# Microscale Transport Processes

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## Lecture No # 21

## Electrowetting (Contd)

Could be a continuation of what we have learned in the last class namely Electrowetting it is a application, the new field of digital micro fluidics, which has recently becoming more and more important. And we are going to concentrate more on the applications of digital micro fluidics into various processes and we will see, how our basic understanding has been transformed into some unique applications in this interesting area of wetting.

We know when when an an electrode is placed in contact with an electric field, within electrolyte and an electric field is applied, then let us say positive charges are going to accumulate spontaneously on the liquid on the solid side of the liquid vapour and liquid solid interface. As a result of which it is going to induce it is going to attract from the electrolyte negative charges and they are going to accumulate on the liquid side of the liquid solid interface.

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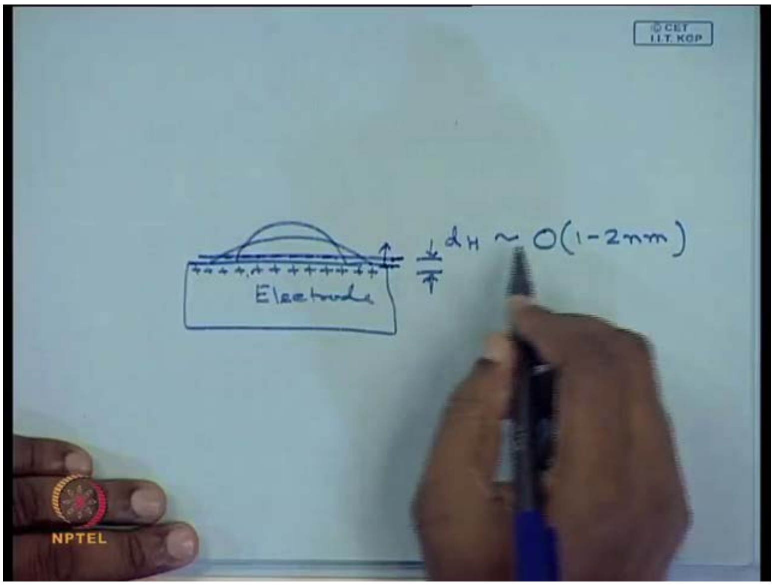

So, ideally it I mean it would look something like this, we let us say we have the electrolyte and the electrode and an electric field is placed on placed and there would be accumulation of some charges. Let us say positive charges on the solid side of the interface and a droplet is sitting, droplet of an electrolyte is sitting on this electrode. So, the negative charges will spontaneously be concentrated near the liquid side of the liquid solid interface, this would result in a change in the surface energy and the and to achieve equilibrium the contact angle will reduce and the droplet would spread.

So, that is the basic concept of electrowetting and what we have seen in the last class is that there are ways to quantify the changes in this changes in the energy, we we have taken the taken taken recourse of minimizing the minimizing the free energy of the process. Since it the accumulation of charge is a is a spontaneous process this would be associated with a reduction in reduction in the in the Gibbs free energy of the system. And the equation from that equation two well known relations Laplace equation and the young's equation can be obtained.

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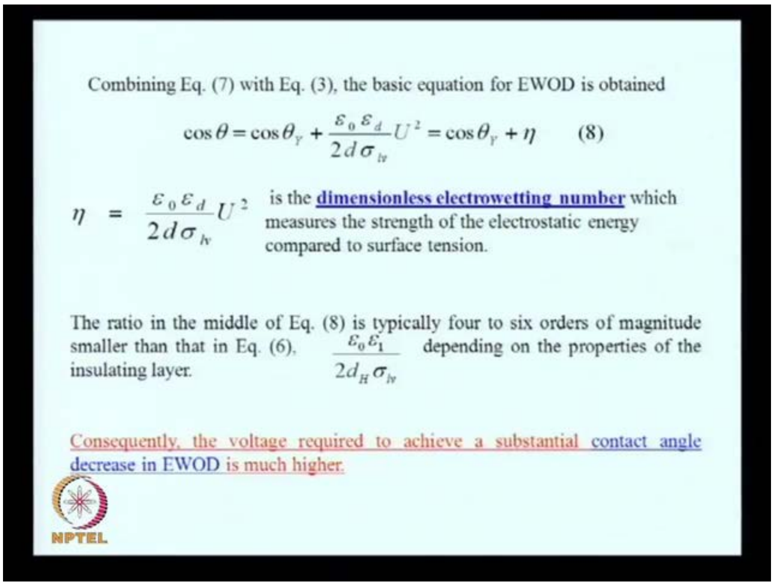

Combining Eq. (7) with Eq. (3), the basic equation for EWOD is obtained

$$\cos\theta = \cos\theta_Y + \frac{\varepsilon_0 \varepsilon_d}{2d\sigma_{lv}} U^2 = \cos\theta_Y + \eta \qquad (8)$$

$\eta = \frac{\varepsilon_0 \varepsilon_d}{2d\sigma_{lv}} U^2$ is the **dimensionless electrowetting number** which measures the strength of the electrostatic energy compared to surface tension.

The ratio in the middle of Eq. (8) is typically four to six orders of magnitude smaller than that in Eq. (6), $\frac{\varepsilon_0 \varepsilon_1}{2d_H \sigma_{lv}}$ depending on the properties of the insulating layer.

Consequently, the voltage required to achieve a substantial contact angle decrease in EWOD is much higher.

And finally, incorporating the concept of electrowetting the following equation has been has been derived has been, we have seen this class, where cos theta is the angle cos theta is the angle it is essentially the contact angle on application of voltage. Theta Y is the contact angle at equilibrium contact angle without any voltage and U is the applied voltage, sigma is the surface tension, d is the thickness and so on.

Now, when we applied when we we when we saw this equation for the case of electrolyte in contact with an electrode in direct contact with an electrode, which is electrowetting we saw that the amount of voltages, amount of potential difference that can be applied between the electrode and the electrolyte is rather small, it is only of the order of few 100’s of mille volts.

So, the change in contact angle though very fast and the change in contact angle per unit change is voltage is large, we are limited by the by the voltage the maximum voltage that we can apply in such a system, because if the voltage crosses; let us say few few volts out of a few few few volts then, electrolysis would occur and the current would start flowing from the electrode to the electrolyte.

So, the changes that can be that can be brought by applying voltage in pure electrowetting is rather small. So, in order to move the droplet or produce any significant movement of the droplet, which is our basic aim in electrowetting for electrowetting applications that, would not be possible with simple electrowetting.

So, the new concept which is coming is to have to introduce a dielectric layer in between the electrode and the electrolyte, so the dielectric layer is now is now separating the electrolyte is is not is is is is not allowing to have any electrical contact between the electrolyte and the electrode. So, now you have the liberty to go for higher voltages and since the capacitance of the dielectric and the capacitance capacitance, I mean of of the of the charged layer very close to the electrode surface in an electrolyte are vastly different, then the equation has been modified in the following form as we as we see here.

So, this is the young Lippmann equation for electrowetting on dielectric. So, what we see here is the same, that the change in change in contact angle with application of voltage, this is the equilibrium contact angle, the interesting thing here is the d in this equation is different from d H in electrowetting.

Now, if you remember in electrowetting, we we understand that the charges are going to be the charges in the electrolyte are going to be concentrated near the near the interface the near the near the liquid solid interface. However, these charges the distribution of these charges as a function of distance from the from the electrode is rather complex there would be some sort of a distribution but, to incorporate this distribution into in a in a in a in a closed form in the equation, in any equation would be difficult.

So, the Helmholtz model has been assumed, it has assumed that all the charges are going to be concentrated in a plane at certain distance, which is equal to d H the thickness of the double layer at a at some distance from the interface.

So, this d H is generally of the order of 1 to 2 nanometers, so this is only a model and it tries to depict a much more complex picture of the entire process by by assuming that everything is is at a certain distance from from this from the from the interface. So, this Helmholtz model has been used and in this equation, what we see is that, the d in this equation the d what we see in this equation in electrowetting it is to be replaced by d H; whereas, in the keys of electrowetting and dielectric the value of d is of the order of few microns.

So, in electrowetting we we get a d of the order of 1 or 2 microns whereas, in the case of electro electric I am I am sorry for electrowetting on dielectrics we get the value of d to be of the order of 1 micron whereas, the d where the case of electrowetting only would be of the order of few nanometers. Therefore, the value of the electrowetting number which is which is denoted by eta is going, which measures the strength of the electrostatic energy compared to surface tension, it is going to be vastly different between electrowetting and electrowetting on dielectric.

Let us see, now the advantages of electrowetting on dielectric, we understand that since the electrowetting number is so, different from that of the electrowetting electrowetting number the in order to achieve in order to effect some contact angle change equal contact angle change you need to have a very high voltage for electrowetting on dielectrics. So, EWOD typically requires higher voltages to to cause a change in the contact angle; however, you are not limited as in electrowetting to only a few 100’s of mille volts, you can go to 200, 300, 500 and you you can.

Therefore, have a larger changes in contact angle, which is a prerequisite for the movement of droplet from one point to another, which we will see and discuss in the in the in this class itself.

So, what is a limit can we go to 1000 volts 2000 volts and have a change complete change can we make a droplet like a thin film well there are two problems, the first thing is dielectric breakdown, each dielectric be depending on what is the material of the what what is the material of the dielectric and what is the thickness can withstand a certain potential difference.

If the potential difference crosses that value, then we we we have we start to have current passing through the dielectric, which is known as dielectric breakdown. Now when that dielectric breakdown takes place that dielectric would be unusable, we cannot use the dielectric again for for EWOD any EWOD applications. So, we are limited by that but, people have reported voltages of five hundred 500 volt across the dielectric without having dielectric breakdown.

So, by increasing the thickness or by choosing the proper dielectric, we should be able to operate at even higher voltages but, everything comes with a price. So, if we increase the thickness of the dielectric, then in order to change the contact angle by certain amount you require, even higher voltages. The second one is known as contact angle saturation what we saw is that there is a parabolic relationship between the voltages applied and the contact angle changes.

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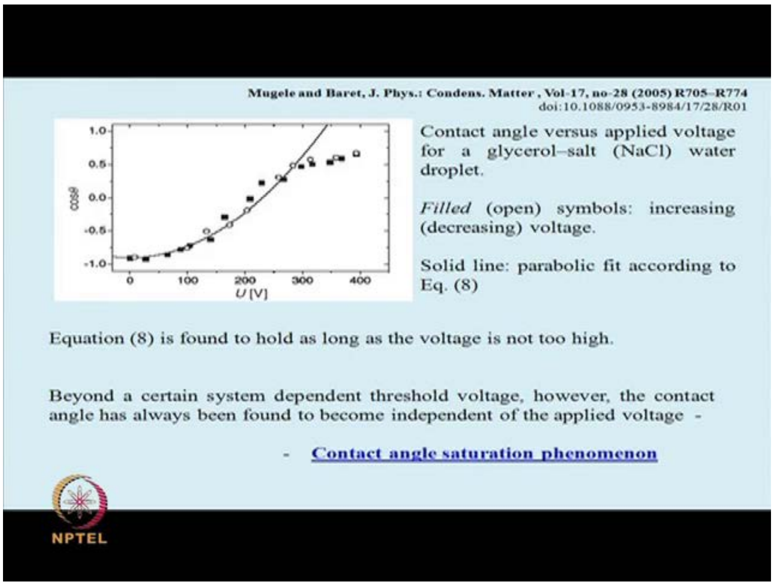

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Contact angle versus applied voltage for a glycerol–salt (NaCl) water droplet.

*Filled* (open) symbols: increasing (decreasing) voltage.

Solid line: parabolic fit according to Eq. (8)

Equation (8) is found to hold as long as the voltage is not too high.

Beyond a certain system dependent threshold voltage, however, the contact angle has always been found to become independent of the applied voltage -

- **Contact angle saturation phenomenon**

So, if we if we look at this figure, we can see that cos this variation of cos theta with the applied voltage U and it follows more or less young Lippmann equation up to certain voltage. Let us say when the voltage is above close to 280 also but, if you if I increase the voltage beyond that value then, you would see that the that the contact angle becomes more or less independent of increase in a applied voltage.

So, this specific phenomenon is known as contact angle saturation, so we we can go only up to certain voltages and beyond that either it would be the case of dielectric breakdown or it would be case of contact angle saturation. So, therefore, at say it it is its common knowledge that you can never make a partially wetting droplet to completely wetting. So, before you do that, you are going to hate the phenomena of contact angle saturation and I must say here, at this point is that the contact angle saturation phenomena is still not well understood.

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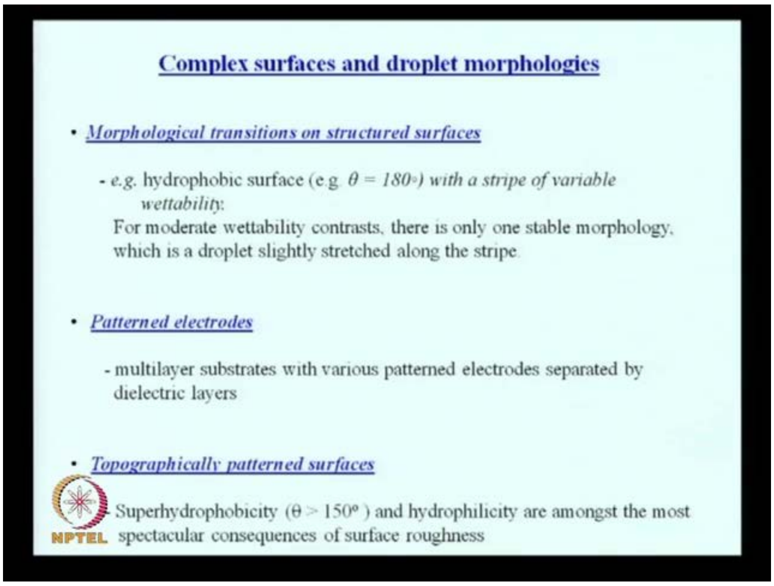

Complex surfaces and droplet morphologies

- *Morphological transitions on structured surfaces*
  - *e.g.* hydrophobic surface (e.g. $\theta = 180°$) *with a stripe of variable wettability.*
    For moderate wettability contrasts, there is only one stable morphology, which is a droplet slightly stretched along the stripe.
- *Patterned electrodes*
  - multilayer substrates with various patterned electrodes separated by dielectric layers
- *Topographically patterned surfaces*
  - Superhydrophobicity ($\theta > 150°$) and hydrophilicity are amongst the most spectacular consequences of surface roughness

So, we are now going to we will with this background we are going to start our this class with complex surfaces and droplet morphologies, how the complex surfaces would give rise to motion in the droplet. So, we know that hydrophobics there are there are cases where hydrophobic surfaces with a strip of variable wettability can be used to move a droplet. So, let us say we have a surface in which the hydrophobicity keeps on changing.

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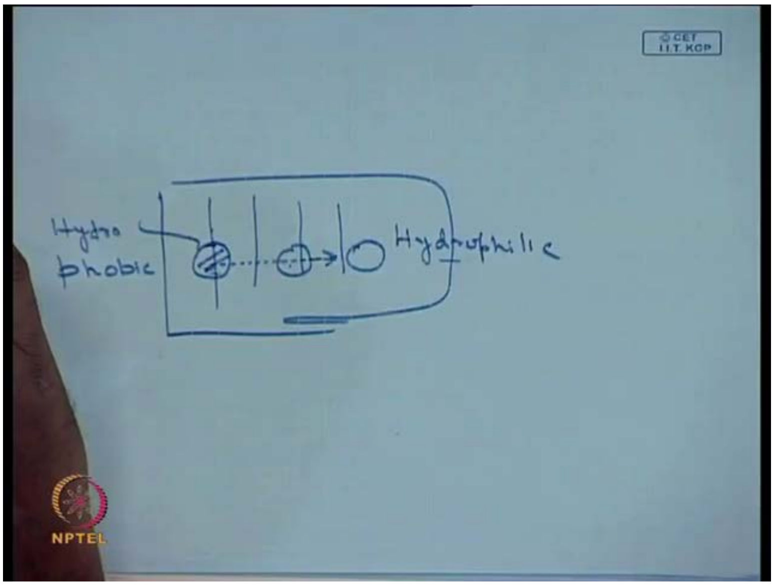

So, as we as I move the surface becomes more and more hydrophilic, so if I have one strip which is highly hydrophobic the next strip slightly less hydrophobic and so on. So, as I move in this direction the hydrophobicity decreases, so this portion is truly hydrophilic and this region is hydrophobic; what we see is that if a droplet is kept here then the natural tendency of the water droplet, would be to move in this direction. So, if I can provide the right value of hydrophobicity gradient, then there are reports that the droplet will move in the direction of in the direction of more hydrophilic regions.

So, this is one way by making the droplet move but, as you can see it is difficult to achieve and the velocities that you are going to get in using such a process is rather rather small people. People have also worked with patterned electrodes and by patterned electrodes, I mean when when you have a pattern separated by dielectric layers and this is something we will we will may see in greater detail in a next class in the next slide next slides. There is another thing is we can induce super hydrophobicity and super hydrophobicity where the typically the theta value could be of the range of 150 and this is something, which requires some more analysis and study.

So, topographically patterned surfaces can give rise to drastically different values of hydrophobicity and this could be beneficial in many cases as far as droplet movement is concerned.

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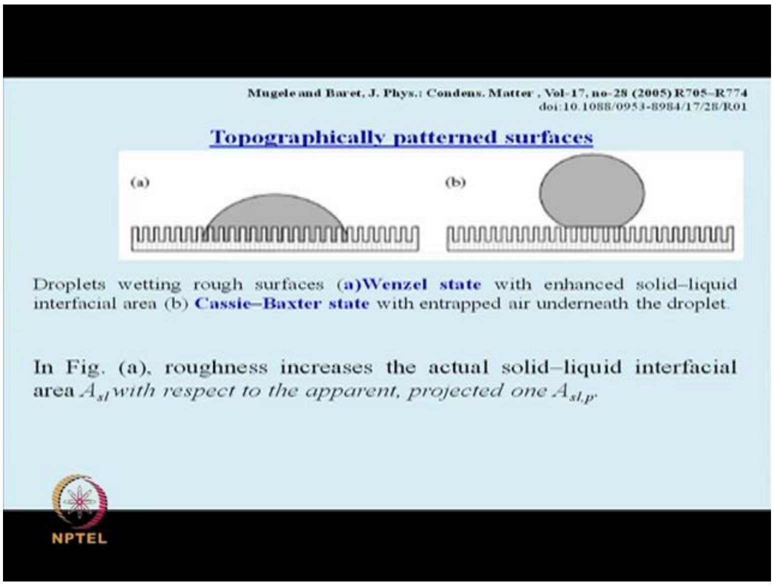

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**Topographically patterned surfaces**

Droplets wetting rough surfaces **(a)Wenzel state** with enhanced solid–liquid interfacial area (b) **Cassie–Baxter state** with entrapped air underneath the droplet.

In Fig. (a), roughness increases the actual solid–liquid interfacial area $A_{sl}$ *with respect to the apparent, projected one* $A_{sl,p}$.

So, I bring you to the next topic, which is two extremes how would a droplet behave when it is based on a topographically modified surface. So, we all have seen what would happen when rain drops fall on a lotus leaf, the lotus surface of the lotus leaf is not smooth it has certain cilliers; cilliers are nothing but, vertical pillars which are embedded on the surface of the lotus leaf. So, these are the cilliers and when the rain drop falls on the cillier it is not going to wet the region in between the cillier.

Therefore, thereby the rain drop will never come in contact with the surface with the surface of the leaf rather it would suspend on the cillier; therefore, if you just tap the tap the lotus leaf the rain drop will simply roll away. So, the ease of movement of a rain drop on a lotus leaf is a perfect example of what would happen, when the surface becomes super hydrophobic. On the other hand you can have a situation in which because of some geometric, let us say concentrations the rain drop is not sitting on the cillier, rather it fills the spaces in between as well and thereby coming in contact with with the lotus leaf.

So, these are two extremes, in one extreme it is simply suspended on the on the pillars, so to say on pillars on the surface and in other case it fills the spaces in between the pillars as well. So, these two contrasting behavior of a droplet on a nano structured surface is typically expressed either a Wenzel state, where a where the liquid fills the spaces in between; and the second is the Cassie-Baxter state, where they are simply sitting on these pillars.

So, if I if I think of the contact area the projected contact area which is which which is simply this and in this case this is the projected contact area. Now, if you compare the actual wetted area and the projected contact area, these two are different for both the both the cases for the case of Wetzel state, the wetted area is more I mean the actual wetted area is more than the projected wetted area.

Whereas, for the case of cassia state the actual wetted area is less than the projected wetted area and these two cases would give rise to two different laws. So, there are there are, so if you if you see that in figure a in Wetzel state the roughness increases the actual liquid solid interfacial area, which we call as ASL with in comparison to the projected area which is denoted by ASLP.

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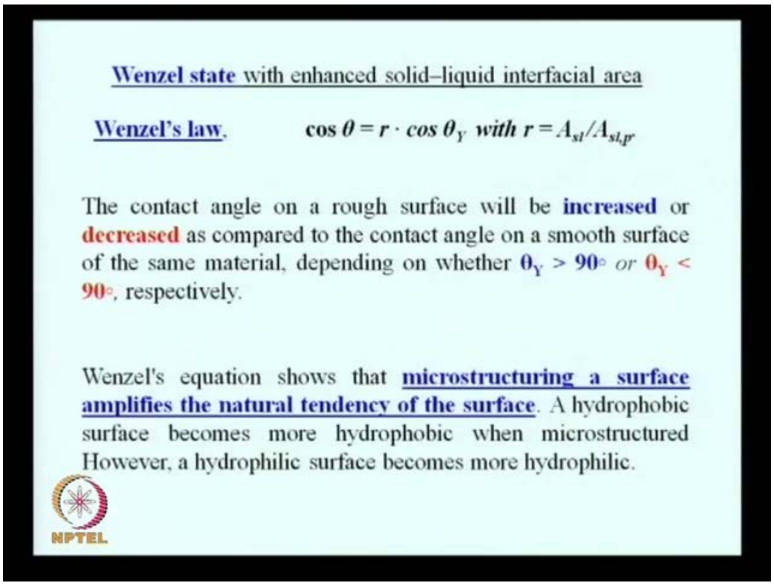

**Wenzel state** with enhanced solid–liquid interfacial area

**Wenzel's law.** $\cos\theta = r \cdot \cos\theta_Y$ *with* $r = A_{sl}/A_{sl,pr}$

The contact angle on a rough surface will be **increased** or **decreased** as compared to the contact angle on a smooth surface of the same material, depending on whether $\theta_Y > 90°$ *or* $\theta_Y < 90°$, respectively.

Wenzel's equation shows that **microstructuring a surface amplifies the natural tendency of the surface**. A hydrophobic surface becomes more hydrophobic when microstructured However, a hydrophilic surface becomes more hydrophilic.

So, there is a relation famous relation which is a phenomena logical relation, so it cannot be derived as such but, a large number of experiments support the existence of such a law which is known as the Wenzel's law. Which which denotes the contact angle as a function of the equilibrium contact angle and this factor r is the ratio of the areas, so this is the actual area the wetted area and this is the projected wetted area. So, this is the area which would which would be wet if there are no structures on the surface, so the value of r for the case of Wetzel's Wenzel state would definitely be more than one.

Now, if you look at this equation you would see certain interesting things and which would give rise to which is give which will give rise to a concept that may have certain applications in areas. Now you can see by looking at this equation that the contact angle on a rough surface will increase depending on whether your equilibrium contact angle is greater than 90 degree or if it is less than 90 degree.

So, what you see here is that the, if those let us say the contact angle is more than 90 degree, so it is a hydrophobic surface without without any any superstructures on it without any structures on it. Now what you do is you you provide structures on it, so the value of r is going to be greater than 1and this theta Y is greater than 90. So, what this would provide is that the cos theta will increase, so providing superstructures providing structures on the surface, which is inherently hydrophobic will enhance the hydrophobicity of the surface and vice versa; which is which is very very very important and interesting.

So, this would tell us that the micro structuring a surface amplifies the natural behavior of the surface. So, if you have a hydrophobic surface and you provide such structures then, the surface will become more hydrophobic, if it is hydrophilic to begin with then providing these structures will increase the hydrophilicity of the surface. So, this is the beauty of Wenzel's law, because it tries to it describes two different behavior of the surface, when you provide superstructure, when you provide structures on it. So, the superhydrophobicity can be explained by Wenzel's law.

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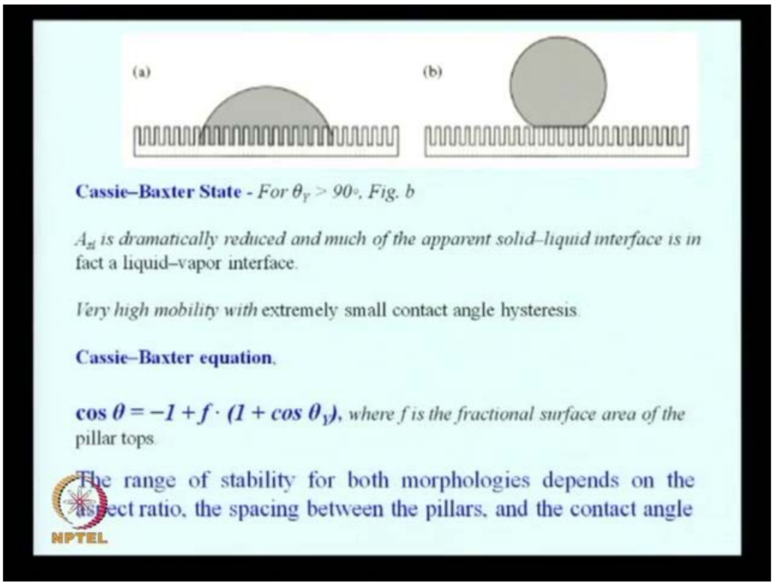

**Cassie–Baxter State** - *For $\theta_Y > 90°$, Fig. b*

*$A_{sl}$ is dramatically reduced and much of the apparent solid–liquid interface is in* fact a liquid–vapor interface.

*Very high mobility with* extremely small contact angle hysteresis.

**Cassie–Baxter equation**,

$\cos\theta = -1 + f \cdot (1 + \cos\theta_Y)$, *where f is the fractional surface area of the* pillar tops.

The range of stability for both morphologies depends on the aspect ratio, the spacing between the pillars, and the contact angle

Now, let us think of the Cassie-Baxter state where we know that ASN is dramatically reduced and much of the apparent solid-liquid interface is in fact, a liquid-vapor interface. So, this this droplet is you can think of as if a large portion of this droplet is sitting over over an air water interface rather than water solid interface; and you can well imagine that this reduces the friction between the droplet and the solid surface considerably.

So, if the if the friction is friction gets reduced then, it would be easy to move the droplet from one point to another. So, the role of angle which is defined as the tilt angle at which a droplet sitting on the surface begins to roll off that would be lower for the case of Cassie-Baxter state compared to that of Wenzel state. And this high mobility and small contact angle hysteresis as can be observed in Cassie-Baxter state, has certain uses.

And there is also phenomenon logical equation, which connects the contact angle which is theta with the equilibrium contact angle and f is the fractional surface area of the pillar tops. So, the pillars which are provided on the surface, the area of the top of those pillars is is is is denoted by f and this equation is a Cassie-Baxter state.

Now, there is also some interesting studies, which are going on to predict that (()) is it possible to predict whether a droplet on such a surface is going to behave in as if it is in the Wenzel state or it is going to behave as if it is in the Cassie-Baxter state. Till today there is no definitive theory, which would which would predict when it is going to be in the Cassie state or when it is going to be in the Wenzel state. But, there are certain observations, which can be made based on molecular dynamic simulations and experiments.

Which tells us that the behavior of the droplet (()) is these two states would depend on the, what is the aspect ratio of these pillars the spacing between these pillars and the interaction denoted by the contact angle, between the liquid droplet and the solid droplet. So, obviously if your if your pillars are closely spaced, the chances are that you are probably going to get a Cassie-Baxter state. If the pillars are widely separated you get Wenzel state the if the if the if the height of the pillar is more, you would most likely you are going to get Cassie state.

If the attractive force between the liquid molecules and the solid molecule is high then, it is its likely that the liquid will fill up the spaces in between the pillars, thereby giving rise to Wenzel state but, there is no definite theory which would allow you to calculate or to evaluate, whether you are definitely going to get this state or the other and in many practical situations the situation would be something in between the two.

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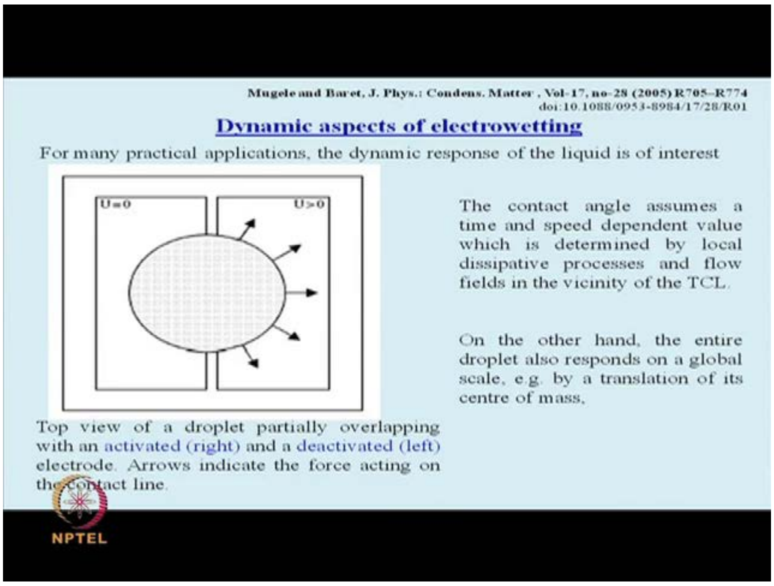

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**Dynamic aspects of electrowetting**

For many practical applications, the dynamic response of the liquid is of interest

Top view of a droplet partially overlapping with an activated (right) and a deactivated (left) electrode. Arrows indicate the force acting on the contact line.

The contact angle assumes a time and speed dependent value which is determined by local dissipative processes and flow fields in the vicinity of the TCL.

On the other hand, the entire droplet also responds on a global scale, e.g. by a translation of its centre of mass.

Now, we are going to concentrate on practical aspects or the practical aspects of the dynamics of a droplet on an electrode or on a dielectric. Now the if you if you see this figure, it the left hand side is 1 electrode where it is kept at 0 potential 0 voltage and the right hand side is another electrode, where which is switched on and the droplet encompasses both the electrodes. Now when this is switched on when this electrode is switched on the contact angle will reduce and the contact line, the edge of the droplet will have a tendency to move in this direction.

So, if the conditions are right, then the then then mass from mass from this portion of the droplet will move towards the towards the adjoining electrode and the entire droplet will probably shift from the left to the right. So, the activated by choosing the activated and the deactivated electrode and by operating at the right voltage with the right separation in between the two electrodes, the droplet can be made to move from one electrode to the next electrode.

So, this is this is this is this is the concept but, there are certain problems associated with there are certain interesting phenomena associated with movement of the droplet from one electrode to the other, which I have depicted in here.

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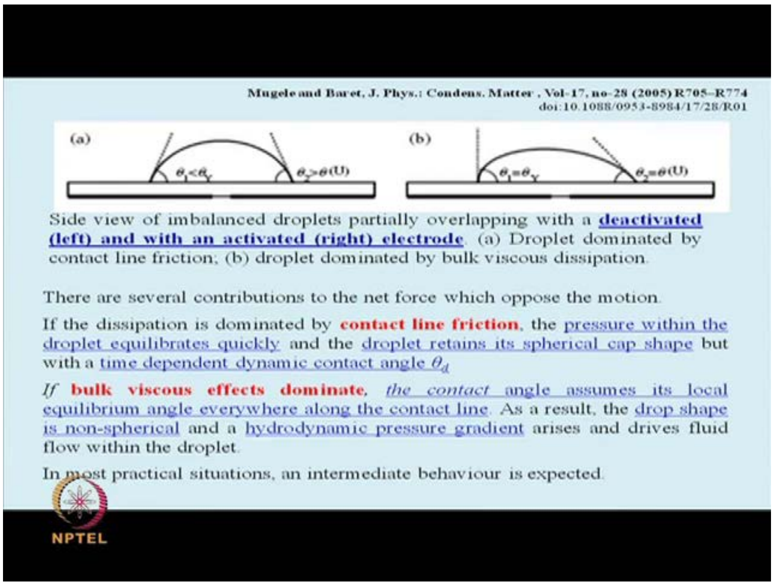

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Side view of imbalanced droplets partially overlapping with a **deactivated (left) and with an activated (right) electrode**. (a) Droplet dominated by contact line friction; (b) droplet dominated by bulk viscous dissipation.

There are several contributions to the net force which oppose the motion.

If the dissipation is dominated by **contact line friction**, the pressure within the droplet equilibrates quickly and the droplet retains its spherical cap shape but with a time dependent dynamic contact angle $\theta_d$

*If* **bulk viscous effects dominate**, *the contact* angle assumes its local equilibrium angle everywhere along the contact line. As a result, the drop shape is non-spherical and a hydrodynamic pressure gradient arises and drives fluid flow within the droplet.

In most practical situations, an intermediate behaviour is expected.

Now this is a schematic view of an imbalance droplet, which is partially overlaps one electrode, which is switched on and another electrode which is which is switched off. Now, the left droplet is dominated by contact line friction, so this is the location of the contact line, now as the droplet tries to move what would happen is the contact line friction, may pin the contact line right at this point; thereby not allowing the droplet to move in this direction.

And the on the other hand we may have a droplet, which is going to be a droplet, which is going to be dominated by bulk viscous, dissipation inside the droplet. So, this there is several contributions to the net force which oppose the motion.

Now, if you have the contact line friction governing the entire process, then the pressure inside the droplet will equilibrate very quickly and more or less the spherical shape will be will be will be retained and it would be difficult for the droplet to move. Whereas if your viscous forces are going to dominate, then your going to have a short change in contact angle on the electrode, which is switched on.

So, you may have a situation in which the droplet there will be flow in the droplet natural flow in the droplet from left to right and this would left to right, And this would give rise to motion of the droplet in a in motion of the droplet from the off electrode to the on electrode. Now liquid motion can also be achieved only if you cross certain threshold voltage.

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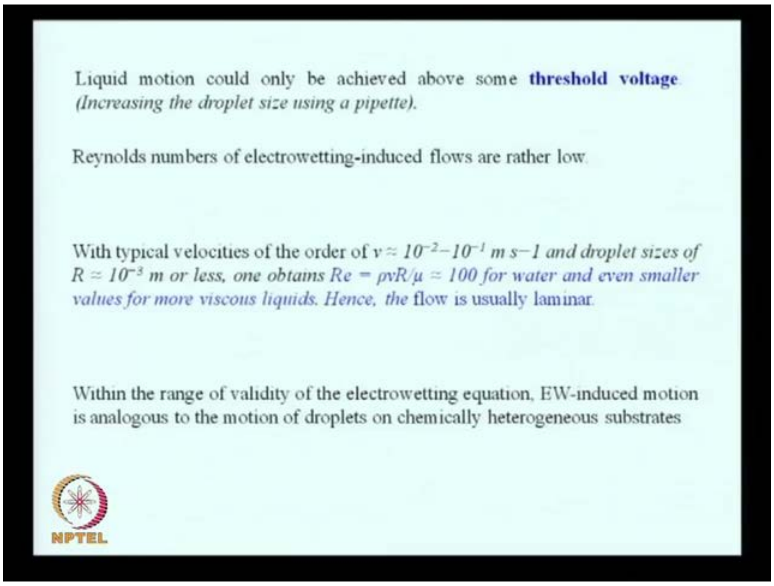

Liquid motion could only be achieved above some **threshold voltage** *(Increasing the droplet size using a pipette).*

Reynolds numbers of electrowetting-induced flows are rather low.

With typical velocities of the order of $v \approx 10^{-2}-10^{-1}$ m s−1 *and droplet sizes of* $R \approx 10^{-3}$ *m or less, one obtains* $Re = \rho v R/\mu \approx 100$ *for water and even smaller values for more viscous liquids. Hence, the* flow is usually laminar.

Within the range of validity of the electrowetting equation, EW-induced motion is analogous to the motion of droplets on chemically heterogeneous substrates

So, there would be inherent inertia in the droplet, which has to be over come, in order for the droplet to move. Now this threshold voltage would depend on the nature of the surface, the thickness of the dielectric, the combination of the liquid solid and so on. But, in many cases you will probably have to be up let us say up to 50 volts before you can see appreciable change in contact angle and there after you would probably see the movement. And the Reynolds number of such flows are can be evaluated to be quiet small.

So, if it is a small for example, in in in for the case of water for the case of water the velocities are going to be of the order of 10 to the power minus 2 to 10 to the power minus 1 meter per second. And we have droplet sizes of the order of millimeters and the Reynolds number would be roughly about 100. So, the flow will mostly be laminar, when the droplet moves on the surface.

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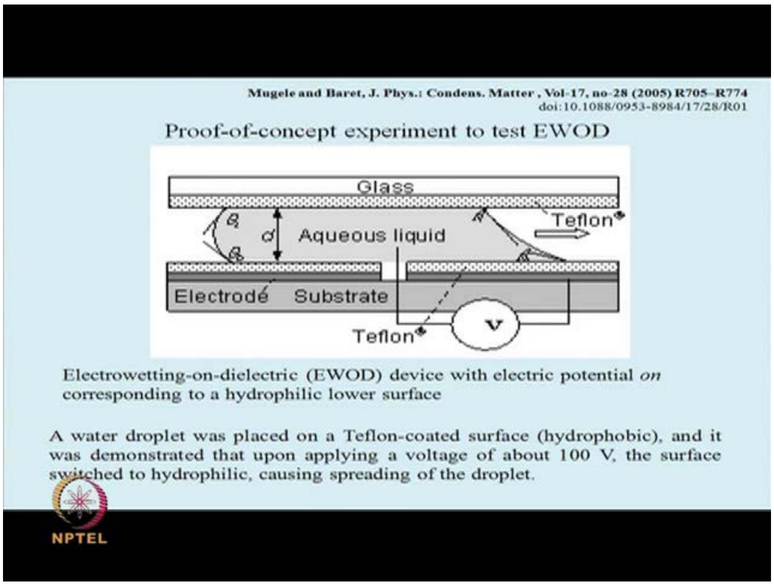

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Proof-of-concept experiment to test EWOD

Electrowetting-on-dielectric (EWOD) device with electric potential *on* corresponding to a hydrophilic lower surface

A water droplet was placed on a Teflon-coated surface (hydrophobic), and it was demonstrated that upon applying a voltage of about 100 V, the surface switched to hydrophilic, causing spreading of the droplet.

Now this is a proof of concept experiment to test how EWOD works, now here you see that we have an electrode electrode electrode and then this is the dielectric and we have thin hydrophobic coating on the surface; such that the electrode the such that the droplet or the plug as is as in this case can move easily with less amount of contact angle hysteresis.

So, the common hydrophobic material, which is coated on the dielectric is Teflon and this is a glass coated with Teflon. And some liquid is an aqueous an aqueous solution of an electrolyte is sitting over here and this forms a large contact angle. Now in this electrode is switched on you can see that the contact angle has reduced considerably and the tendency of the liquid will be to move from left to right.

So, a water droplet which was placed on the Teflon coated surface, in it you can see that by applying a voltage of about 100 volts the droplet is made to move from the neutral electrode to the electrode which has been switched on.

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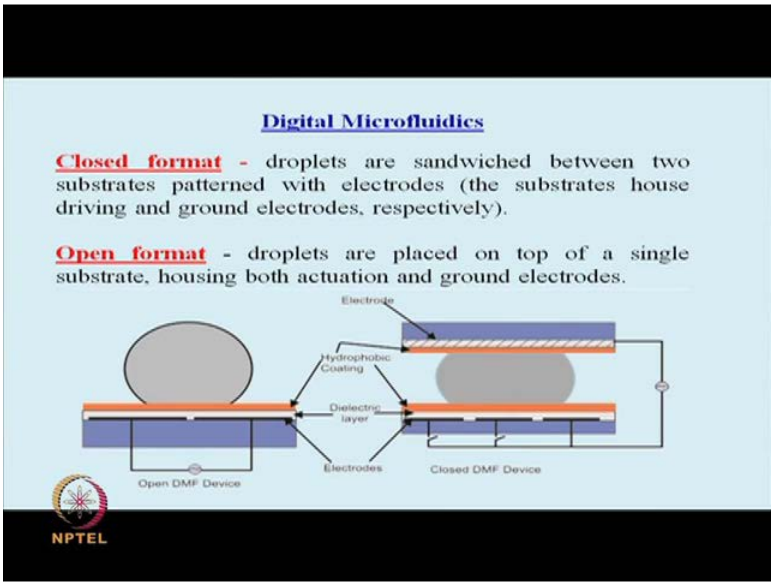

**Digital Microfluidics**

**Closed format** - droplets are sandwiched between two substrates patterned with electrodes (the substrates house driving and ground electrodes, respectively).

**Open format** - droplets are placed on top of a single substrate, housing both actuation and ground electrodes.

Now, the from from the coming slides are taken from a very interesting paper, which has appeared in advanced matters in 2008 and this summarizes the present status of digital micro fluidics as we know it.

Now, as the two figure suggest you can have closed digital micro fluidic system as has been as as you can see in the left side of the of the figure and an open digital micro fluidic device. So, if you think of a closed system then you have a number of electrodes which are embedded and this is glass this is a glass cover or it could even be an electrode and a hydrophobic coating and a plug of liquid is situated over here.

So, as these electrodes are progressively turned on and the preceding electrode turned off the plug will move over the electrode in the direction in which the electrodes are sequentially being turned on. So, you have definite movement closed in in a closed channel towards the electrode, which has been turned on; whereas if you see an open system a droplet sits over the electrode surface and over the dielectric surface and it is expose to vapor.

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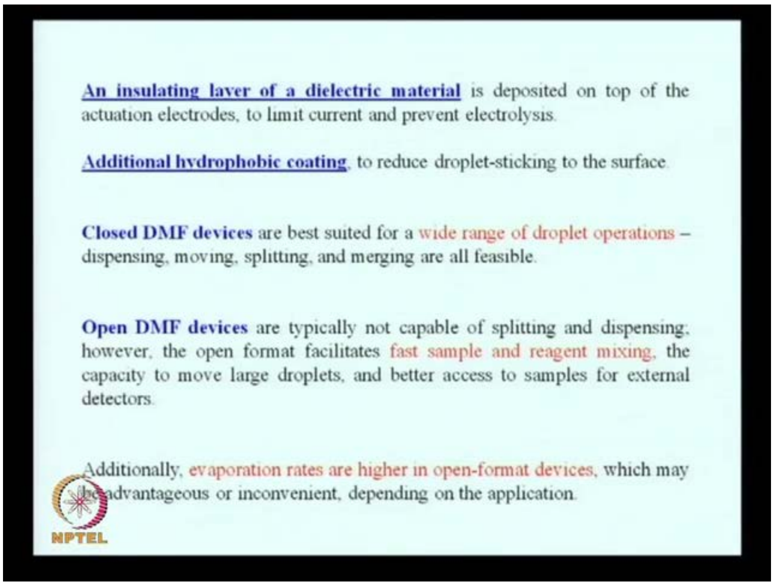

**An insulating layer of a dielectric material** is deposited on top of the actuation electrodes, to limit current and prevent electrolysis.

**Additional hydrophobic coating**, to reduce droplet-sticking to the surface.

**Closed DMF devices** are best suited for a wide range of droplet operations – dispensing, moving, splitting, and merging are all feasible.

**Open DMF devices** are typically not capable of splitting and dispensing; however, the open format facilitates fast sample and reagent mixing, the capacity to move large droplets, and better access to samples for external detectors.

Additionally, evaporation rates are higher in open-format devices, which may be advantageous or inconvenient, depending on the application.

So, there are certain advantages to this closed format of DMF and the open format of DMF and we would see what they are. Now this I have already described is the importance of the insulating layer, importance of the hydrophobic coating and so on. The close DMF devices are very well suited for a number of droplet operations, you can move droplet, you can split the droplet into two and even you can merge two droplets to to make one large droplet.

Whereas open DMF devices are not capable of splitting and dispensing as efficiently as in the close DMF devices, however, they are very fast and simple mixing can be achieved in open DMF format. So, if you have two droplets sitting at two points, then you they can be made to come close merge become a large droplet. So, one reactant 1 and reactant 2 can be made to come together mix and the reaction starts the advantage here is that since the length scale is.

So, small the resistance to mass transfer would be extremely small and the reaction would take place in such a droplet in a at a very fast rate and you would be able to monitor the progress of the reaction from from outside. The most common way to monitor such reactions could be using an optical microscope using a fluorescence microscope. There are certain other advantage depending on whether you call it as an advantage or disadvantage is the evaporation is possible from from closed sorry sorry from an open digital micro fluidic system.

Now, if you have a reaction which is going on in a droplet and if evaporation takes place that is basically definitely a disadvantage but, let us see you are using the droplet to cool a surface, so to cool hot spot. So, in that specific case evaporation from a droplet can be beneficial, so depending on what application we are we are thinking of the evaporation from droplet in an open micro fluidic system, could be an advantage or a disadvantage

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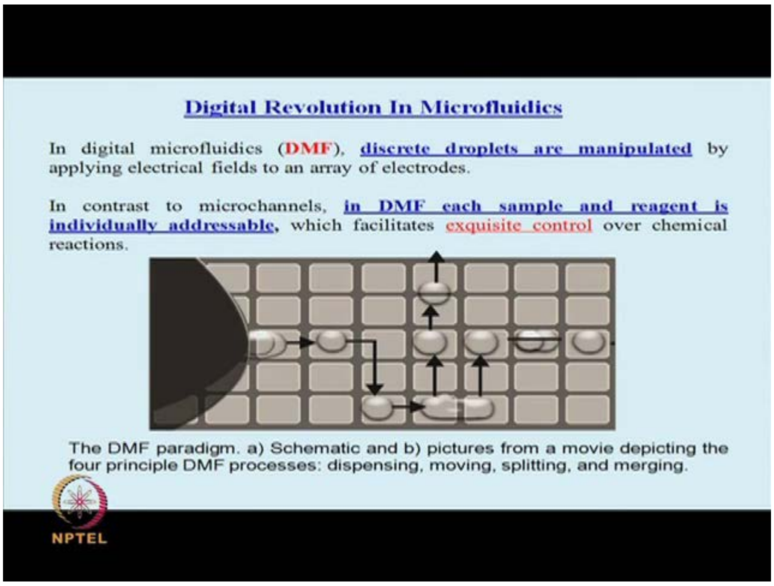

**Digital Revolution In Microfluidics**

In digital microfluidics (**DMF**), **discrete droplets are manipulated** by applying electrical fields to an array of electrodes.

In contrast to microchannels, **in DMF each sample and reagent is individually addressable**, which facilitates exquisite control over chemical reactions.

The DMF paradigm. a) Schematic and b) pictures from a movie depicting the four principle DMF processes: dispensing, moving, splitting, and merging.

Now, this is an interesting picture which where I would like to spend some time, now we would like to see how discrete droplets can be manipulated by electro by electric fields to an array of electrodes.

So, this checker board, the board that you see I mean the all these are individual electrodes, this is a large droplet of let say an electrolyte. And you are first going to split this droplet, first going to going to extract a droplet out of this larger pool of liquid. So, what you do is, you switch this on this electrode is switched on, where where this the other electrode is switched off.

By switching it on at the we we at the at at the right voltage for the right amount of time a droplet a small droplet can be can be spliced from the larger pool of liquid and you you simply get one droplet; and then the droplet is made to move on the on on the electrode surface in a specific direction. The direction of the droplet movement would be governed by how your switching this on and off. So, in order to bring it to over here, this electrode will be switched off, this would be switched on. The moment it comes over to this electrode the next would be switched on and this would be switched off.

So, you can have tangible movement of the droplet in a specific direction and it comes to this point. Now when it comes to this point the middle electrode is switched off, the left hand side is switched on and the right hand side is switched on as well. So, part of the liquid contained in the droplet sitting on the middle electrode, will move to the left part will move to the right. And again with the right combination of voltages and time you would be able to divide this droplet into two droplets, which are then again going to move independent of one another into parts program from outside.

So, one droplet will move in this direction and the other droplet will move in the other direction. Now, here I have a reactant, I would like to let us sat for example, measure the content of something, let us say glucose into this this droplet. Let us say this is this is this is this is a blood sample and I have taken small very small micro droplets of blood created micro droplets of blood brought it here, the reagent comes over here these two droplets merge.

And then this becomes reactor and the progress of the reaction and the outcome of the reaction would allow me to quantify the specific chemical, that I am looking for, let us say sugar in this case blood sugar in this case; and I would be able to measure the blood sugar sugar in the using such a droplet. The other droplet which has traveled in a different path will be made to come in contact, with another reagent which for example, measures what is the urea content of the blood.

So, this in essence is the concept of lab on chip, so, on a small chip you can have several reagents parked at different points on the chip and by splitting small droplets from a large drop relatively large droplet. And then again splitting that small droplet into a number of microdroplets, making them move in a specific direction, coming them in contact or letting letting them come in contact with different reagents.

And monitoring the reaction of the reagent with that microdroplet of blood on a chip itself on a small chip itself, you can probably make a number of measurements of chemicals their concentration present in in in in the blood. So, this has revolutionized or this as the potential to revolutionize the the testing the arrays that we do with biochemical systems.

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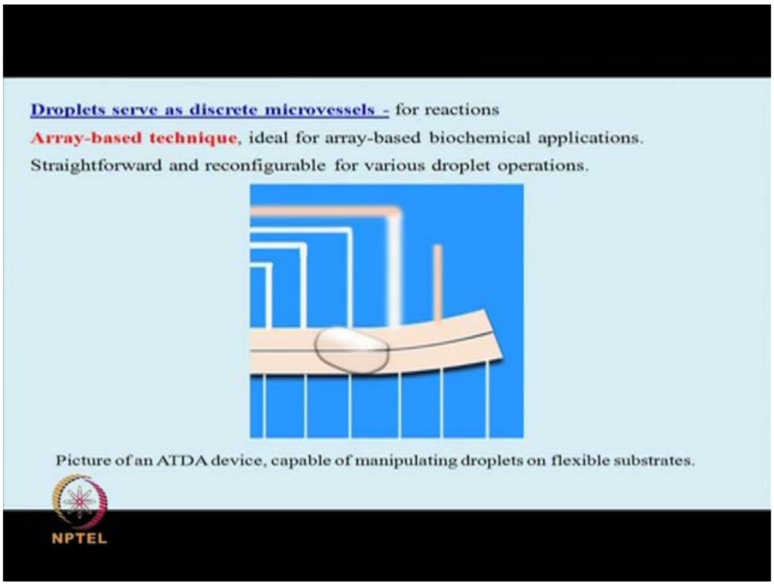

**Droplets serve as discrete microvessels -** for reactions

**Array-based technique**, ideal for array-based biochemical applications.

Straightforward and reconfigurable for various droplet operations.

Picture of an ATDA device, capable of manipulating droplets on flexible substrates.

Now, the next is another interesting example of a droplet moving over an inclined surface. Now if you if if if you see that this surface is not smooth it is it is a curved surface. So, the droplet starts from here and with the right combination of switching on and off of these electrodes and with the right voltage, the droplet may be will be will be forced to move in uphill. So, that is that is very interesting like that the body force, the droplet can rise and it can overcome body force.

So, you would you see that it is it such an strong powerful technique for for any array based biochemical applications it is straight forward it is reconfigurable and you can control everything from outside by simply writing any program in which way, in what sequence and to what value your your electrodes are being switched on. So, this is this picture is I mean, if you look carefully you would see there are number of electrodes.

So, it is it is again a checkerboard design where you have number of electrodes over here and here in the x and in the in the y direction and the scale here is given as one millimeter. So, a droplet which is sitting on an electrode but, in contact with the adjacent electrodes you can do, so many operations on this, you can split the droplet such that part of it goes to the to to to this side and the part goes to the other side or you can make the droplet to move in any specific paths that you want.

And everything you can configure, everything you can reconfigure you can reuse the system as many times has you want and you can do a verity of droplet operations on this surface itself. So, this is and unique thing, unique advantage of digital micro fluidic systems, whereas small drop or a small volume of liquid can be manipulated anyway you want.

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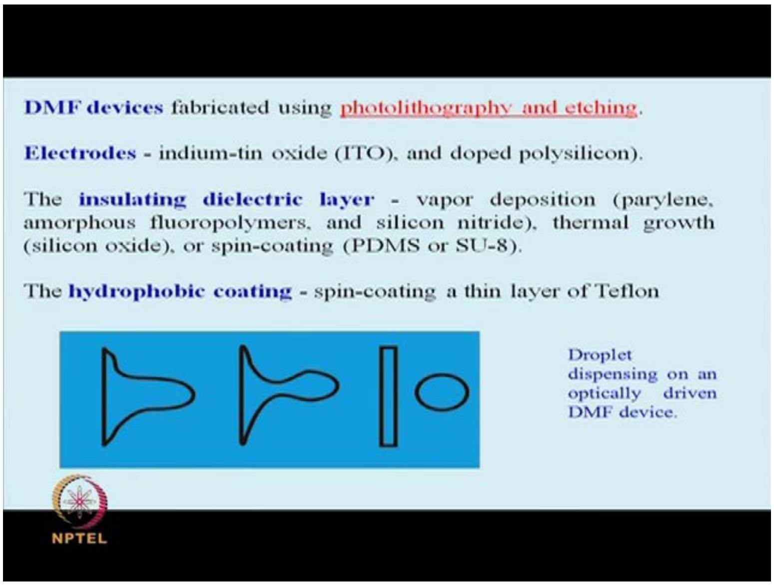

**DMF devices** fabricated using photolithography and etching.

**Electrodes** - indium-tin oxide (ITO), and doped polysilicon).

The **insulating dielectric layer** - vapor deposition (parylene, amorphous fluoropolymers, and silicon nitride), thermal growth (silicon oxide), or spin-coating (PDMS or SU-8).

The **hydrophobic coating** - spin-coating a thin layer of Teflon

Droplet dispensing on an optically driven DMF device.

So, this is a very strong and powerful technique, now these these some of the electrodes which are used, these these are information about the material that are used for electrodes. The ITO coated glass is a very common electrode and the insulating dielectric layer can be vapor deposited with these following chemicals, you can grow a silicon oxide on a silicon vapor. And the silicon oxide will act as a dielectric layer and the advantage is that is you you can control the thickness of the silicon oxide there by changing the dielectric changing the dielectric changing the dielectric changing the breakdown voltage. And you can you can tune it in such a way that you can operate silicon oxide, coated silicon wafer in electro weighting experiments over a large range of voltages.

And the hydrophobic coating that you see generally on on the surface are are Teflon it is a specific chemical specific solvent which dissolves Teflon which is a fluoro carbon. So, in in fluoro carbon Teflon powder is dissolved and the dielectric is coated, spin coated with Teflon and this enhances the contact angle and this also reduces the sticking of the droplet on the dielectric surface.

So, now the droplet is free to slide over the surface and this provides more mobility, enough mobility in enhanced mobility on such surfaces, so the coating of Teflon is extremely important. And the next figure which shown here is very interesting, this is something which I have not covered. So, far we have seen is that by applying an electric field, you would be able to change the surface energy and when you change the surface energy, the manifestation that is in a change of the contact angle.

If the contact angle if the contact angle changes in in in a non-uniform way in a in in in an asymmetric way then, the droplet will move to certain side. So, the same change in the surface energy of a surface can be brought upon by by optical by optics. So, there are certain optically active surfaces, which when when we shine light mostly laser light on it it is surface energy changes. So, whatever we were doing with electric field can also be done by by by light by shining light on a specific portion of the surface.

So, let us say here in this figure you can see that a droplet a droplet sits on a surface in some portion of it is, I mean you we shine a green laser on it. So, from a large droplet exactly like what you do in electro wetting EWD, you can you can extract a droplet because the contact angle changes; and the tendency of the liquid would be to move from the larger drop to the region where the contact angle is less.

So, by shining light alternately at different points you can make the droplet move with the light that is fascinating, so by controlling by shining light on surface you can bring a droplet to that point. So, you you do you do electro wetting, but that requires lot of planning, lot of fabrication and so on. You need to have electrodes electrodes probably embedded on the surface, embedded inside the surface photolithography photo lithographically you have to cover it with a dielectric, you have to cover the dielectric with a Teflon layer. So, to to hydrophobic layer and then you provide current and the droplet moves from one point to other.

Now, there is a flexibility but, still it is the path is going to be limited, wherever the electrodes are you can make the droplet move or in in that direction only but, if I have an optically active surface. So, every or the only thing I have to do is I have to shine light at a specific spot. The spot where I shine the light will change it is energy surface energy, the contact angle will change and the droplet will preferentially move to that spot. So, by shining a laser light, shining a laser on a specific point, you can as if you can take the droplet in any path that you want. You can you switch off the light and the droplet stops at that point, you switch on the light and move the move the move the light the droplet moves with the light spot as the contact angle in front of the droplet keeps on changing, because of shining of light.

So, this has tremendous potential in terms of flexibility in terms of having in terms of having any kind of motion that you may think of on a on a surface. In fact, the motion of droplets or motion of particles, when you shine light on optically active material has given rise to fantastic applications for example, optical tweezers and so on.

So, you have a surface optically active surface and you apply an electric field, the moment you shine certain portion of it with light and if the conductivity, let us say of that of that of that area changes; then you are going to have concentration of field channeling of fed lines towards that spot. So, the particles are then going to move towards that spot and will start depositing, will start accumulating in the area which which which is which were light is being shown.

So, as a result of which you can have some sort of a separation or concentration of particles or you can bring a specific particle from the bulk to a specific point, where you want it to be. So, the application of optoelectronics and into into this field in in digital microfluidics is anonymous (Refer Slide Time: 48:10). Now this I have already described is that the example of lab on a chip and how you can move droplets and so on.

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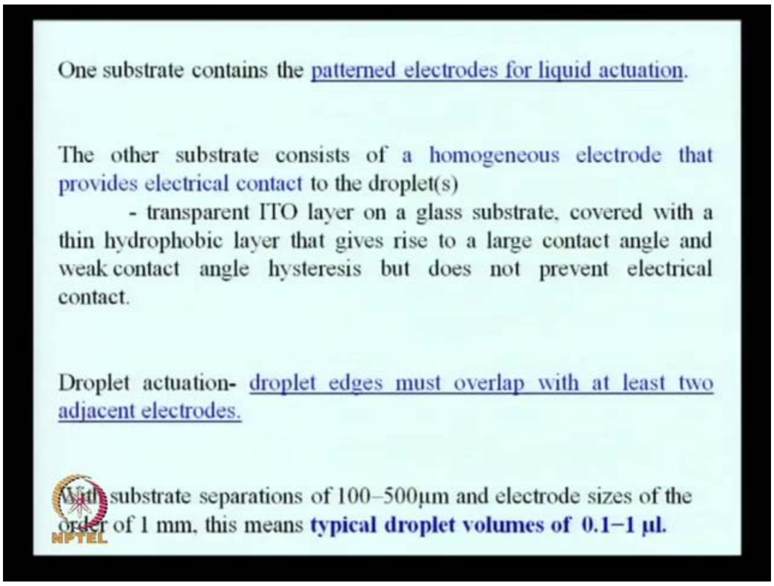

One substrate contains the patterned electrodes for liquid actuation.

The other substrate consists of a homogeneous electrode that provides electrical contact to the droplet(s)

- transparent ITO layer on a glass substrate, covered with a thin hydrophobic layer that gives rise to a large contact angle and weak contact angle hysteresis but does not prevent electrical contact.

Droplet actuation- droplet edges must overlap with at least two adjacent electrodes.

With substrate separations of 100–500μm and electrode sizes of the order of 1 mm, this means **typical droplet volumes of 0.1−1 μl.**

So, I will move on to the next is the substrates that are used it could be a transparent glass with ITO coated having a thin the hydrophobic layer. And the droplet edges must overlap with at least two adjacent electrodes, in order to have any kind of actuation. And the typical droplet volumes which are encounter are encountered in this or these operations are between point one to 1 micron per liter 1 micro liter.

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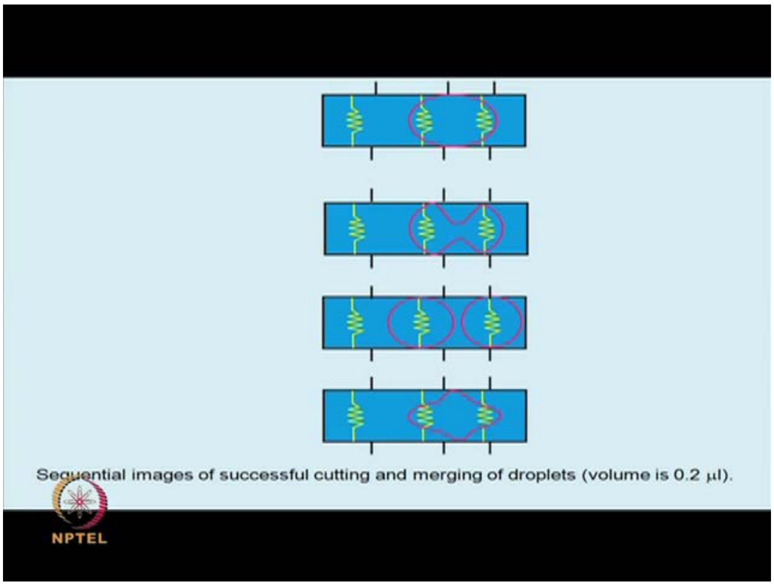

Sequential images of successful cutting and merging of droplets (volume is 0.2 μl).

Now, if you look at this figure carefully, what you see here is what I what I was describing before electrode number 1, electrode 2 and electrode 3, are droplet the outline of which is by this white line sits mainly on one but, overlaps with two and three all are off right now, certainly 2 and 3 are switched on. So, what would happen the some liquid will move towards 2 and some will move towards 3 and you get two droplets, both the droplets are now on 2 and 3. However, overlapping with part of 1, so from one droplet you have created two droplets, next is everything is this 2 and 3 are switched off, but three is switched I mean 1 is switched on.

So, liquid from two will move towards 1 from 3 it will also move towards 1 and then you are going to form a large droplet, so and everything is switched off. So, essentially you get back conditions in figure a in this keys, so you created two droplets and you merged two droplets. So, this has tremendous potential in as I mentioned in many applications including these droplets behaving as micro reactors.

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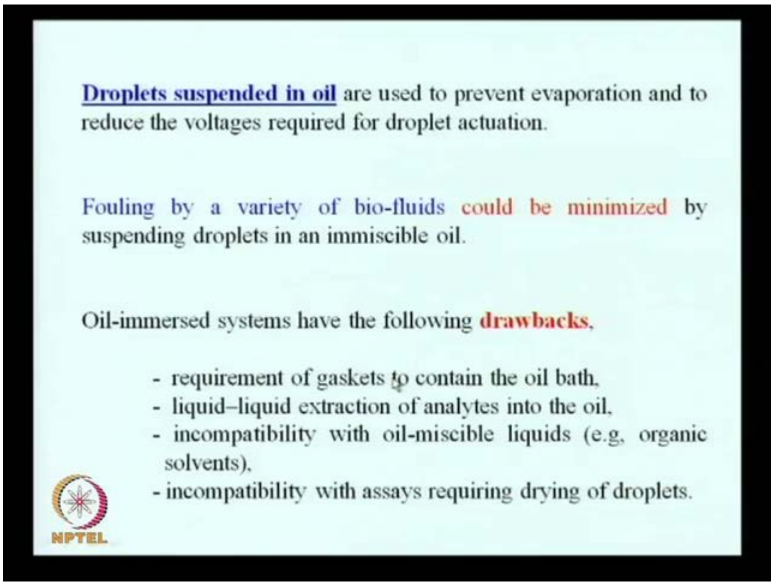

**Droplets suspended in oil** are used to prevent evaporation and to reduce the voltages required for droplet actuation.

Fouling by a variety of bio-fluids could be minimized by suspending droplets in an immiscible oil.

Oil-immersed systems have the following **drawbacks**.

- requirement of gaskets to contain the oil bath.
- liquid–liquid extraction of analytes into the oil.
- incompatibility with oil-miscible liquids (e.g. organic solvents).
- incompatibility with assays requiring drying of droplets.

In some cases specially in closed digital micro fluidic systems, the droplets are suspended in oil they they have suspension in oil does are fulfills two purposes. One is it does not allow any evaporation to take place and the second is there are certain bio fluids, which which corrode the surface or which which deposits on the surface and it is difficult to clean such a surface.

So, if I provide an oil interface droplets are suspended in oil, then these these problems will not be encountered. However, the oil immersed systems have certain drawbacks and I have listed some of them that you would require special gaskets to contain them; there are there would be if you have an oil droplet and water droplet then, there is a possibility that the analytes will will move from the water to the oil and thereby you may lose certain chemicals and so on.

And in some cases you require the require the drawing of the droplets at the at the end of the experiment, which you at the end of the measurement, which would not be possible if you have an oil based system.

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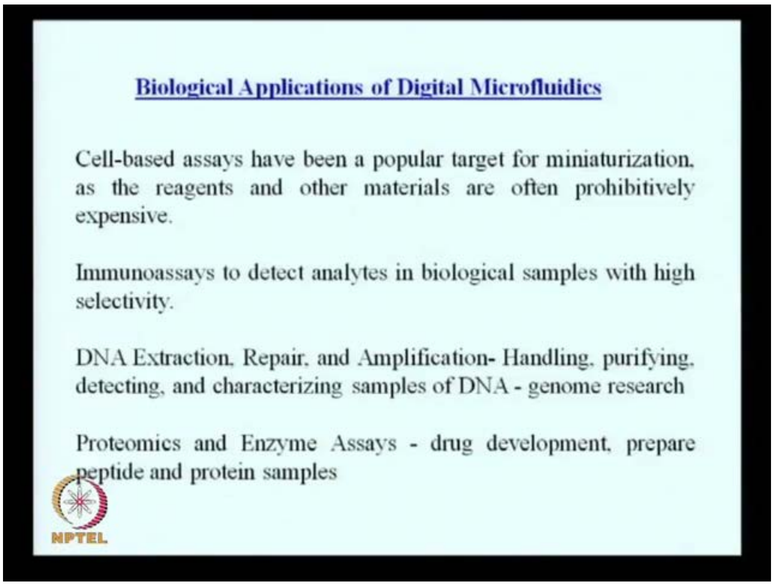

Biological Applications of Digital Microfluidics

Cell-based assays have been a popular target for miniaturization, as the reagents and other materials are often prohibitively expensive.

Immunoassays to detect analytes in biological samples with high selectivity.

DNA Extraction, Repair, and Amplification- Handling, purifying, detecting, and characterizing samples of DNA - genome research

Proteomics and Enzyme Assays - drug development, prepare peptide and protein samples

So, there are a number of applications of biological applications of digital micro fluidics. So, starting from cell based assays to immune assays and so on, which in the literature you will find a large number of such uses.

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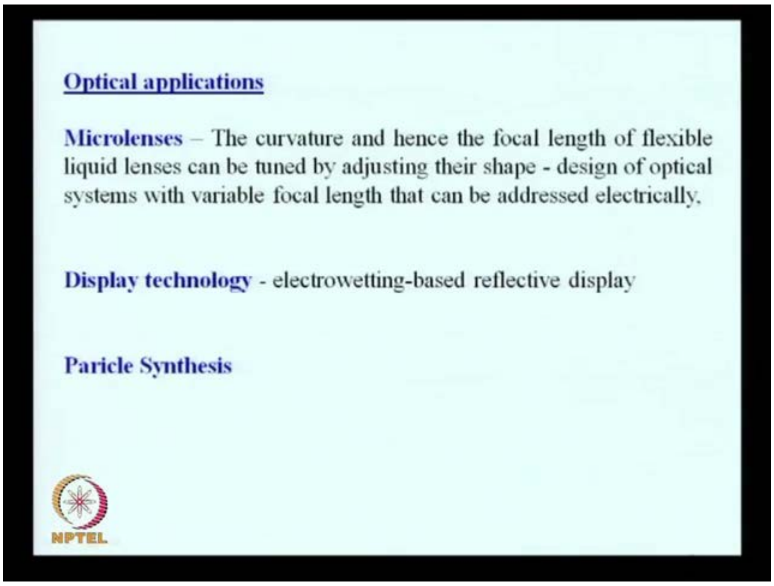

Optical applications

**Microlenses** – The curvature and hence the focal length of flexible liquid lenses can be tuned by adjusting their shape - design of optical systems with variable focal length that can be addressed electrically.

**Display technology** - electrowetting-based reflective display

**Paricle Synthesis**

The in the optical applications, I would the only spend I will I will only say few words about the micro lenses, because if you if you could create a lens using a droplet a liquid droplet the advantage is that it is very flexible and by applying the right electric field, the curvature the contact angle and hence the curvature of the of the of this of this micro lens can be modulated.

So, you can have you can vary the curvature by varying the contact angle and by varying the electric field. So, these are extremely sensitive extremely sensitive control of the focal length of the optical, of the micro lens of the made from a liquid droplet can be achieved and which have applications in display technology and so on.

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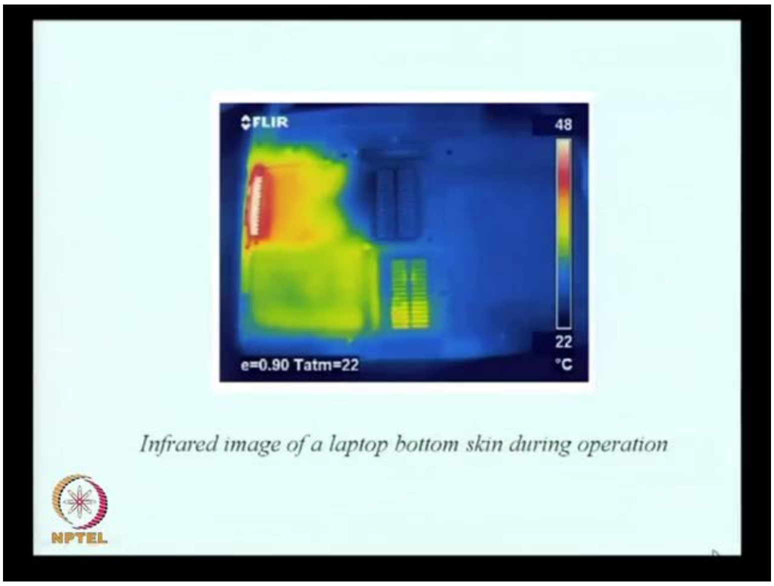

*Infrared image of a laptop bottom skin during operation*

And one more application is this, is the thermal image of a laptop the bottom of a laptop and you can see there the certain regions, which are very hot, certain regions which are cold.

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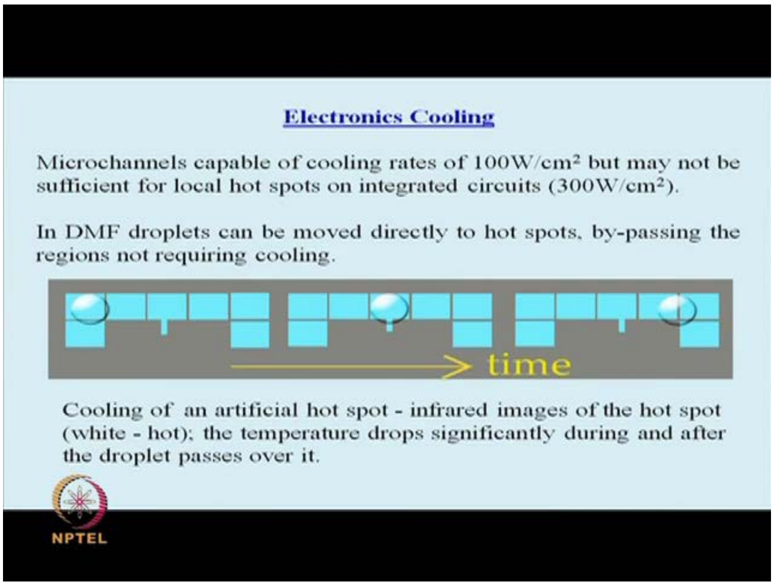

**Electronics Cooling**

Microchannels capable of cooling rates of 100W/cm$^2$ but may not be sufficient for local hot spots on integrated circuits (300W/cm$^2$).

In DMF droplets can be moved directly to hot spots, by-passing the regions not requiring cooling.

Cooling of an artificial hot spot - infrared images of the hot spot (white - hot); the temperature drops significantly during and after the droplet passes over it.

And if I would like to use the droplet for electronics cooling, you would see that this is the droplet, this is a hotspot the whiteness shows the hotspot. And as the droplet moves comes to this point, the hotspot disappears as the droplet moves away from it you would see a faint reappearance of the hotspot.

So, by controlling the frequency of the droplets, the velocity of the droplets the hotspot generation on on electronic chips can be controlled, which is a very interesting example of application example of droplet movement.

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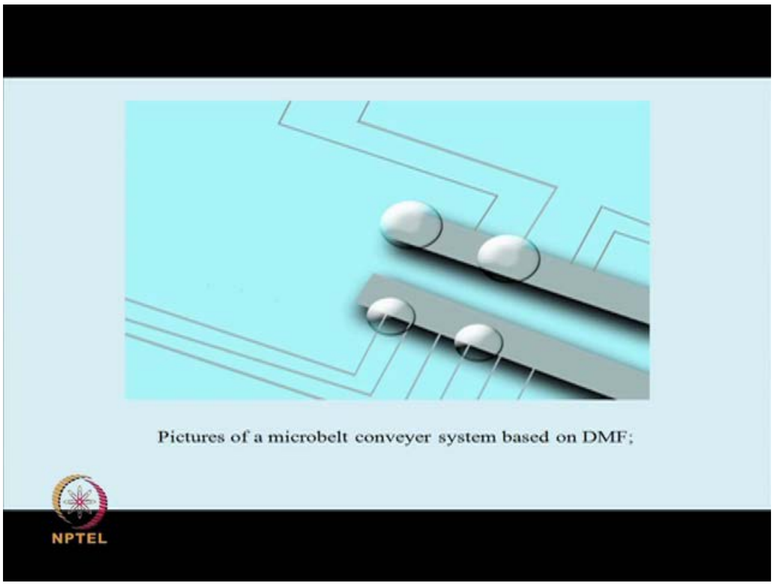

Pictures of a microbelt conveyer system based on DMF;

And finally one interesting unique example of DMF to close today's class, this this figures you can see therefore droplets; the droplets moves simultaneously keeping equal distance in between them. So, what we do what what is done is thin sheet is placed on them as you can see over here, so now, it acts like a conveyor belt. So, droplet droplets move with the equal velocity and this also moves with the with the with the with the droplets and therefore, if you can keep something on top of it then that will the entire thing will act as a conveyor system.

And this is what you can see in this figure very interesting example, you see something a black thing which is placed on the one on the sheet and the weight of this you can see it it has bent as well, if you know what it is you will be truly surprised this one is nothing, but a ladybug, which is carried on a silicon vapor supported by four droplets.

So, in unique application of digital micro fluidics to end the class and this shows that you can truly do some really interesting and fascinating things with digital micro fluidics. And the entire process is based on the concept of electro wetting or electro weighting on dielectrics, thank you.