in this particular area, ion metal interaction zone of a single ion and material under ion beam processing as you can see here and then there is optical photons, x-rays that are produced and then there is a backscattered ion and nuclear reaction products.

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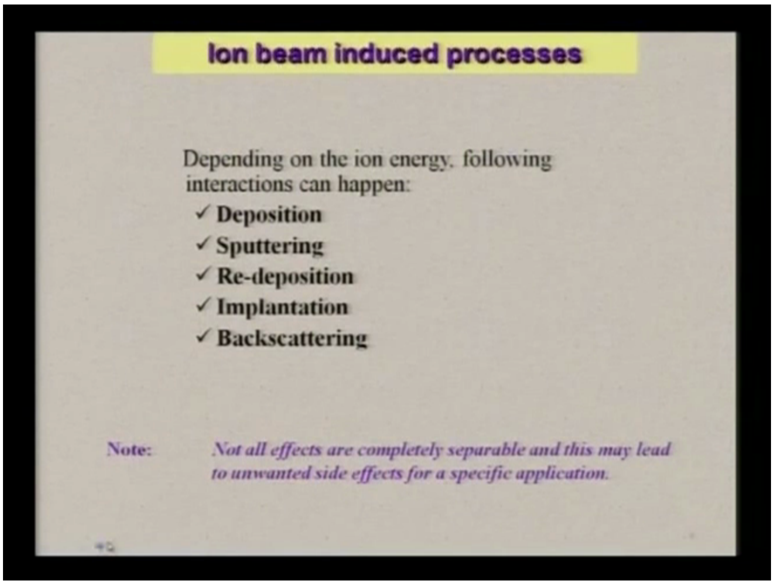

Ion beam induced processes, depending on ion energy following interaction can happen. Deposition as I mentioned to you earlier also, sputtering, re-deposition of the material, implantation of the ion, backscattering. Not all effects are completely separable and this may lead to unwanted side-effects for a specific applications. So these are the some of the things which are happening when you hit the ion beam on the virgin surface of the work piece.

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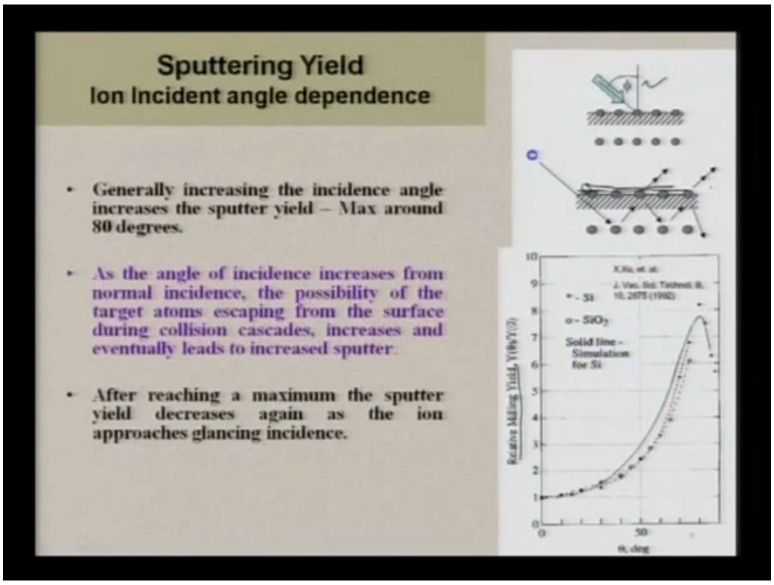

Sputtering yield depends on ion incident angle dependence. As you can see here on the right side Phi is the angle at which ion is hitting the work piece surface. Now this angle is very important what is going to be the sputtering yield depends substantially on this angle of incidence is apart from the energy of the ion beam. You can see here in this figure theta is the angle which shown at the top figure on the right side and you can see for different materials the relative milling yield is depending on the angle of incidence.

As angle of incident is increasing the sputtering yield is increasing and there is an optimum value or maximum value beyond which if you further keep increasing it there is a decrease in the yield and this is quite obvious that once this tries to tend to be this 90 degree angle than the ion will be just moving like this without really separating out the atoms from the top surface and that is why you can see that beyond the maximum value it starts decreasing.

So generally increasing the incidence angle increases the sputtering yield and maximum is observed at around 80 degrees. As the angle of incidence increases from normal incidence, the possibility of the target atoms escaping from the surface during collision cascades, increases and eventually leads to increased sputtered. Here our objective is to remove as many atoms from the top surface with the help of a single ion as possible but without damaging the top surface of the work piece.

After reaching a maximum the sputtering yield decreases again as the ion approaches glancing incidence, as I have explained here that once it reaches to the 90 degree then this ion will be just moving like this really rather than removing the material from the top surface.

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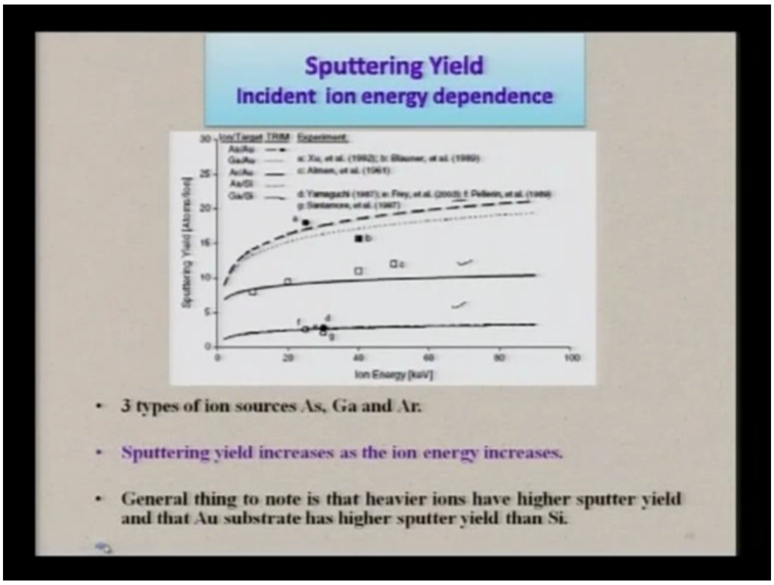

Sputtering yield incident ion energy dependence, as you can see here sputtering yield and ion energy and which is obvious higher the energy of the ion more number of atoms will be removed from the top surface of the work piece but there are certain disadvantages also as I will show you later on that if too much of energy and ion consist then it will it to the defects and we will see it later on.

Here you can see clearly that there is some increase in the sputtering yield or in the yield for different types of materials the sputtering yield is different and for while varying this ion energy there is some increase in the yield, so this clearly shows that for different types of the materials yield is different and it is changing with the ion energy, 3 types of ion sources are there, As, Gallium and Arsenic. Sputtering yield increases as the ion energy increases. General thing to note is that heavier ions have higher sputter yield and that Au substrate has higher sputter yield than silicon Si.

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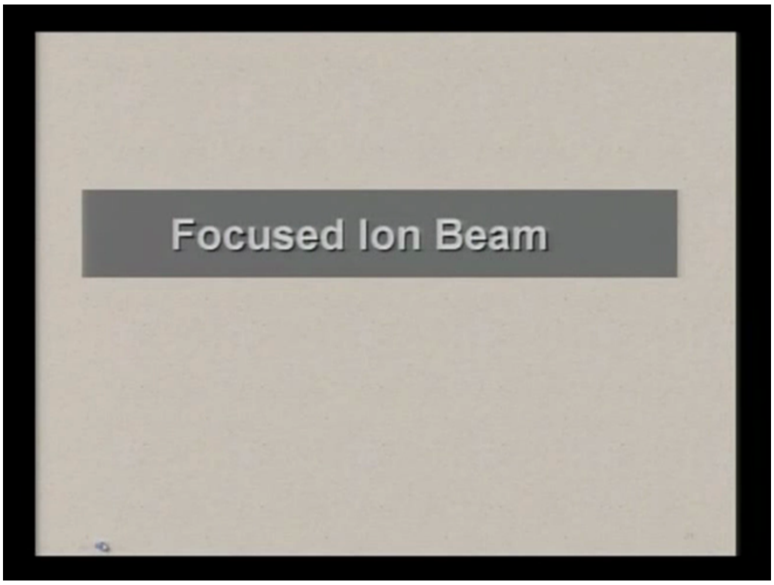

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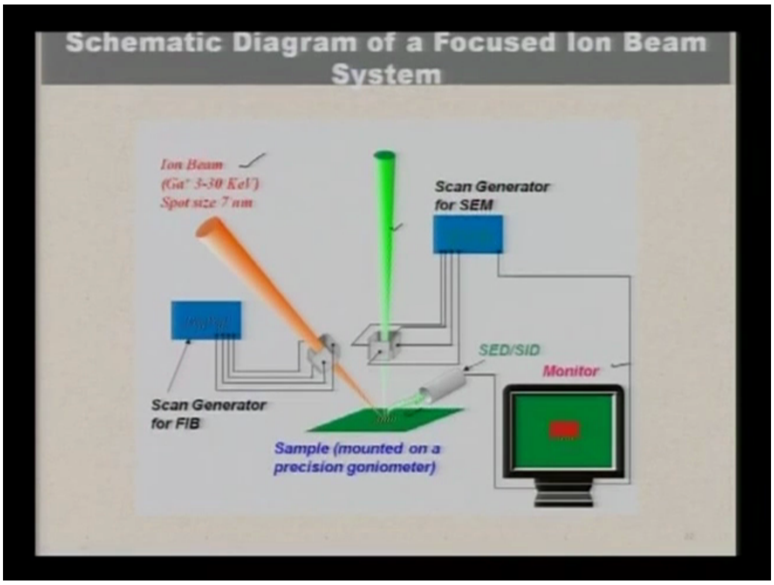

Focused ion beam. Schematic diagram of a focused ion beam system, this gives you an overview of what kind of this ion beam setup is. Now you can see clearly there is ion beam, gallium, 3 to 30 kilo electron volt, spot size is 7 nanometres then scanned generator for scanning electron microscope you have here then there is a SED, SID then there is a monitor of a computer and sample mounted on a precision goniometer that is here.

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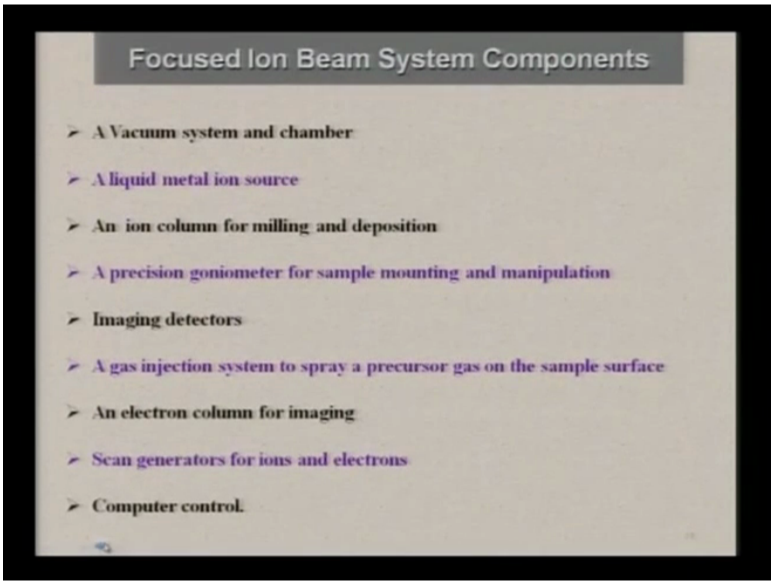

Focused ion beam system components, a vacuum system and a chamber, a liquid metal ion source is there, and ion column for milling and deposition of the material on the substrate. A precision goniometer for sample mounting and manipulation because manipulation of the location of the work piece will make different shapes and sizes of the micro-nano structures that are to be fabricated or that are to be made with the help of focused ion beam.

Imaging detectors with the help of this focused ion beam, you can also do the imaging you can also find out the surface textures of the work pieces or the structures and that is another very important applications of this. A gas injection system to spray a pre-cursor gas on the sample surface. An electron column for imaging purposes is needed just like scanning electron microscope you can use it as the one for scanning of the images. Scanned generators for ions and electrons and definitely whole of the system ion beam or focused ion beam system is controlled with the help of the computer.

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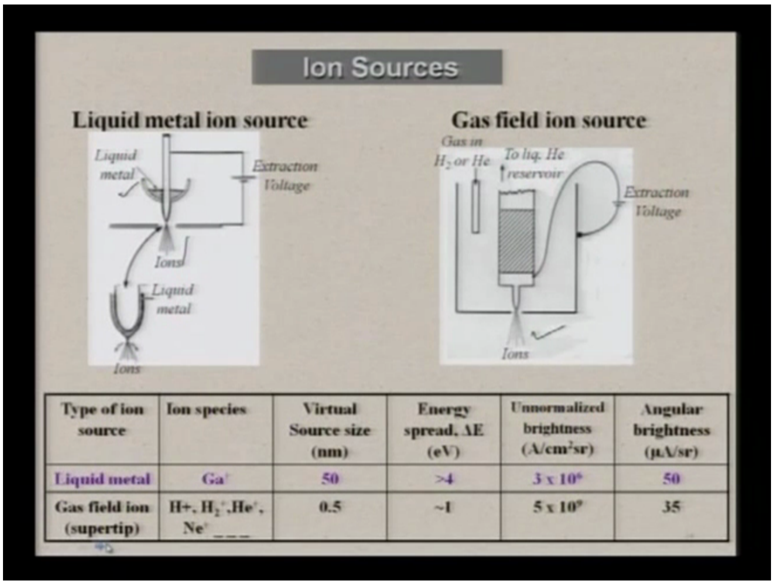

Type of ion source	Ion species	Virtual Source size (nm)	Energy spread, ΔE (eV)	Unnormalized brightness (A/cm^2sr)	Angular brightness (μA/sr)
Liquid metal	Ga^+	50	>4	3×10^6	50
Gas field ion (supertip)	H+, H_2^+, He^+, Ne^+	0.5	~1	5×10^9	35

There are various sources with the help of which you can produce the ion beam, as you can see here liquid metal ion source, liquid metal is shown over there and then you have extraction voltage and you can get the ions in the form of a column as you can see in this particular figure then you can have gas field ion source, in place of the liquid you can use the gas field ion source.

Here are the ions extraction voltage and other details are shown over here, you can have hydrogen, helium gas. Liquid metal gallium, virtual source size is 50 nanometre, energy spread delta E is greater than 4, electron volt and then un-normalised brightness and other details for both the cases liquid metal as well as gas field ion are given in this particular table.

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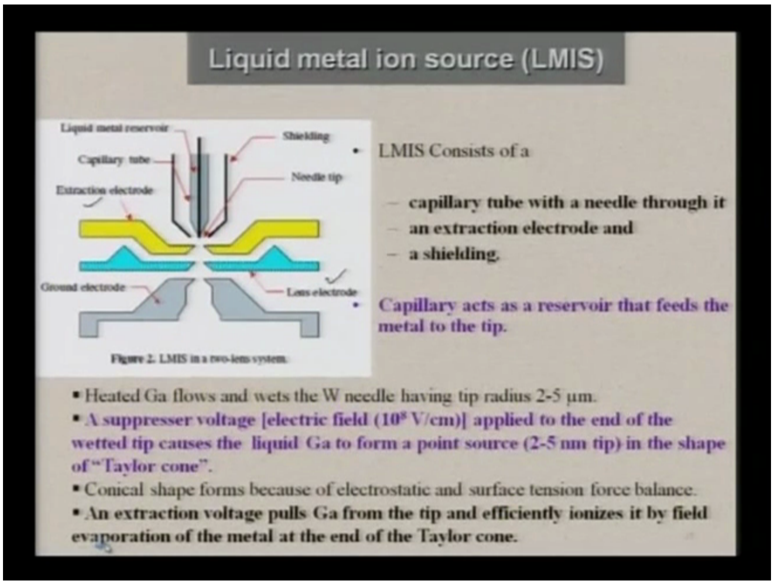

Now some more details of the liquid metal ion source are given over here. Liquid metal reservoir is there, capillary tube is there and then you have extraction electrode then needle tip and shielding is there. You have lens electrode over here and then ground electrode and each part has its own functions.

Capillary tube with a needle through it and extraction electrode and a shielding are shown over there in the schematic diagram over here. Capillary acts as a reservoir that feeds the metal to the tip. Now from that tip only you're going to extract the ions. Heated gallium flows and wets the tungsten needle having tip radius as 2-5 microns. A suppressor voltage electric field 10 raise to power 8 volt per centimetre applied to the end of the wetted tip causes the liquid gallium to form a point source 2 to 5 nanometre tip in the shape of Taylor cone.

A conical shape forms because of electrostatic and surface tension force balance. And extraction voltage pulls gallium from the deep and efficiently ionises it by Phil evaporation of the metal at the end of the Taylor cone.

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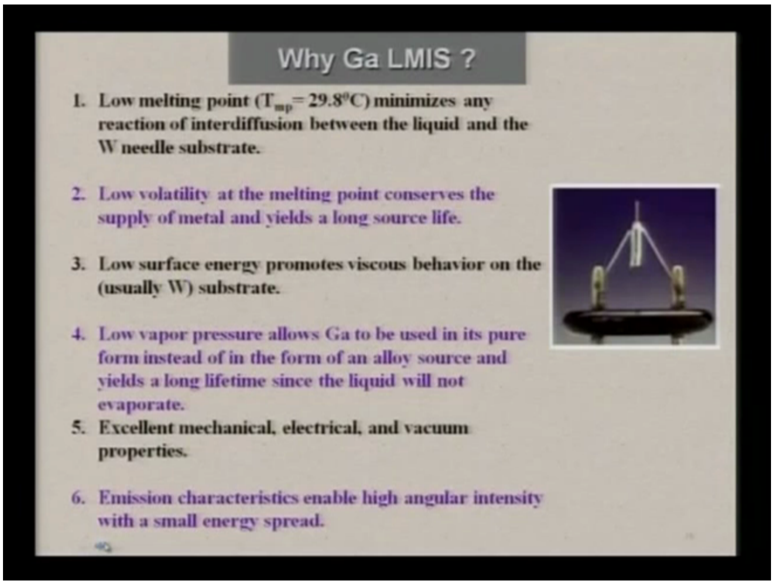

Now why Ga liquid metal ion source, low melting point, gallium has low melting point low melting point minimises any reaction of inter-diffusion between the liquid and the tungsten needle substrate. Low volatility at the melting point conserves the supply of metal and heels a long source life. Low surface energy promotes viscous behaviour on the substrate.

Low vapour pressure allows gallium to be used in its pure form instead of in the form of an alloy source and yields a long lifetime since the liquid will not evaporate. Excellent mechanical, electrical and vacuum properties are there. Finally emission characteristics enable high angular intensity with a small energy spread.

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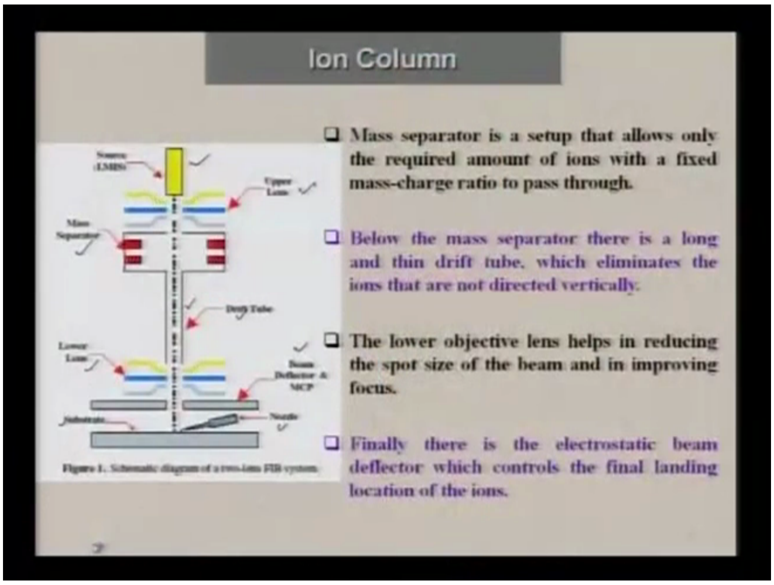

Now you can understand how this focused ion beam is produced in the FIB system. Here is the LMIS source which I have just explained in the earlier slide and you can see upper lens is there then mass separator is there. You have the drift duke then lower lens and beam deflector and MCP and then there is a nozzle for the supply of the gas and there is a substrate which is shown over here.

Mass separated is a set up that allows only the required amount of ions with a fixed mass charge ratio to pass through and here is the mass separator. Below the mass separator there is a longer and thin drift tube that is shown over here which eliminates the ions that are not directed vertically. The ions maybe at an angle to the normal to the surface and those ions are separated out by this particular tube.

The lower objective lens helps in reducing the spot size of the beam and in improving focus because we want as small the beam size as possible and the lower beam, lower objective lens helps in this particular objective to achieve. Finally there is the electrostatic beam deflector which controls the final landing location of the ion because when this focused beam is coming out then beam deflector is there and this beam deflector helps exact location of the beam on the substrate where you are going to remove the material or you are going to deposit the material. So that pinpoints for locates exact location of the beam to hit the substrate.

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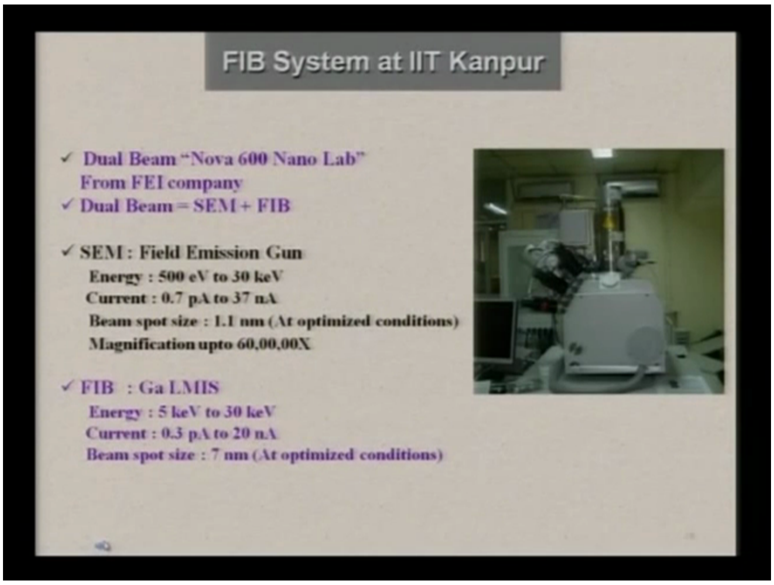

This is the FIB system available at IIT Kanpur which we will explain in the later part of this particular lecture. Dual beam Nova 600 Nano lab from FEI Company it was purchased. It has dual beam one is the SEM that is scanning electron microscope plus focused ion beam. SEM is field emission gun. Energy is 500 electron volt to 30 kilo electron volt. Current is 0.7 pica ampere to 37 nano ampere.

Beam spot size is 1.1 nanometre at the optimum conditions and magnifications is as high as 6 lakhs times you can obtain the magnifications. Focused ion beam gallium liquid metal ion source in this particular case. Energy is mentioned over here, current, beam size is 7 nanometre at optimise conditions.

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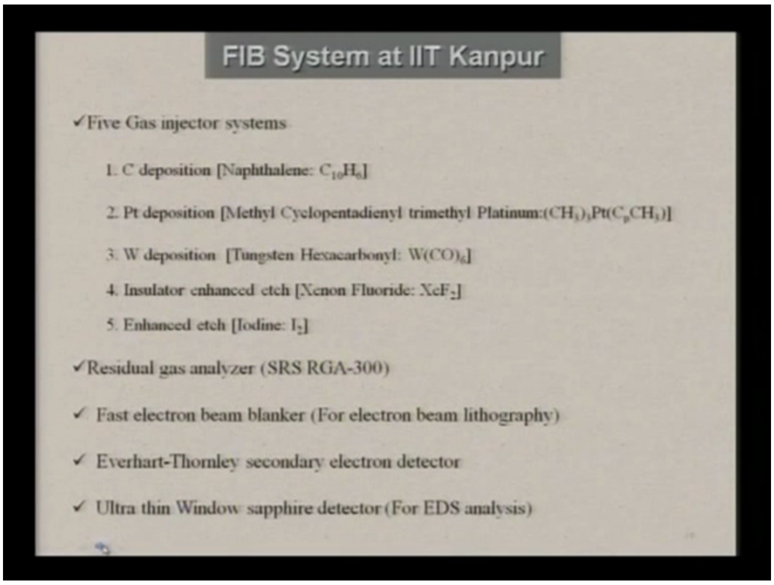

5 gas injector systems are there. C deposition, Pt deposition, tungsten deposition, insulator enhanced etch, enhanced etching with the help of the iodine, residual gas analyser is there, fast electron beam Blanker for electron beam lithography is there and Everhart Thornley secondary electron detector. These are some of the facilities available in the FIB system at IIT Kanpur. Ultra-thin window sapphire detector is also there.

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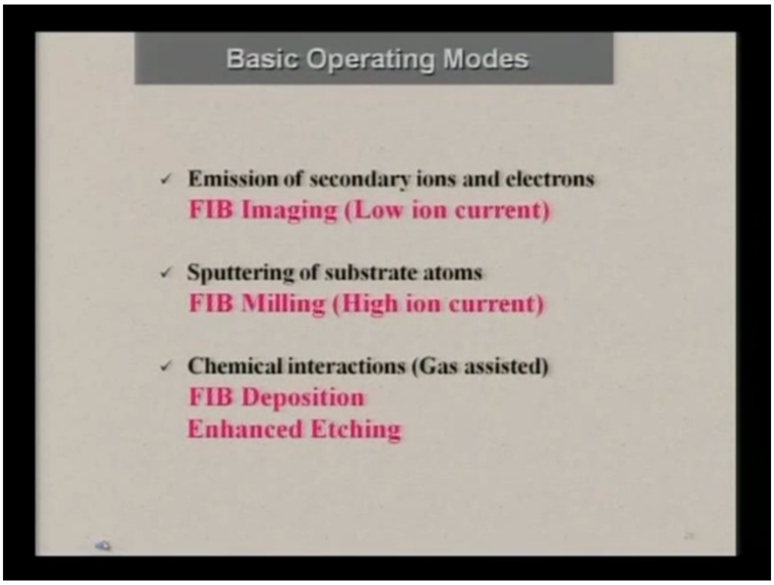

Basic operating modes of FIB system at IIT Kanpur, emission of secondary ions and electrons. FIB imaging used at low ion current. Sputtering of substrate atoms FIB milling operation is performed, definitely when you're performing the milling kind of operation or material removal and operation you need high current compare to when you are using this for imaging purposes. Chemical interactions gas assisted. FIB deposition this is very important because it is not only the removal of the material for which you can use this FIB, you can also use it for deposition of the atoms of other materials then that material may be in the form of the gas. Enhanced etching.

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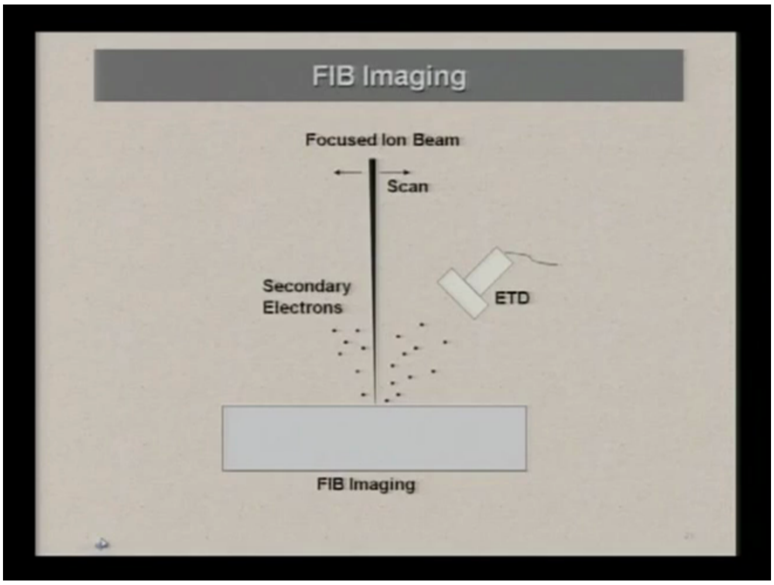

FIB imaging you can see this is how it is used that you have to secondary electrons, focused ion beam you can do the scanning of this for the imaging purposes.

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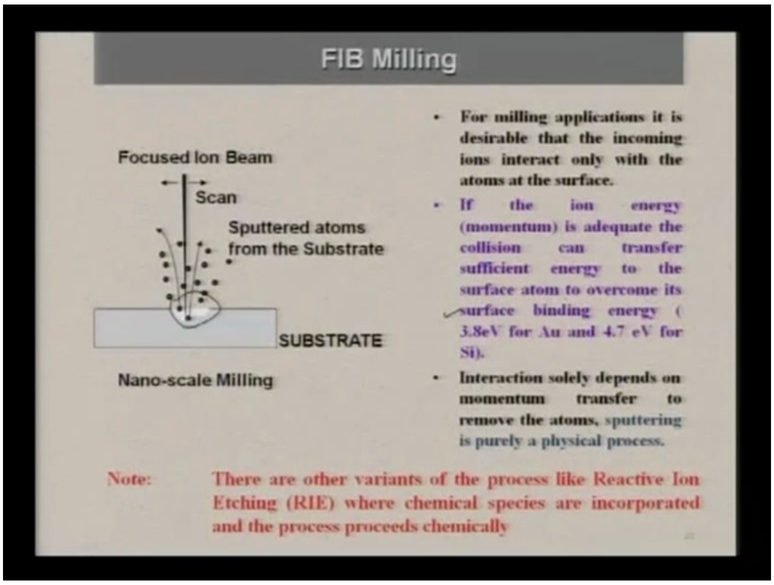

For milling purposes when FIB focused ion beam is hitting the work piece surface can see that atoms are scattered and the material is being removed from here, you scan the work piece and you can get the desired work piece shape by nano-scale milling operation. For milling application it is desirable that the incoming ions interact only with the atoms at the surface but in this particular case as you see here if the energy of the ion is more than really the energy required to separate out 2 atoms then what will happen?

Then more than one atom will be sputtered out from the top surface and the ion will get implanted inside the substrate which is not really desirable. If the ion energy is adequate the collision can transfer sufficient energy to the surface atom to overcome its surface winding energy that is what is shown here 3.8 electron volts for gold and 4.7 electron volts for silicon. If it is more than that interaction solely depends on momentum transfer to remove the atoms sputtering is purely physical process collection is expected there. There are other variants of the process like reactive ion etching where chemical species are incorporated and the process proceeds chemically.

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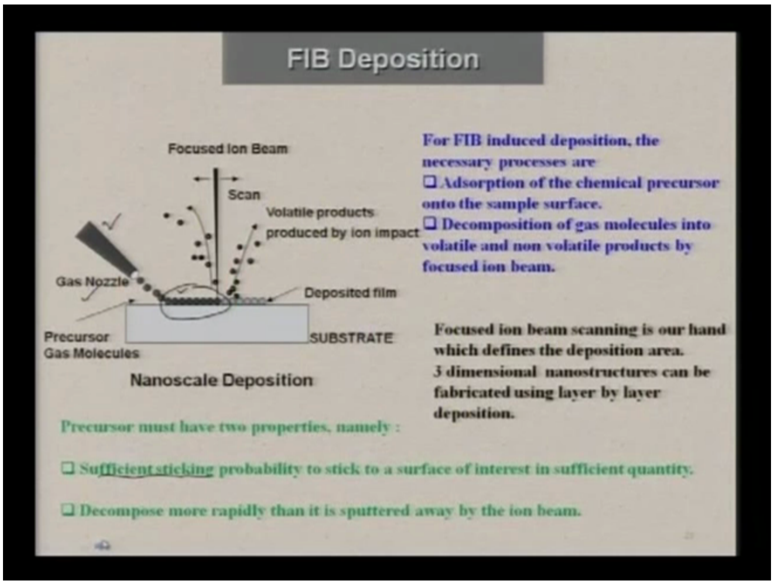

This is another very important application FIB deposition, as you can see here nano-scale deposition is shown over here important is here precursor gas molecules which are supplied with the help of the gas nozzle over here and then focused ion beam scanning is done and when interacts with this gas atoms they get deposited over there and the film of the gas whichever gas is supplied from there is formed on the substrate.

For FIB induced deposition the necessary processes are adsorption of the chemical precursor onto the sample surface as you can see here, this adsorption is very essential otherwise the material or the atoms will not get adhere to the substrate. Decomposition of gas molecules into volatile and non-volatile product by focused ion beam. Focused ion beam scanning is our hand which defines the deposition area.

3 dimensional nanostructures can be fabricated using layer by layer deposition by using this particular nano-scale deposition process. Precursor must have 2 properties namely sufficient sticking probability to stick to a surface of interest in sufficient quantity this is what I mentioned sometime back that this atom they should stick to the work piece surface or substrate, so that they remain and they form the microstructure or nanostructures later on. Decomposed more rapidly than it is sputtered away by the ion beam, these are the 2 essential properties for the precursor gas.

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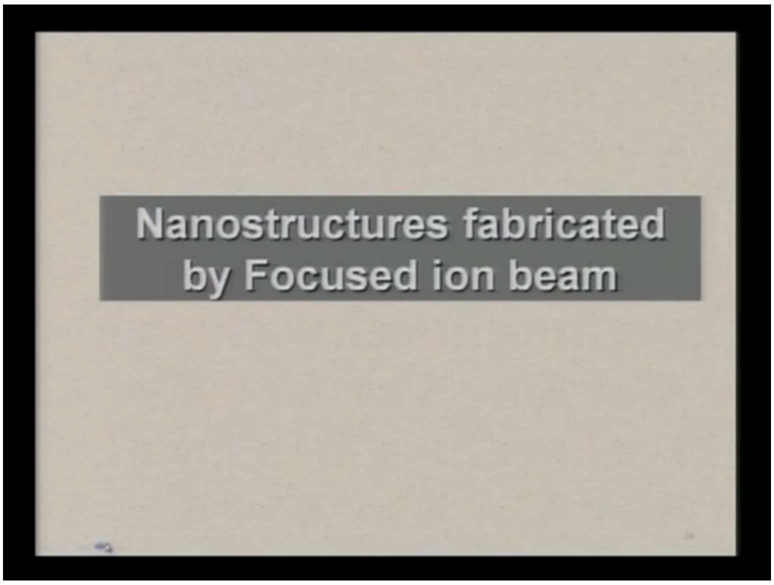

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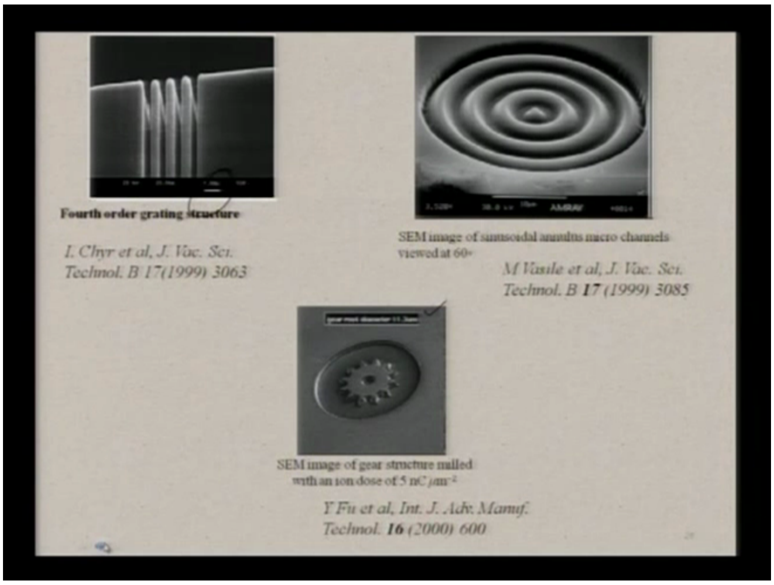

Nanostructures fabricated by focused ion beam. You can see here for order grating structure which has been formed with the help of this focused ion beam machining and you can see the scale over here 0.5 micron, so you can judge the size of the grates that are being formed over here is somewhere less than 1 nanometre. Here again SEM image of sinusoidal annulus micro-channel viewed at 60 degree. This is another SEM image of gear structure milled with an ion (())(26:40) of 5 Nc per micro-meter square. So you can see gear root diameter is 11.3 micrometer.

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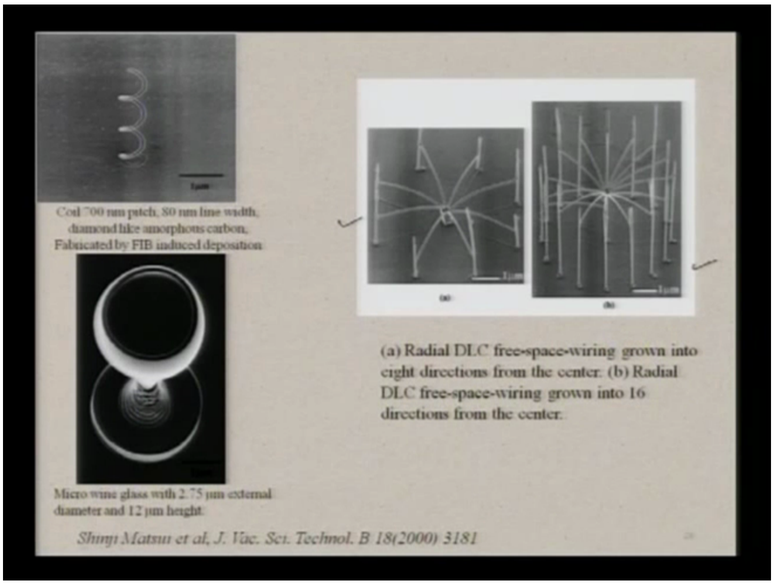

There is another very interesting application of focused ion beam, here is a coil kind of the thing which has been developed using the focused ion beam deposition process, there is another micro-wine glass again developed with the deposition process layer by layer deposition process and then this is a complicated radial DLC free space wiring grown into 8 directions from the centre over here and there is another radial DLC free space wiring grown into 16 directions from the Centre on the right-hand side and these are some very interesting complicated applications of the focused ion beam deposition processes.

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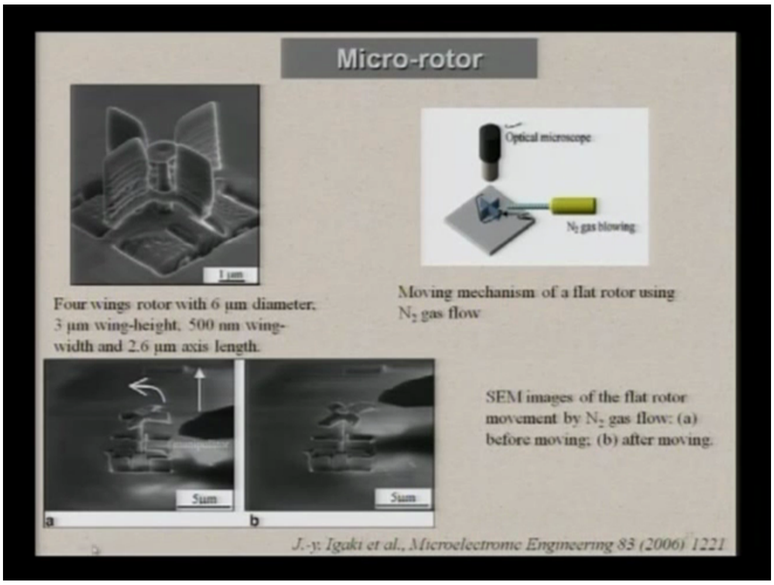

Micro motor 4 wings rotor with 6 micrometre diameter, 3 micro-meter wing height, 500 nanometre wing width and 2.6 micrometre axial length. So you can see these are the kind of the micro-nanostructures can be formed by layer by layer deposition using focused ion beam. Moving mechanism of a flat rotor using nitrogen gas flow. Now you can supply the gas and then this rotor will start rotating depending upon the direction of the gas in which you're supplying it and you can see with the help of the optical microscope.

And then some other applications SEM images of the flat rotor moment by nitrogen gas flow before moving and after moving, you can see here this is the one and this is after moving and very interesting and wonderful applications of the focused ion beam deposition and that scanning.

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Thank you very much, now Mr Neeraj Shukla of physics department Ph.D. scholar of IIT Kanpur will demonstrate you FIB set up that we have purchased at IIT Kanpur and some more details and applications and some of the very interesting micro-nanostructures that have been fabricated at IIT Kanpur, thank you.

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Hello viewers myself Neeraj Shukla, I will be describing there about focused ion beam instrument. I'm a graduate student from Department of physics pursue my Ph.D. over here and I will be telling you about focus ion beam and its applications and what is the principle behind its working? So in next 25 minutes I will first describe what is a principle involved and then there will be demonstration of the instrument as well as the structures made by the instrument.

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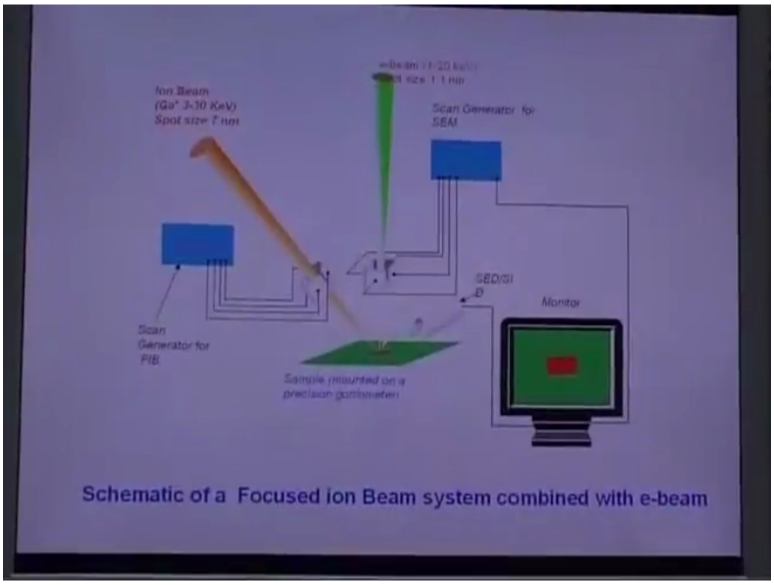

So let us see what is FIB all about? Okay, this is just a schematic of focused ion beam setup this is called dual beam setup and it is equipped with both electron beam as well as ion beam. So what you see here in this geometry this is electron beam and energy is from 1KV to 20KV and this is ion beam and energy can be varied from 3 KV to 30 KV and beam spot size is 7 nanometre.

Here electron beam means per size can be 1.1 nanometre and as you see here that there are some electrostatic arrangements, 2 parallel plates and coupling, here also you can see 2 parallel plates opposite to each other and these are all for generating scan images of patterns you want to generate, so like we can generate any bitmap image and make ion beam go in that fashion, so that you can image the patterns made by FIB.

So the purpose of dual beam is whatever you structure with ion beams you can simultaneously image by electron beam or later on, you do not have to take out your sample, so that is the usefulness of having dual beam and then there is a secondary electron detector which is used for scanning electron microscopy and this is a monitor where all the scans and their parts are generated.

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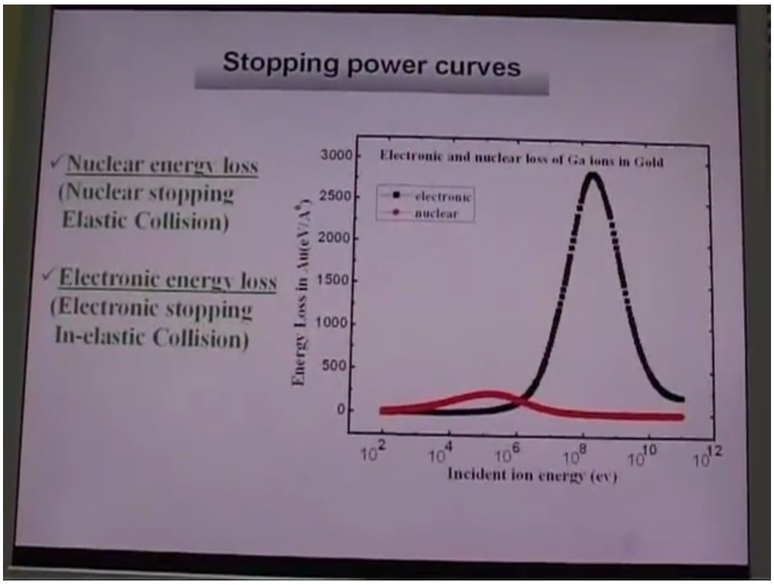

Now I will explain you what are the principles involved in ion beam nano-structuring, so as you can see that this is stopping power curves. So when an ion beam interacts with a solid there are 2 types of interaction that happen, one is electronic and one is nuclear energy loss and for example here we have simulated 30 KV gallium ions in gold I would not say 30 KV it is like whole range and the gallium ions we are concerned here with focused ion beam they are of 30 KV energy range.

So here we have talked about full range of gallium ions starting from 100 electron volts to 10 to power 12 electron volt. So you can see that this red curve represents nuclear energy loss and the this black curve represents electronic energy loss of gallium ions in gold substrate and nuclear energy loss can also be termed as elastic collisions and electronic energy loss is termed as inelastic collisions.

As the name suggests this nuclear energy loss, so when energy of the incident particle is very small let us say this is one this you can say as 10Kv this 10 to power 4ev means 10 KV, so at 10 KV you see that electronic losses pretty small and nuclear energy loss prevails. So you can see that at low energies this nuclear energy loss and prevails over electronic energy loss.

So when an ion interacts it loses its energy by giving it to the nucleus, nucleus also does a recoil as well as incident ions gets scattered of the nucleus and it goes in Cascade and from the surface atoms are ejected. So nuclear energy in this regime when an ion hits sputtering phenomena takes place, sputtering means ejecting out of substrate atom by incident ions. So you can see that it has nothing to do with electronic energy loss.

So if you have to structure your sample by ion beams, so you have to stick into this energy range and as you go to the higher energy range. Let us say this 10 to power 6ev are beyond that, that is the energy range in case of accelerators there this electronic energy loss is too much and nuclear energy loss small. So this clearly tells you that as you increase the energy beyond this point there will be no sputtering because nuclear energy loss is only responsible for sputtering this electronic energy loss what it does?

It just heats up the solid because incident ion energy is transferred to the electrons only and they just heat the solid and I mean they do not take substrates atoms out. It can happen but only in the Polymer's case and other but in normal metals it is not responsible for sputtering.

And also one thing is to note down that when energy is small that when energy of the incident (())(35:05) cross-section is too much as compared to when energy is higher. So in this regime cross-section of incident ions is very small that is why ions go very deep it into the substrate and here they just interact with the surface. So this energy range is used for ion beam sculpting, ion beam milling and other fascinating nano fabrication applications and this part is used for ion implantation and other applications in semiconductor industry for other radiation effects and that is the scope of some other study. So we will stick to this energy range from 10 KV to 30 KV in the present sample which we have to study.

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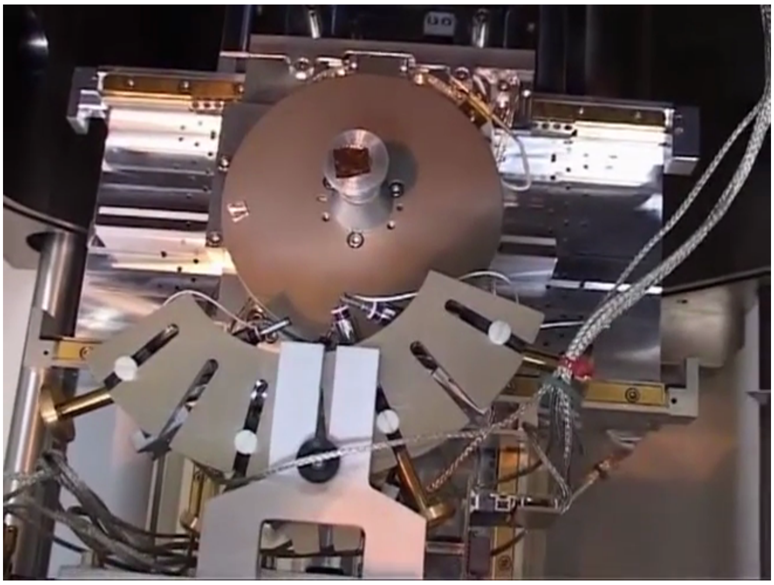

Now I will explain you FIB components and how it is peripheral auxiliary accessories enables very high precision nano Manufacturing. So this is what you see is a piezoelectric stage and it is capable of 5 axis moments. So can you please run the home stage? This I am running home stage procedures and then system itself finds out its coordinates in all the 5 dimensions, 5 I mean that X, Y, Z axis and then this is getting tilted right now and then there is rotation.

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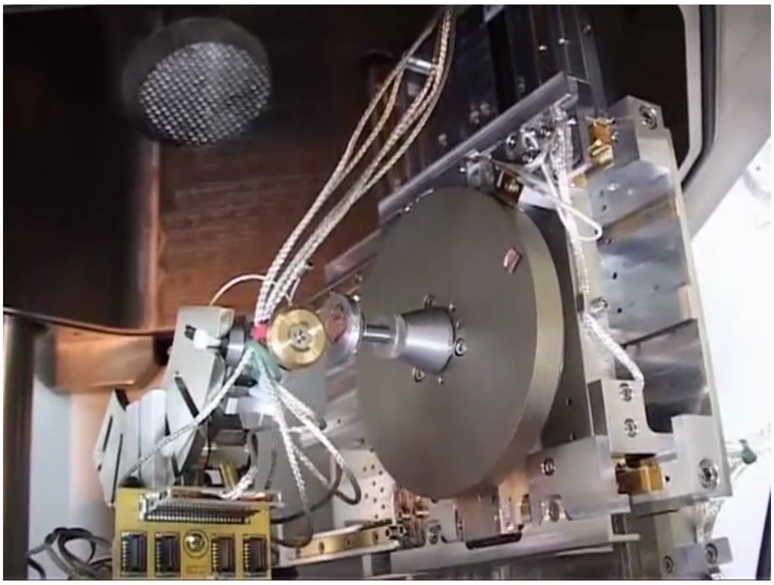

So X, Y, Z, tilt and rotation, so this is home stage procedure is running, so that system knows its coordinates. So it will go into the extremities of all the dimension is and thereby finding out its origin and then you can ask stage to move wherever you want.

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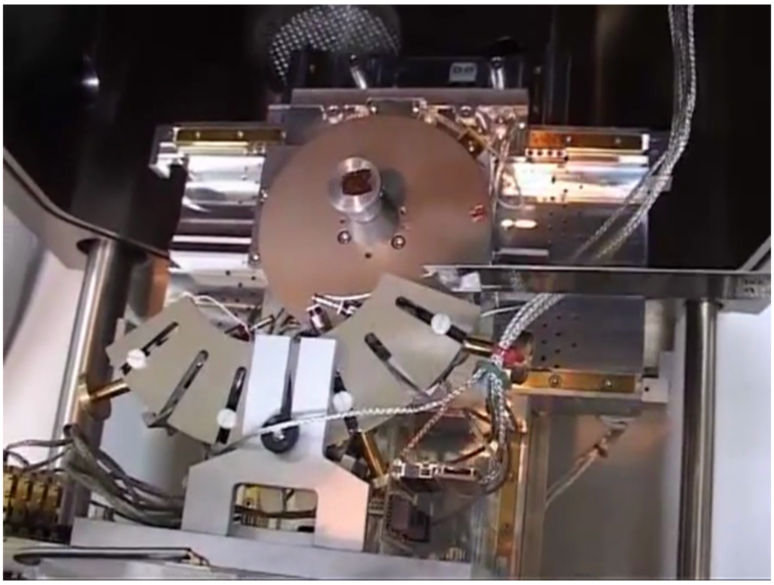

This is an auxiliary arrangement for nano manipulation; you see there are arms this, this and this. This is too manipulate some nano structure you have made and this is substrate holder where we mount our substrate and this one is perpendicular to the electron beam and when we have to do some nano milling by ion beam we have to tilt it by 52 degree. So that this substrate surface becomes perpendicular to the ion beam.

So when substrate is tilted at 52 degree than this surface becomes perpendicular to the ion beam and at the same time we can do imaging by the electron beam. Now I will explain few other parts that how is it capable of doing deposition also. I mean so far we have talked that it is capable of milling and it is also capable of deposition. So let me explain you some other parts.

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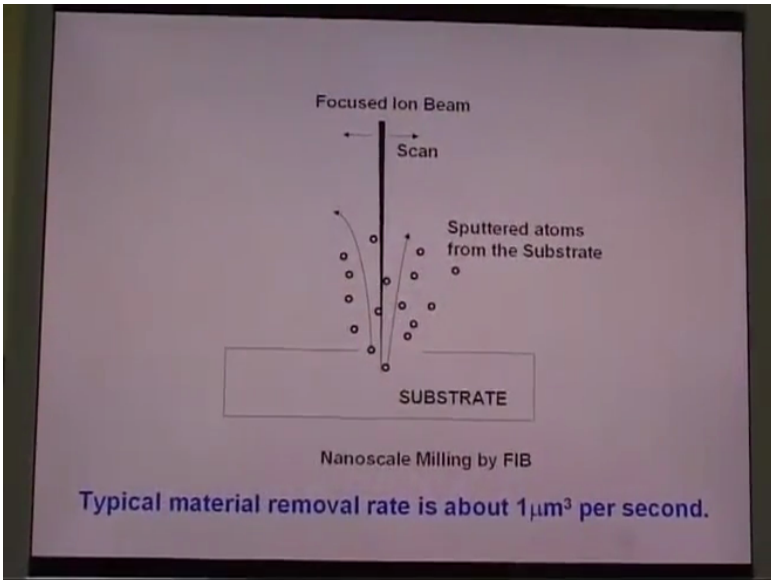

As I explain that in low-energy regime when ion interacts nuclear loss is prominent and that is responsible for the material sputtering. So here what you see that when this ion beam hits the substrate materials is eroded. So this is just a typical material removal rate is about like 1 micron cube per second.

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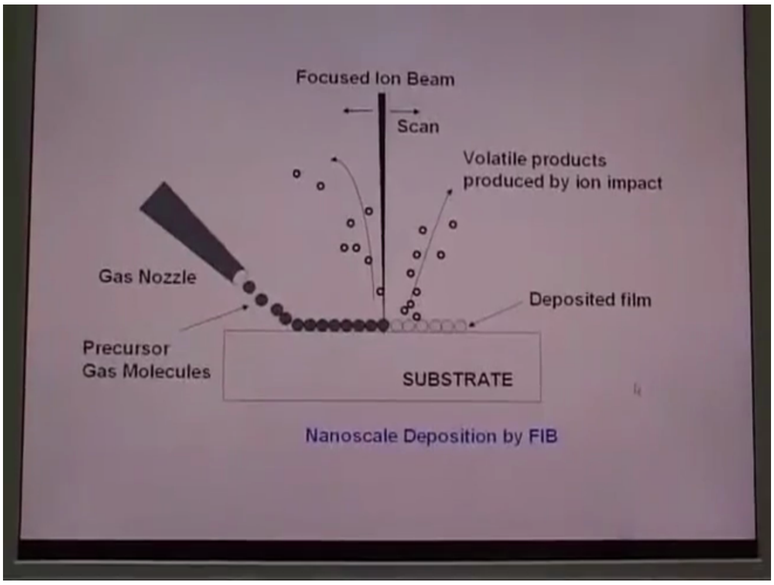

There is one other aspect of focused ion beam that you can have nano-scale deposition by FIB, this is also termed as ion beam induced chemical vapour deposition and this process what we do? That ion beam assist deposition of some other components for example platinum, tungsten, carbon, SiO2 and gold and there can be many more. So the principle involved is that you have a precursor gas, this is just a nozzle of that gas and precursor gas can be various types.

Just for instance that if you have to deposit platinum you have to have one organometallic gas such that it contains 1 platinum atom. So it is a very long chain organometallic gas and that is the job of Chemist to come up with various types of gas which will assist the deposition of different components. So as I said that in case of carbon we need tungsten, carbonyl it is a very long change and very big-name.

So suppose you have made some organometallic gas and then you spray it with the nozzle, this nozzle dimension's are pretty small (())(40:07) some 50 to 60 micron and they are kept very close to the vicinity of the substrate in about 100 micron from the substrate and then the gas space that organometallic gas on top of substrate and as I showed you that there is for plates around the beam based for scanning the beam in desired dimensions for making bitmap images and patterns.

So beam scan in a preferential manner and your gas is everywhere, so wherever beam goes it cracks that organometallic molecule by giving its energy to them and when it decomposes these organometallic gases, cracking means decomposition here and so it decomposes it into various components volatile and non-volatile. Volatile will be some ethane, methane and other gases and non-volatile component will be that metallic atom that is contained in that organometallic gas.

So this way the platinum, tungsten, carbon can be deposited and their deposition is assisted by ion beams and so in whatever manner you want you can deposit that beam and this approach is called bottom to top approach.

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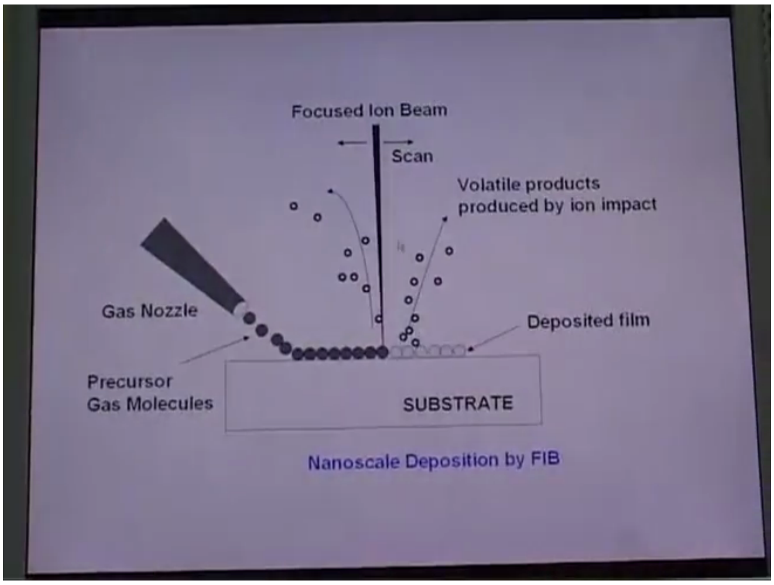

And the previous approach is called top to bottom approach and which this focus ion beam is capable of doing both.

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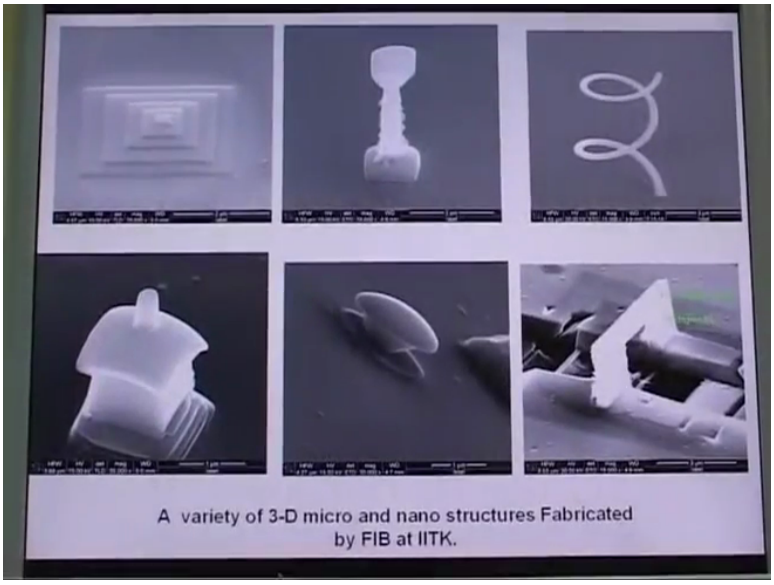

These are some of the patterns which have been made by the FIB, here you can see that encapsulated pyramid type of a structure and here you can see that a dumbbell shaped structure has been made and these are all layer by layer deposition that you deposited one layer then other player than other player and then smaller you did then smaller and then overhanging structures also can be made and these are all made in very gradual manner, it is not like in one go you have been able to make them.

Very thin, you can just divide all this metal by thin slices and then one by one it has been done and similarly we can deposit some you can see this than a spring can deposit then some other fascinating three-dimensional structures and this is some lens and this is a bridge kind of structures, so it can be used for nano pirani gauges to sense temperature is the principle special measurements. So it can be used as a thermocouple.

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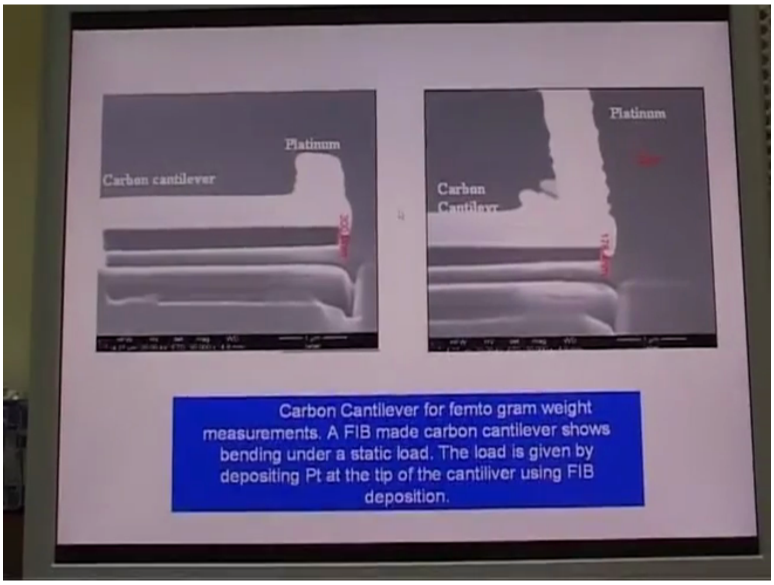

This is some cantilever fabrication and loading mass on them by focused ion beam. So first of a wall is made and then as I explained that there are 5 dimensional moment of the stage. So first you make this wall then again make the stage at grazing angle to the ion beam and then do the undercut then again rotate the stage in such a manner, so that the top surface becomes perpendicular to the ion beam then again further you deposit this platinum. So this way this is a multistep process to reach this process, it is not one step you first deposit this then mill then again deposit this load and then you can measure how much is the bending of the cantilever by the load you have put in.

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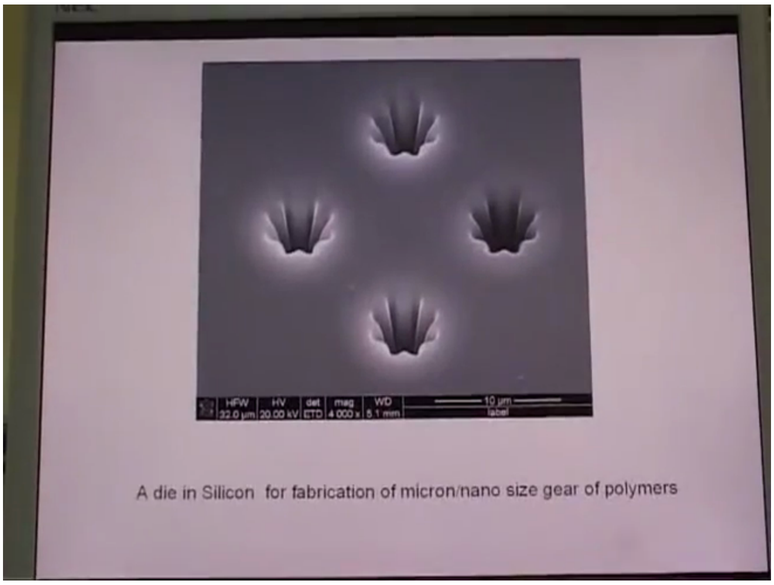

This you can see that some dye can be made also with the help of FIB for casting Polymer grooves. So here you can see that these dyes have been made in silicon and to cast Polymer or any other substrate suitable substrates materials grooves. So this all have been made FIB. So here for making this type of structures you first come up with a bitmap image of this kind and then mill with the help of FIB.

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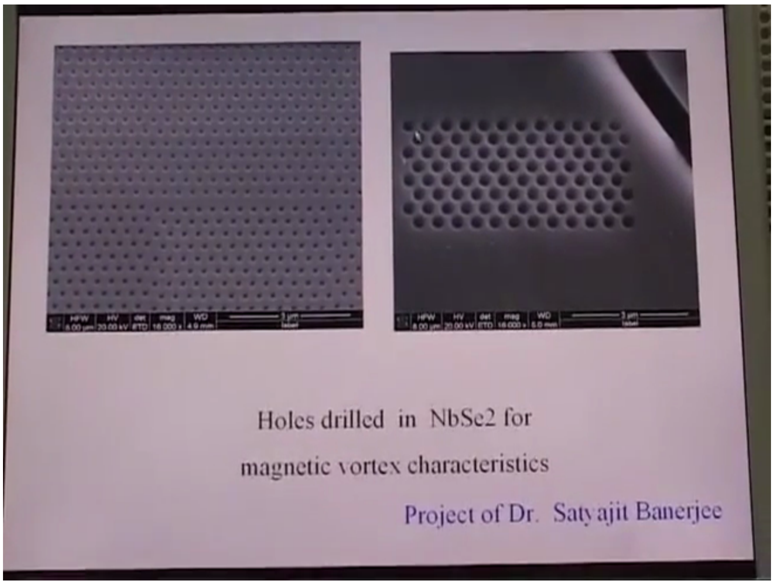

These are some other patterns which have been milled without any precursor gas. So the idea is when you have no precursor gas ion beam will mill when you have precursor gas ion beam will deposit that particular organometallic material. These are some holes drilled in niobium selenide.

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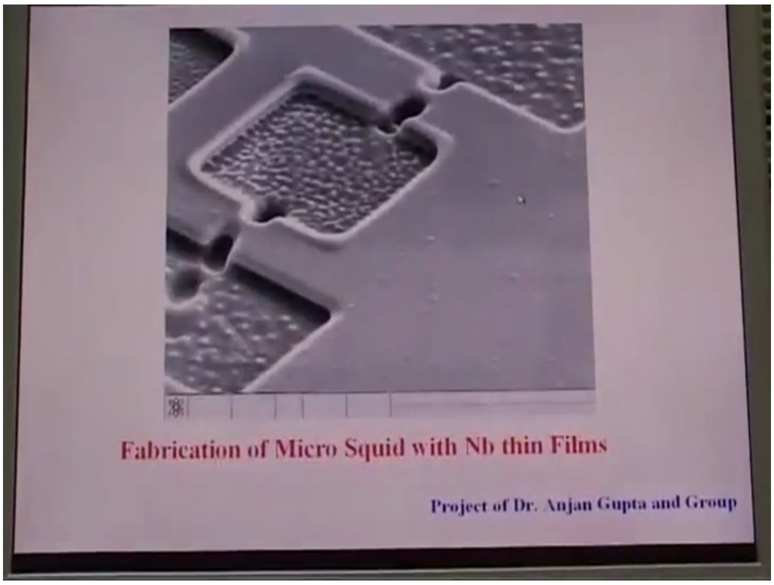

This is a fabrication of micro-squid with the help of niobium thin films.

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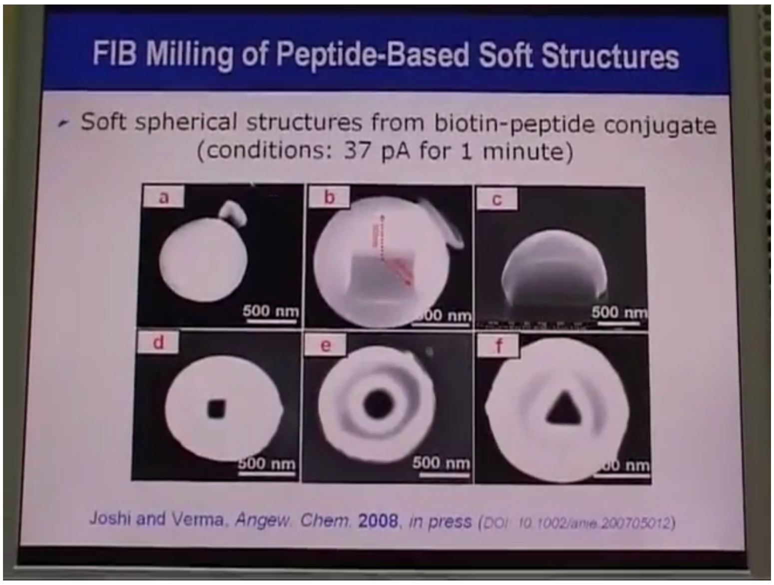

Again FIB milling has been useful in peptide-based soft structures you can see various types of studies have been done on soft polymers.

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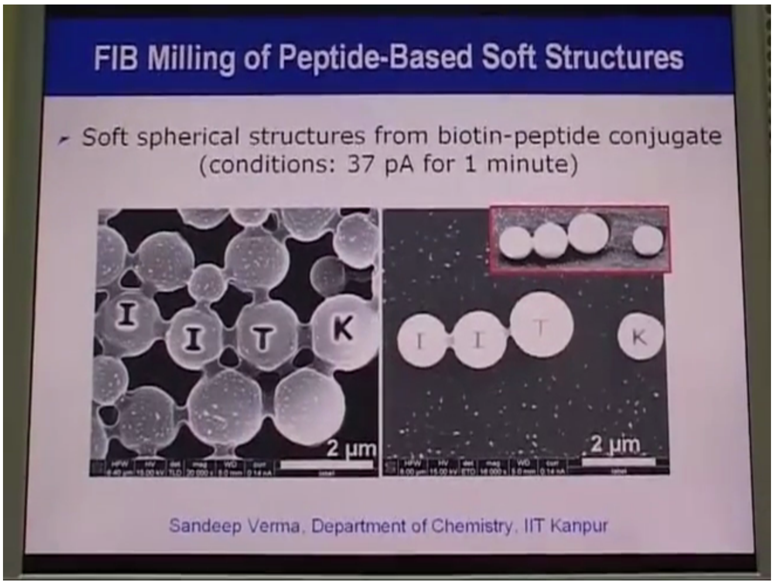

Here it has been useful in writing name and you can see the scale it is at 2 micron and it is on peptide substrate.

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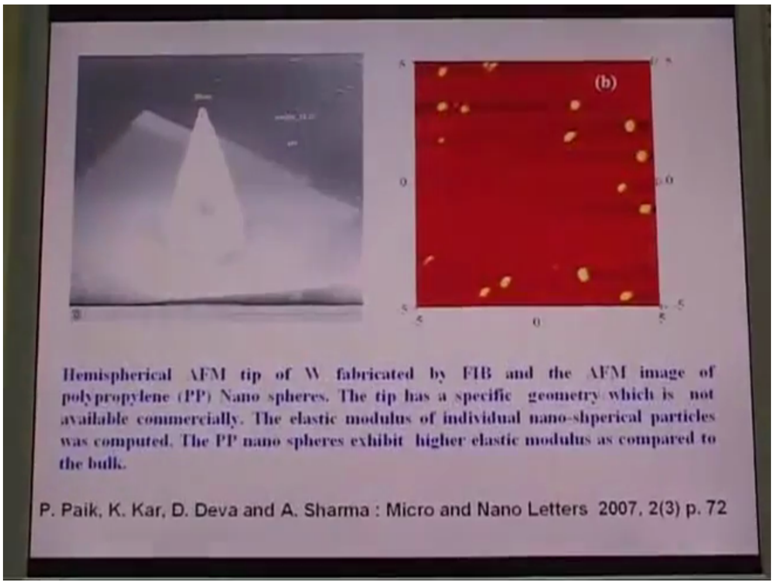

This is also useful for deposition tungsten tip, as I explained that structure has been gone one by one like one big circle with some height then again further with a smaller diameter than with some elevated height and like that you reach at the tip. So this tungsten tip has been used for AFM imaging by one of our Institute groups and they have also been able to image AFM images with the help of this tip and that is this image.

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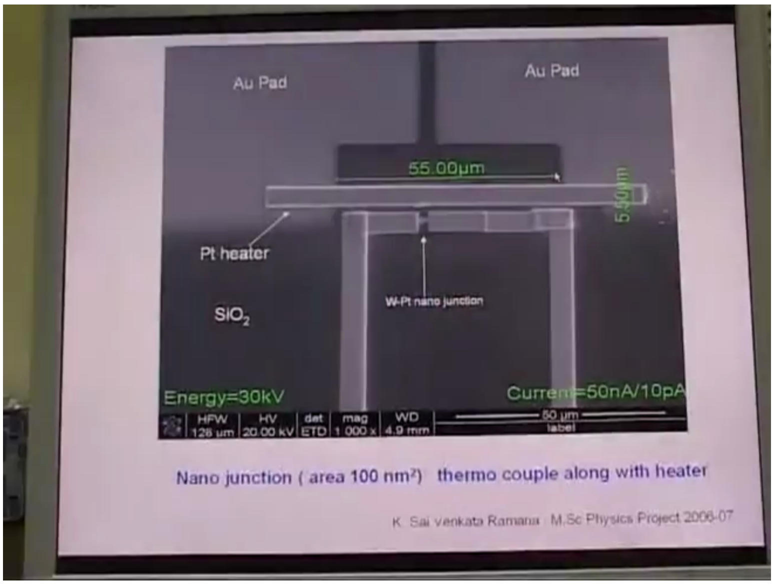

This is another application of focused ion beam that we can make nano thermocouple and so that you can use them either as a pressure Sensor or temperature sensor in aero-dimensional. So here but you see that these are gold pads well separated by this and this separation was also done by ion beam milling. So this is one example where milling and deposition both have been done.

So first you fabricated gold pads and then you electrically disconnected, you see that here in this region has been milled by FIB and then further you deposit this platinum wire. So this wire has been deposited by focused ion beam using platinum precursor gas and then again you deposited this part is tungsten and this part is platinum and they have been this junction dimension is 100 nanometre by 100 nanometre and they are very close to the this heating wire.

So the idea is that we heat through this pad we apply current through this wire and then it heats up due to resist heating and then what happens? That this heat is sensed by this tungsten platinum nano junction and so again these are connected to some pads where the voltage Thermo EMF generated is measured through these 2 pads.

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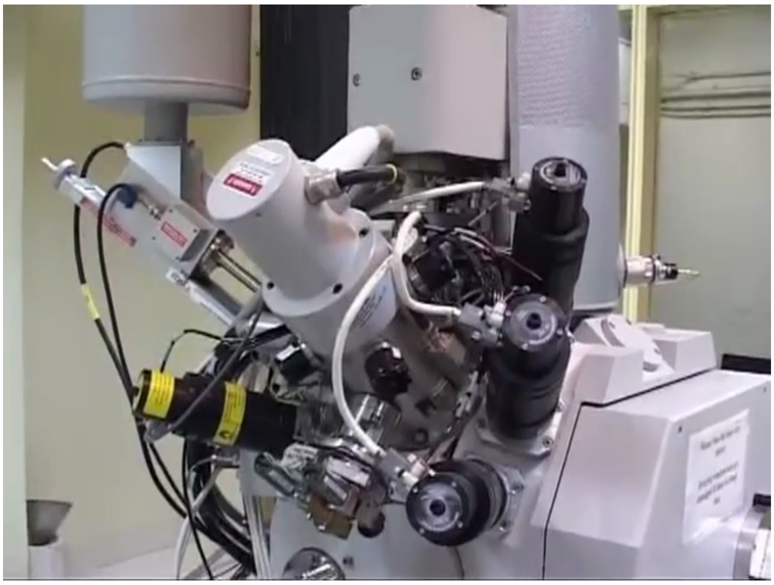

Now I will explain the system overview that how in actuality all the components look. So this is electron beam as I have explained in the schematic and this one is ion beam and these are 3 precursor gases we have 1, 2 and 3, these corresponds to platinum, tungsten and carbon and this one is EDAX energy dispersive x-ray spectroscopy and this one is used for elemental composition mapping of the substrate.

So this whenever electron hits various phenomena takes place like second electron injection, x-ray emission, so that there is one more detector for x-ray detection and this is helpful for elemental mapping and these are 2 other bottles this is genome fluoride and this is iodine gas these are used for insulator etching, genome fluoride and Iodine is used for metals etching by ion beam. So etching in insulators is very tough that is why these gases assist etching by ion beam and these 3 assist deposition by ion beam.

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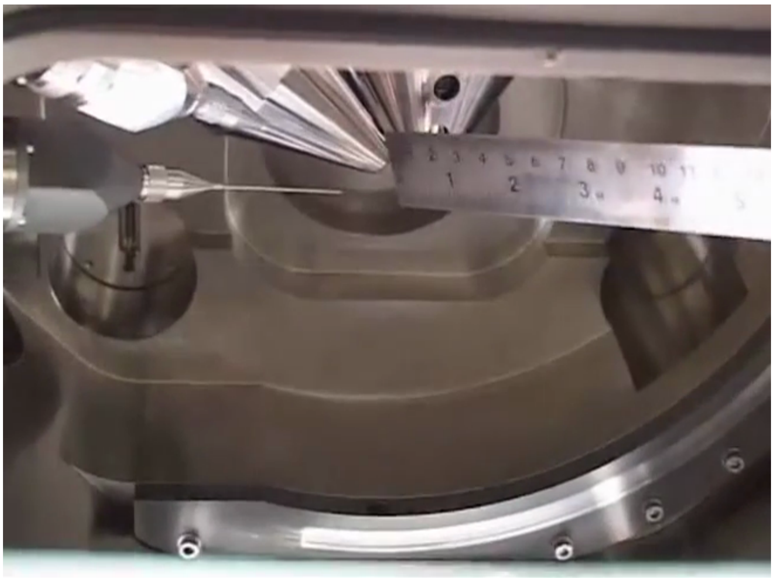

I will just explain how they go inside the chamber, so as you can see inside the chamber this is electron beam this is ion beam and these 3 are the precursor gas nozzles and one has to be very careful handling these precursor gases because if you incidentally the substrate the tip might be broken.

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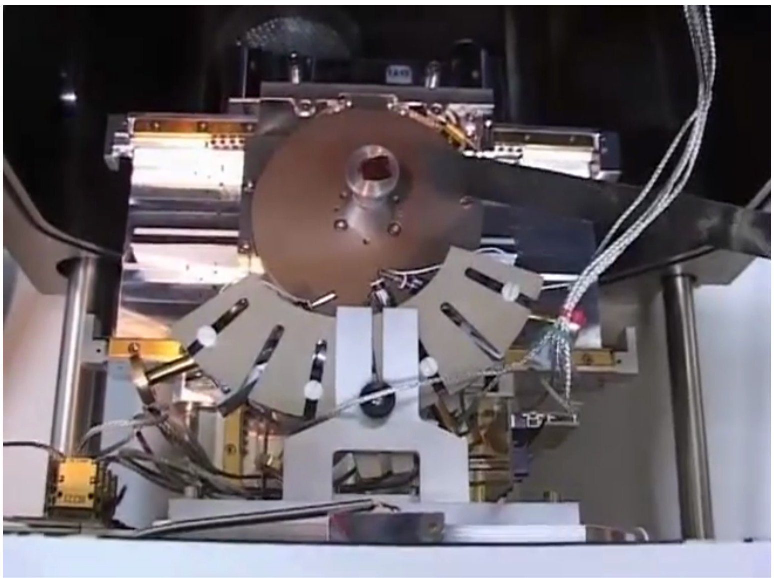

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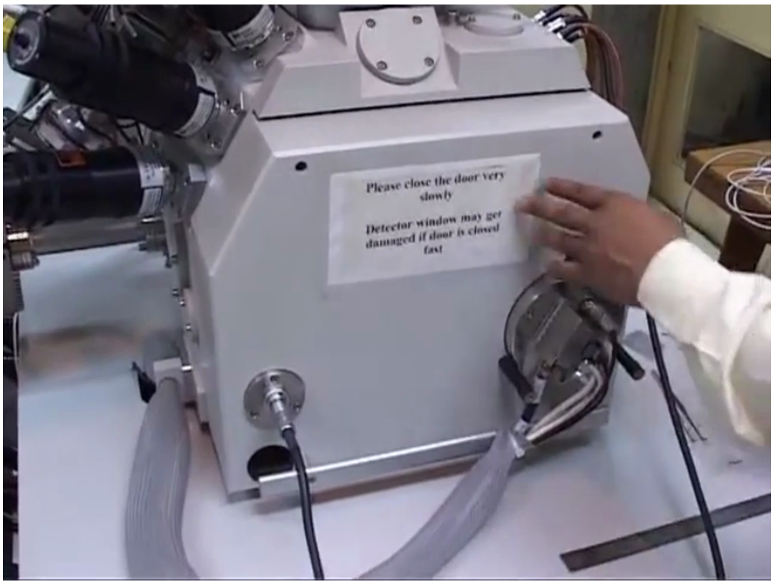

And substrate is mounted over here and precursor gases come very close to this substrate as I explained that around 100 micron and one has to be very careful while mounting the sample this the distance from the top surface to this base is kept within some permissible limits and it should not go beyond that otherwise it might hit the electron pole pieces and ion column in the precursor gases and then when we load when we close in and then the substrate reaches close to the precursor gases.

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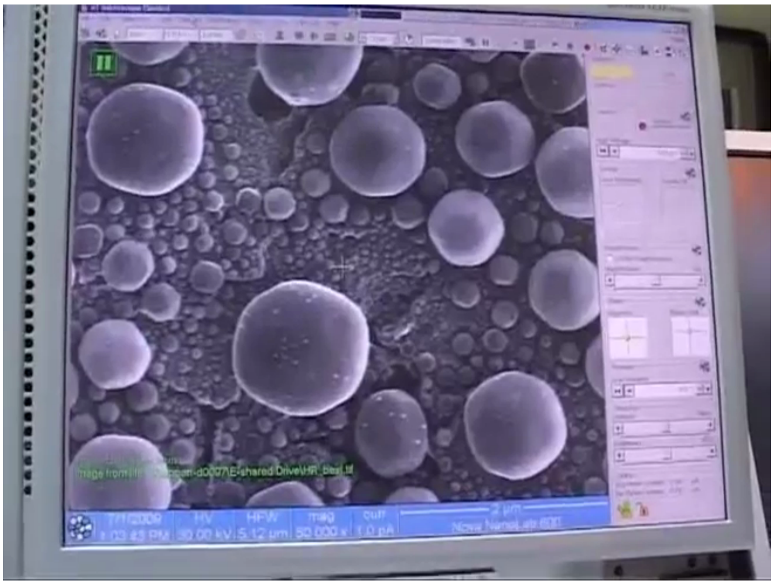

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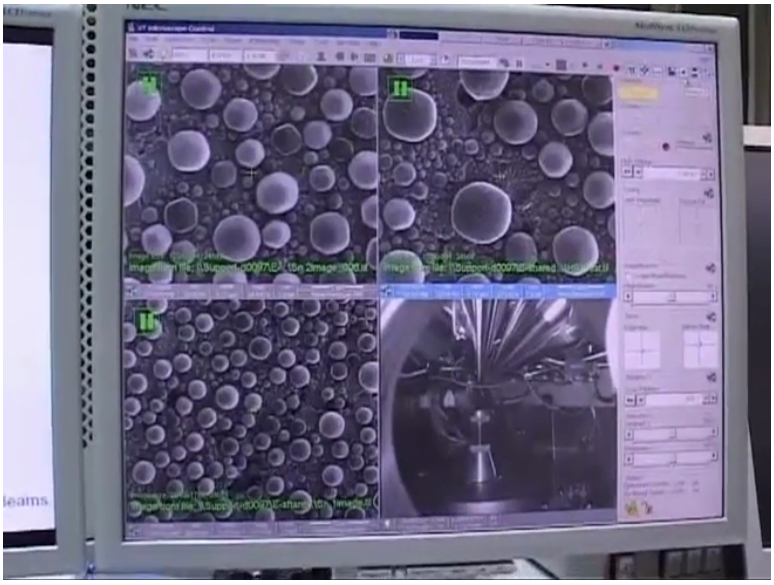

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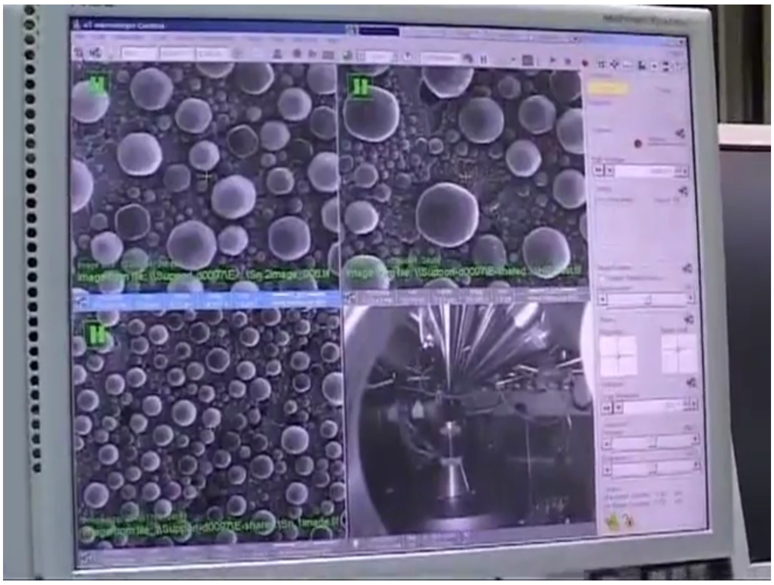

And then we found the system whenever we have mounted ever substrate and then there is a console. Now after we load the sample we pump the system. So this is a computer control for nano fabrication of focused ion beam and as you see that there are 4 quarts, here you see the CCD image of FIB chamber and as explained that this is a ion beam, this is electron beam and there are various precursor gases and this 4 quarts, this one is used for electron beam imaging, this one is used for ion beam milling, this quart.

Any quart can be used but we have been using this for electron, this for ion beam and this you see that we select the beam on and then you can select the high-voltage and there for us some lens alignment and procedures and you can magnify these images in the screen using this knob and then when you have 2 patterns some images you just select whatever kind of pattern you want to mill.

Let us say rectangle, just select the rectangle and then when you select the beam current it shows the time available for milling. So you select here X, Y and Z dimensional of the patent to be milled or to be deposited on some substrate and we can also select polygon, circle, line, so suppose we have selected here a circle and its dimension we can give inner diameter we can give.

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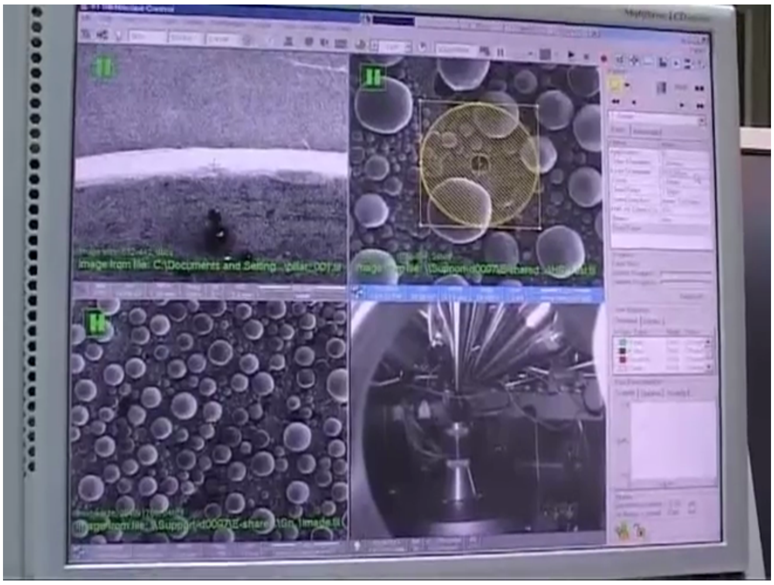

Suppose if we give some inner diameter than it will be a annular ring. So inner radius and outer radius you can give and so that you can mill the way you want. So here you can see that it is like annular ring. So inner diameter is 200 micron and outer is 1200 micron. So whenever we radiate something we can immediately look in the electron (())(52:35) that how we have sculpted the ion beam pattern over here and these are the various controls for various precursor gases platinum, tungsten as I said the genome fluoride enhanced its then carbon deposition and then this is again insulator enhanced etch.

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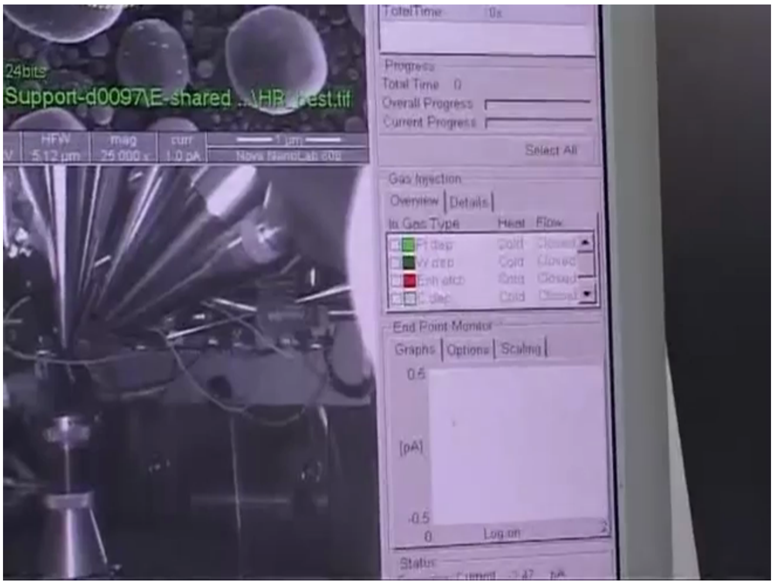

So this one is for Iodine this enhanced etch and this one is for insulator enhanced etch that is genome fluoride is here. So these are all controls for 5 precursor gases and here with the help of these controls the first heat these gases up and then the flow is opened and then ion beam is incident and then that cracks the precursor gases and this is how this focus ion beam fabrication works.