Bio - Microelectromechanical Systems

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Module No. # 01

Lecture No. # 34

Hello and welcome back to this lecture 34, on Bio-Microelectromechanical Systems.

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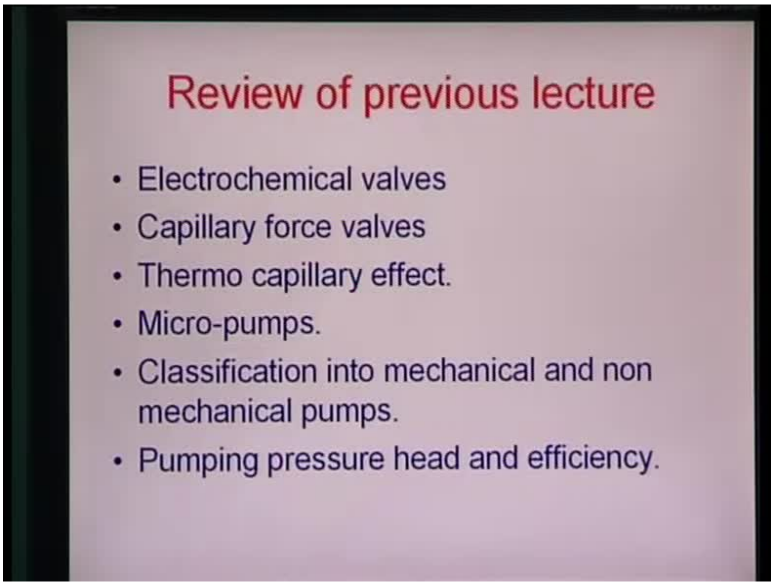

Let us do a quick preview of what we did last time. We talked about designing and development of electrochemical valves, this was followed by capillary force valves and thermo capillary effect. We use this effect also to study micro pumping and valuing later on. As you know, capillary force valves are essentially based on electrical fields applied to bubbles with an unequal or non-homogenous distribution of charge on the surface. Similarly, thermo capillary effect is done by changing the surface tension on both ends, by heating a bubble differentially. The idea is that the bubble move towards the lower surface tension, the surface energy balances for the bubble to move into that direction.

We also talked about micro pumps, then classified them into mechanical and non-mechanical. This is essentially dependent on the way that energy is being added to the system. You can have energy added by means of vibrating membrane or vibrating boundary, which can be the mechanical micro pump. Then, non-mechanical basically would include a form of energy added without any vibrating membrane. Energy is directly pumped in by other inducing mechanisms, like electric fields, magnetic fields, so on, so forth.

We also talked about pumping pressure, head and efficiency. Pumping pressure, as you know, a pressure head is basically also found out by looking at the Bernoullis equation. Efficiency is essentially the actuation efficiency, so this basically equal to the flow rate causing. Therefore, the pumping efficiency is also the difference between or the ratios between the power required for pumping divided by power required for actuating the micro pump.

Essentially power supplied, it is a ratio between the power generated by means of flow and the power supplied into the system. So, this is as far as last lecture goes, now they will be starting on designing. We also talked in the last lecture about one thing, which was a kind of phenomena, which was related to peristalsis. Peristalsis, as we know also is a motion of travelling contractile in a micro channel, which causes flow to happen. Therefore, we essentially discussed about the three layer device, wherein actuation is done by mechanical means, by moving boundaries with high pressure compressed air flowing in a sequential manner into the blisters, which causes the movement of the fluid underneath it.

Essentially, what happens is that the contractile motion is discretized, which results in unidirectional flow within the microchip.

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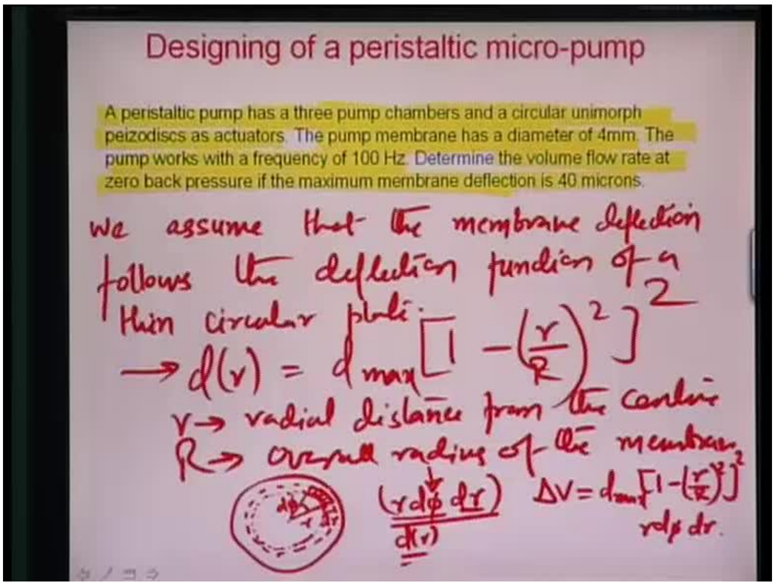

Today, we will be discussing a design problem to begin with, where we talk about how such mechanical pumps can be designed and developed. Therefore, in this particular example, as you see, there is a peristaltic pump, which has three pump chambers and a circular uniform peizodisc as actuator. The pump membrane has a diameter of about 4 mm. The pump works at a frequency of about 100 Hz. We need to determine the volume flow rate at zero backpressure, if the maximum membrane deflection is about 40 microns.

Here, we actually assume that the membrane deflection follows the deflection function of a thin circular plate. We assume the diameter or the deflection at radius r from the center is also equal to d max, which is the maximum deflection at the center minus 1 minus small r by big R square whole square. Essentially, small r is the radial distance from the center of a point and big R is the overall radius of the membrane.

Using this deflection function, we need to find out what really is the volume displacement at a certain radius r, from the center of such a circular unimorph membrane, which is moving and causing the peristalsis effect within the micro pump. Here, essentially, let us draw this, you have a circular chamber here, there is radial distance r over which we are considering the deflection. Also, we are assuming that there is a distance dr in this region of the element, which we are considering the deflection.

Essentially, if you just draw a circle around this point of radius r and another circle at radius r plus d r. If you would like to consider the area, which is available between this r and r plus dr. The area essentially is, if you consider a small angle d phi here, between the radius r and r plus dr. We want to find out really what is the area of cross section or what is the total area of this particular element here, which is shaded as you are seeing, it is really given by rd phi times of dr.

Eessentially, rd phi being this length sector, dr is the small elemental distance between the r and r plus dr, the twin radii as we have seen. We can assume that this particular section here, d phi being very small represents a rectangle. It is not really having an issue of differential distances on both sides, so you have the difference between the opposite sides, is so small, in this case that we can safely assume this whole area to be rectangular in nature. The thickness of the rectangle being dr, the length of the rectangle being rd phi as defined by the length of the r on this particular side.

Having said that we can calculate the delta v, the small elemental volume as this particular element deflects dr, let us say where dr is a function of r deflection. We can calculate the total volume delta v by multiplying this particular area term with the deflection, which is d max times of 1 minus small r by capital R square whole square. So that is what the distance dr would be or the deflection dr would be times of r d phi dr.

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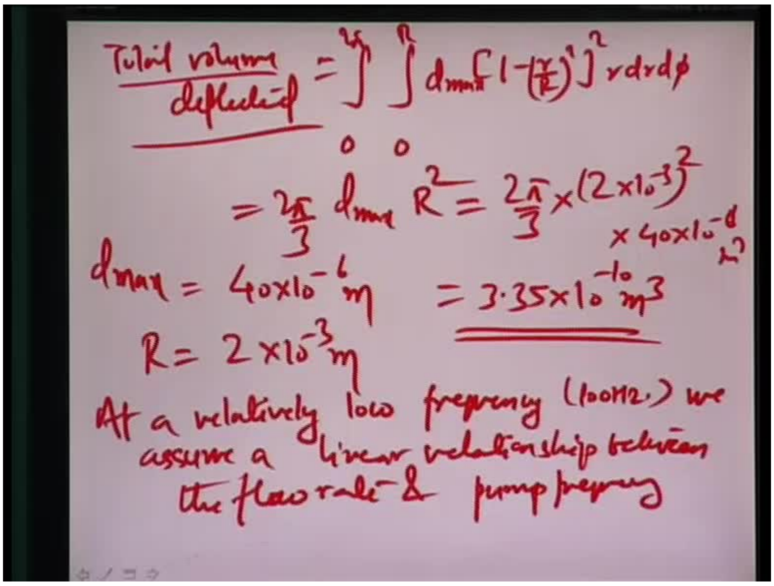

If you want to find out the overall volume in this case, let us say, the total volume deflected of the circular component would also be given as phi varies from 0 to 2 pi radius small r varies from 0 to capital R, you have this is as d max times of 1 minus small r by big capital R square whole square r dr d phi. This essentially comes equal to 2 pi by 3 d max times of square of R.

This is nothing but, as you know, d max in this case is essentially 40 microns. It has been mentioned in the question that maximum deflection at the center is 40 10 to the power of minus 6 meters. Radius R has 2 millimeters size, because the diameter is 4 mm, so as 2 10 to the power minus 3 meters. Therefore, the total volume deflected is essentially equal to 2 pi by 3 times of 2 10 to the power of minus 3 square times of 40 10 to the power of minus 6 meter cube. This becomes equal to 3.35 10 to the power of minus 10 meter cube. This is what essentially the total volume deflected than would be.

At a relatively low frequency, which is actually 100 hertzs in this case - relatively very small, we assume that you know there is a linear relationship between the volume flow rate and the pumping frequency; so, we assume a linear relationship.

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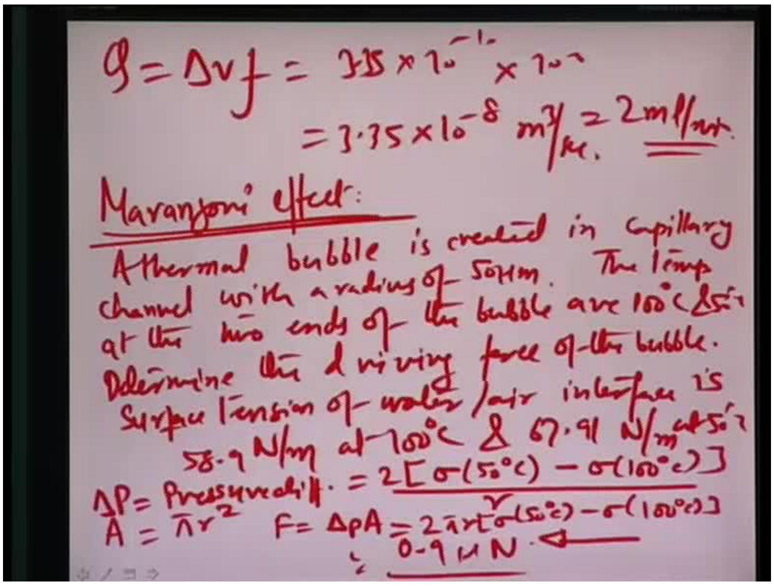

In other words, the pumping rate Q is delta v times of f, which is 3.35 10 to the power of minus 10 times of 100, which is essentially 3.35 10 to the power of minus 8 meter cube per second, which is about 2 ml per minute. That is what essentially the the total flow rate in this particular case would be.

Now, we have also talked about thermo capillary effect. I would like to just do another example with you guys about how this effect gets realized. Let me just reiterate what thermo capillary would mean, it is also known as Marangoni effect. Essentially, you have a bubble, bubble is essentially a two phase, so you have either a gas bubble inside liquid or an oil bubble inside liquids, some kind of change in the continuum. There are two phases which describes a bubble or two states which describes a bubble.

Now, in this kind of a situation, when you heat the surface of the bubble differentially, with one side heated more in comparison to other, there is a change in surface tension and there is a distribution of surface tension across the bubble. The bubble would have a tendency of moving towards the lower surface tension from the higher surface tension. It moves forward in the direction of the lower attention or in terms of it moves forward in direction of the more heated or more prominently heated side. So that is essentially what a marangoni effect or thermo capillary effect would mean.

Let us actually do an example, where we talk about how we can determine the driving force on a bubble, given the surface tensions of water air interface and that to given at different points of temperatures in which the bubble is heated up.

Let us do this example on Marangoni effect. We have a thermal bubble, which is created in a capillary, this capillary has a radius of 50 micro meters. The temperature at the two ends of the bubble are 100 degrees and 50 degrees celsius respectively. You have to determine the driving force of the bubble. Given the surface tension of the water air interface is 58.9 Newton per meter at 100 degree celsius and 67.91 Newton per meter at 50 degree Celsius.

Let us say, so we have a pressure difference at two ends of the bubble, which is estimated as delta P. So, delta P - pressure difference is essentially also defined by twice the surface tension of sigma of air water interface at 50 degree celsius and that at 100 degree Celsius, as you know, with a increase in temperature the surface tension decreases. This is the standard formula of determining the pressure difference, which is existing within a bubble in a certain environment. Delta P is essentially the pressure differential that the bubble can withstand, still becoming 1 integral with respect to the atmosphere.

That essentially is given by the difference in surface tensions across, so one side would have definitely more withstanding capability and another would have less withstanding capability. So, essentially, the total pressure difference in that case across the surface is basically a twice sigma by r - twice delta sigma by r, where delta sigma is the difference between the surface tensions at both temperatures.

Here, both are given, essentially the area here in this case is nothing but, as you know, the 0 contact angle, the total area available on a line wise basis. So, the total area available at 0 contact angle, when we assume the whole droplet has kind of spread over the surface is pi r square, pi times of square of r; r is the radius of the particular bubble in question. The force F is also equal to delta p times of A in that case, which is actually equal to nothing, because you have this area pi r square, you have twice pi r times of sigma at 50 degree celsius minus sigma at 100 degrees celsius respectively, which on calculation comes out be equal to 0.9 micro newtons.

As you are seeing here, the force really arises because of this differential surface tension, is only about 0.9 micro newtons about close to 1 micro 1.0 micro newton. This is sufficient to move the small mass of the fluid bubble towards the surface, which is more properly or more strongly heated up actually, so that is what marongani effect essentially would do.

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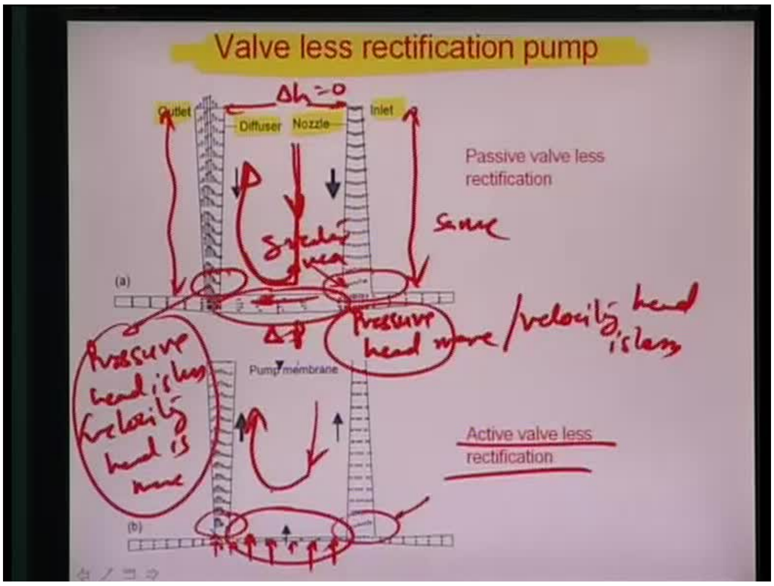

Let us also study some other forms of micro pumps, which may be of interest to the readers. This right here is very good illustration of a valveless rectification micro pump, what essentially it means is that you have, it is all based on again the the Bernoullis principle as you see. This side here, end here acts like a diffuser and here acts as a nozzle. If we assume the overall pressure head or the pressure difference between both sides, between this side and this side, which is also given by height delta h is 0, basically the pressures on both sides here are same to each other.

Therefore, in that kind of a situation, of course because of the greater amount of cross-sectional area here, the pressure head would be more and the velocity head would be less (Refer Slide Time: 17:55). However, in this particular area as you are seeing, so this is here, where the pressure head is more and the velocity head is less. In fact, on the other end, if you look at really in this particular case, the pressure head is less and the velocity head is more.

Therefore, there is a differential pressure delta P between these, which causes the fluid to kind of move in this particular direction. So, it moves all the way from the high pressure zone towards the low pressure zone here, so fluid moves in this direction across the micro channel. Similarly, there can be a situation where the fluid can move in the opposite direction as well, depending on if just you are able to change the geometry here.

Also, there can be active valve less rectification systems, where in, this particular micro channel area can be further using a peristalsis affect, be changed. Therefore, not only there is a pressure head, but also there is a continuous force here, which vibrates the membrane and compresses it. So that all the fluid which is inside actually goes towards the higher velocity head side or lower pressure head side, because more is the cross sectional area, lesser would be the addition in the velocity component here due to this pumping action. Lesser is the cross sectional area, more would be the addition of the velocity component. It acts as kind of an amplifier in the same direction, as we considerd before and the pump actually pumps out fluid from the right end towards the left end. So, that is essentially what this valveless rectification pumping systems do.

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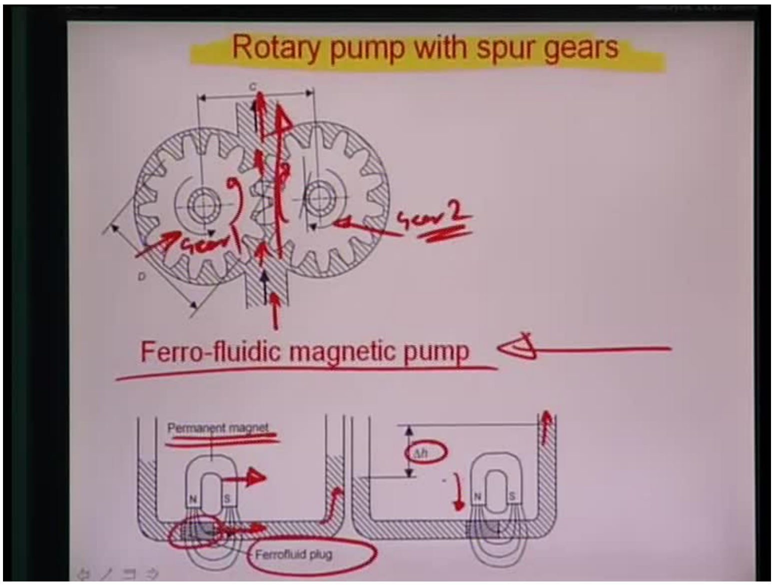

Now, there are other forms of pumping systems, one of them being rotary pumps with spur gears, as you can see here, in this illustration. Here, you see, there are two gears as you can see here; this is gear one, gear two. They are moving in a direction; this moves in anticlockwise, this is actually driven in the clockwise sense, as a result of which, the material which is inside this micro channel, gets pushed forward and flows in this direction.

Therefore, this is also used for cases, where the flows are concerning a little bit high viscous material - high viscous fluids. Here is another illustration of a very interesting Ferro-fluidic micro plump, magnetic micro pump. Here, you create a plug and this plug can be of a Ferro-fluidic nature; that means, you have oil, which is immersing some phurous nano particles and it moves as a plug. Now, when you actually apply a permanent magnet in such a situation, there is always a tendency that as you move the magnet, the Ferro-fluidic plug also moves along with it. In that manner, it pushes the fluid pasted, thus delta h difference can be created, which is supplied by this magnetic field onto this coupling ferrofluidic plug. This is another very interesting moving mechanism of moving fluids at the microscopic length scale, as you can see here, in this particular illustration.

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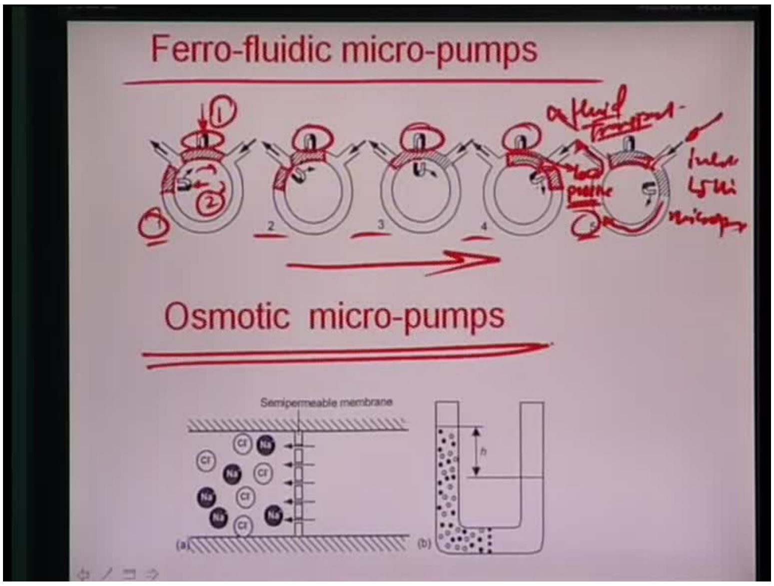

The third kind of pump is really very interesting, it is the ferrofluidic micro pumps. You have to really consider in detail the various stages from 1 to 5 of this particular pump and how it behaves. You have instead of one ferrofluidic plug, two plugs, essentially this particular illustration is one plug and this here as you see is the second plug.

Instead of one magnet, when you have two magnets 1 and 2, which are placed on both ends, one towards the inside of the circle, another towards the outside of the circle; let us say, we call these 2 and 1 respectively. We move further, the magnet 2 is in the clock wise sense. So, as the magnet moves, it drives this ferro magnetic plug along with it as you can see. Here, it has touched this particular system, then it becomes one integral and blocks this port; this is blocking this flow port.

In the next illustration, as the magnet is further moved, so it changes position further and goes here. What happens is that this is a fixed magnet, as you see, this is the fixed magnet, it is not moving. The variable magnet moves the other portion of the plug away from this static plug here, which has been formulated, but what happens is that it creates a zone of low pressure here, in this region, as it does it. As you know, fluid is capable of going into a rushing into the low pressure region, it rushes into this low pressure region, this magnet again comes back, as it comes back, it pushes the whole column here, because this is the static magnet, cannot go forward.

As it pushes this thing, it pushes whole column back into this, so essentially the fluid transport is taking place from this second arm here, as you are seen. This is the second arm, which causes the fluid transport to happen and this is the first arm, which is inlets to the micro pump. Now, as you rotate this fast, the fluid comes into every time as the magnet - as the ferrofluidic material joints here and then splits here, then as it moves along, this whole other path of fluid is actually injected out. That is how the sequence of 5 steps, you can get to realize a continuous flow micro pumping system.

This is again another very interesting example, osmotic micro pumps, they happen specially because of membrane pressure. We have done this before, what osmosis really means, it is the diffusion of ions across semipermeable membrane with concentration gradient across it. You have a salt solution one end, plane water on another end, so there is a tendency of the salts to defuse away from the higher concentration side towards the lower concentration side.

This itself causes some kind of an osmotic pressure, which can drive the fluids across this membrane of the ions cross over. Simply speaking, the ions do not have to move particularly on its own. Essentially, what happens is that it just drives the fluid along with it. Therefore, if there is ion movement, there is automatically a fluid movement as well. You just need to create a concentration gradient across the diffusing mechanisms. This brings us to an end of these micro pumping devices.

We have seen what micro fluidics so far can do with respect to mixes, valves, pumps and different kind of bioas says like the PCR, micro-chip, whether it is space domain, time domain, so on, so forth. You have done a range of applications of microfluidics into biomems, which can serves various useful and important purposes. The only question which remains unaddressed so far is, how do we really fabricate such devices using silicon processing? As you know, as I have discussed before repeatedly, the focus of these biomems or in general mems, is kind of developing novel and newer fabrication techniques of realising these is prototypes?

As we started with silicon in mems, we discussed towards the very beginning of this lecture, there was a general trend of following processors and steps, which are normally used in the silicon industry, because the first material which came into the preview of mems was silicon, but as things moved along, there were polymer mems, there were carven mems, there are basically biological devices or things made up of logical entities, which would be serving as biomems devices, etcetera.

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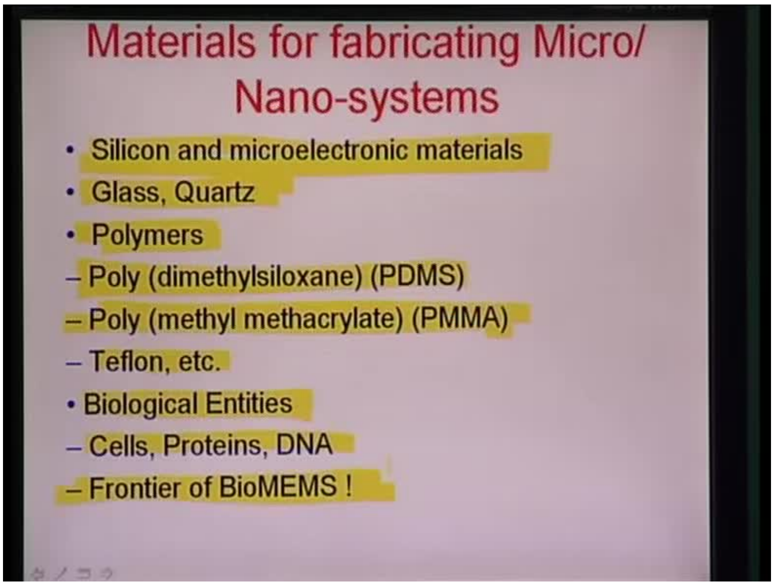

Therefore, we can really study or begin the study of fabricating devices, with alone doing more in details, what we can do with silicon processes. In a nutshell, the materials again, I just like to use this slide from my other lecture, before that we can use a silicon microelectronic materials, primaily glass quartzs, because of there optical transparency. Some polymers here like PDMS, PMMA, you have probably already seen part of this activity before, teflon and biological entities like cells, proteins, DNA, which gives novel frontiers in BioMEMS.

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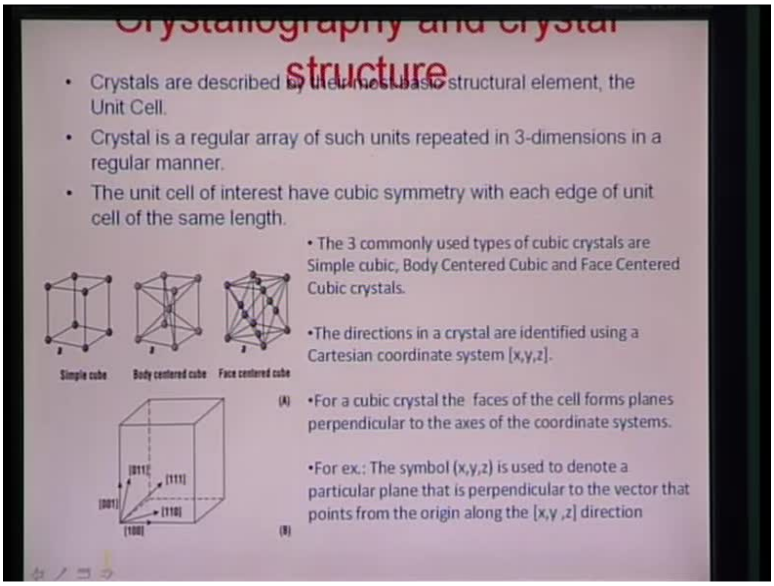

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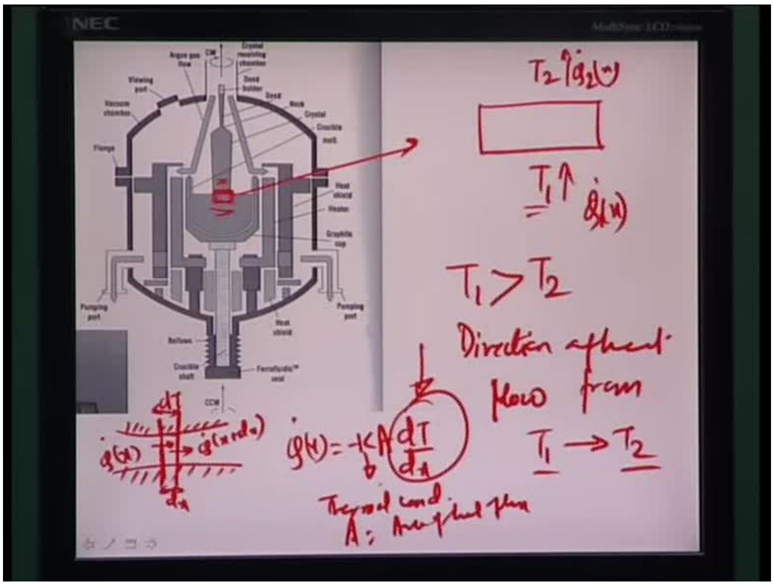

Let us talk a little bit about a crystal structures and how can we organisly characterise silicon as. If you consider this particular area here, it is essentially the transition from liquid to solid. You have liquid state underneathed, solid state over it and this is also the zone of fusion. Let us consider the properties here, let us say that you have a temperature in the solid phase T 2, liquid phase T 1. There is a flow of heat from the higher temperature towards the low temperature. If you actually consider Newton's law of cooling, what its state is if you suppose have a certain sectional area here, in a particular solid, lets say these are 2 6 boundaries, across which you are considering heat transfer.

You have this particular section, across which you are considering what is the rate of heat flow.

Essentially, here, you have Q dot heat which is flowing across this boundary and across this boundary Q dot x plus dx. Essentially, it is a process dependent on the temperature gradient available across this. If I have a temperature T T difference, dT difference between these two surfaces, therefore the heat flux Q dot x is represented as minus K times A times of dT by dx; K is so called the thermal conductivity of the material, A is the area of heat flux, which is perpendicular actually- perpendicular to this particular cross section or the cross sectional plane of this particular figure. The dT by dx is temperature gradient which is available.

Now, you are saying here that there is really a temperature gradient, therefore there should be a heat flow. Let us say, on this side, you have this is a zone of fusion, you have a certain heat flow Q 1 x from the liquid into the zone of fusion and on the side, you have a certain heat flow Q 2 x based on zone of fusion to, thus the solid zone.

Let us suppose, the T 1 is much greater than T 2, because T 1 of course being in the liquid state, would have more temperature than that being in the solid state. The direction of heat flow, therefore by using Newton’s law of cooling, would be from T 1 to T 2 right, from the higher temperature to the low temperature. Let us actually write down the equation of such a flow.

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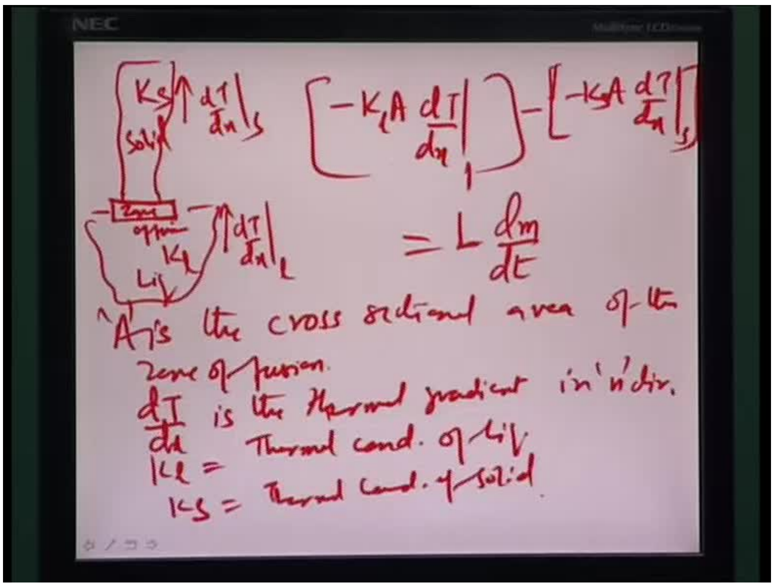

Let us suppose, we have this solid emanating out from the small zone of fusion here and here you have liquid states surrounding, so this is liquid, the solid silicon, this is zone of fusion. Essentially, you have properties Ks as the conductivity of the solid phase, Kl as the conductivity of the liquid phase. Let us suppose that you have a differential dt by dx, this let us consider as there in the liquid phase and this let us considered as there in the solid phase (Refer Slide Time: 29:56).

The total amount of heat flux across the zone of fusion would really be equal to minus Kl times a dT by dx in the liquid phase, the heat across into the zone of fusion minus of Ks solid phase times of A times of dT by dx in the solid phase. That essentially is the total amount of heat which passes into that atmosphere or into the solid phase from the liquid phase. If we consider dm by dt as the formulation of solid from liquid, L b the latent heat of formulation or latent heat of change of state.

Therefore, this amount of heat needs to be lost from the liquid to achieve the solid. So, this amount of the heat is effectively the heat across the zone of fusion, which leads to the formulation of solid silicon. Considering that you have this L dm by dt, which is the amount of heat required by the zone of fusion, dm by dt is of course rate of formulation of mass, is actually equal to minus Kl A dT by dx at the liquid phase minus Ks A dT by dx in the solid phase; A is the cross sectional area of the zone of fusion and dT by dx is thermal gradient in the n direction.

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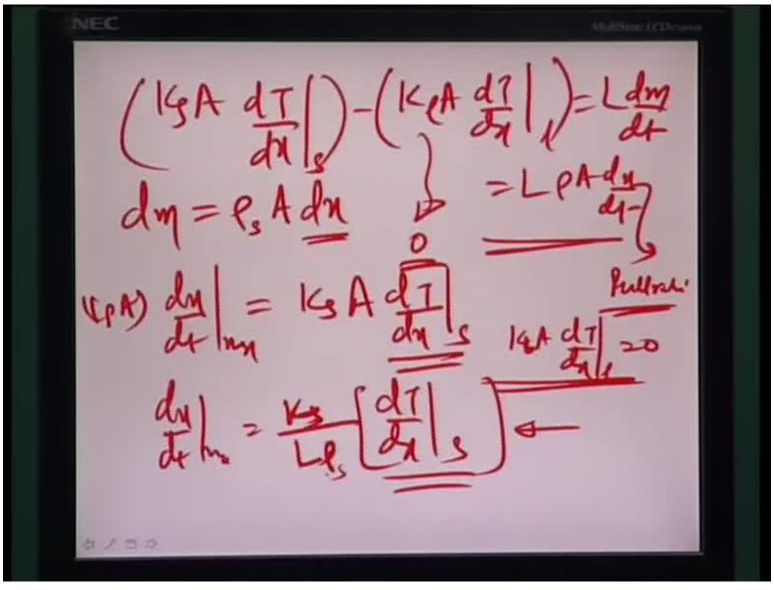

Let me just write this down, so A is the cross sectional area of the zone of fusion and dT by dx is the thermal gradient in n direction. Kl is the thermal conductivity of liquid, Ks is the thermal conductivity of solid. Having said that we can really find out that Ks times of area A times of dT by dx in the solid phase minus kl A times of dT by dx in the liquid phase equal to L dm by dt; dm can be substituted as the density of the the solid silicon times of area of cross section of the particular solid that is formulated. We assume uniform cross sectional area at least the interface times dx, where dx is the differential of solid that is produced in time dT. That is what the whole idea is, so this can be written as L rho a times of dx by dT.

The dx by dT essentially is nothing but the pull rate, the velocity of formation of solid silicon that is what dx by dT would naturally mean. If you assume only the situation, where this dx by dT can be maximum would be the case, when this here effectively is 0, mathematically that is what it is. At the most L rho a dx by dT maxes can be written as a thermal connectivity of the solid times area of cross section times dT by dx of the solid phase.

Essentially, this is corresponding to kl dT by dx of the liquid phase being equal to 0. What it means is that we assume only a 1 directional heat flux a problem or heat, the heat fluxes assume only flow in 1 direction. From the liquid, directly into the zone of fusion, there is no heat loss across the surroundings. Whatever flow or whatever heat flows in, is exactly whatever heat flows out. Therefore, if we consider that to happen, we consider kl A dT by dx 0, then in that case, the maximum velocity comes out to be Ks by L times rho dT by dx in the solid phase.

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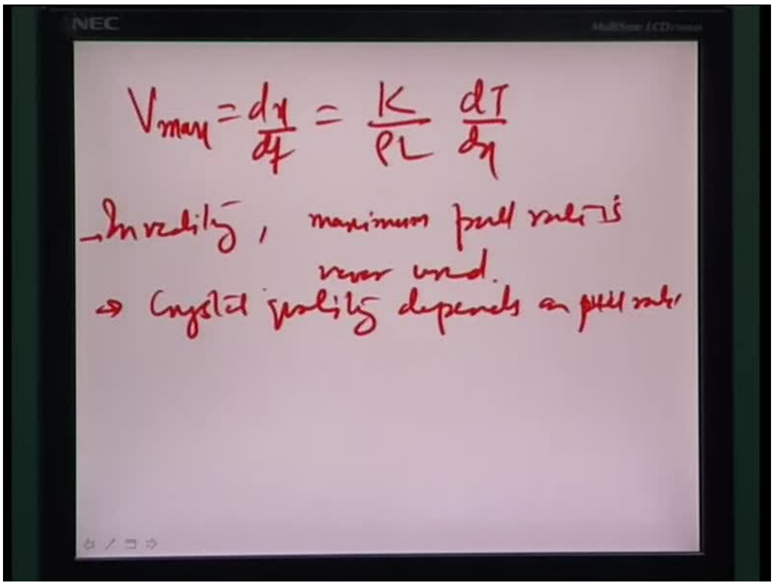

Essentially, whatever the temperature gradient in the solid phase is, from the zone of fusion onwards, would determined and multiplied by thermal conductivity of the solid by things like latent heat of formation. The density of solid silicon, this would determine the maximum poll rate or the maximum velocity. So that is essentially written as V max equals dx by dt equals k by rho L dT by dx. In reality, maximum pull value is never used. As I told you before that the crystal line quality is a very sensitive function of the pull rate, so the crystal quality really depends on pull rate.

You really cannot go very high in terms of the pull rate, otherwise there would be a set of point defects which can qiuckly escape and go into the solid material. However, too much gradient also may create large thermal stresses, thus dislocations, particularly in large diameter wafer.

In a nutshell, it is really the optimum best, which can be derived experimentally as to what the pull rate would be in real terms. So that is one method of how a certain direction or certain orientation prominence of one direction is used in silicon crystals. I would like to close this particular lecture here, the time is almost over. The next lecture, we look at another method of formulation of silicon, followed by some of the more detailed processes of MEMS industry, which are borrowed from micro electronics; thank you.