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Effects of DC electric field on particle transportation and deposition in evaporating droplets

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ROCHESTER INSTITUTE OF TECHNOLOGY

Master Thesis

Effects of DC electric field on particle transportation and deposition in evaporating droplets

by

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DEPARTMENT OF MECHANICAL ENGINEERING

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Master Thesis

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ABSTRACT

Microfluidics(uF) is the science of manipulating and controlling the fluids usually in the range of microliters (10^{-6}L) to picolitres (10^{-12}L). Physical parameters, such as surface tension and contact angle do not play a significant effect on macro scale but play a crucial role at the microscopic level. Microfluidics is viewed as an essential tool for life science research and flexible electronics. A deeper understanding of physical parameters of microfluidics would result in more efficient and lower cost devices ('Lab-on-a-Chip' devices) and foldable electronics. In short, the concepts of microfluidics can be used to reduce the cost, size, and ease of usage in a wide variety of futuristic products.

In our study we are going to explore the effects of electric fields on a particle transport in evaporating droplet and deposition patterns left behind evaporating droplets. We will be studying droplets evaporating on 'Electrowetting on Dielectric' (EWOD) devices where the droplet is separated from the active electrode by dielectric layers. These types of devices are relevant in a variety of applications such as medical diagnostics and optics. We believe that understanding this phenomenon will impact printing and the development of flexible electronics. This work will further the understanding of transport and deposition of particles in evaporating droplets under applied electric field by understanding the effects of particle concentrations and different dielectric layer.

Previous works have demonstrated that particle transport in evaporating droplets and their resultant deposition patterns can be altered under the presence of the electric fields. Applied electric fields have potential to provide real-time control of the particle transport in evaporating droplets by allowing an instantaneous control of the contact line dynamics, electrophoretic manipulation of particles inside the droplet, changes in interface shape, dielectrophoretic manipulation and particle motion inside the droplet due to forces induced by the electric field and evaporation. Our work is going to provide a deeper insight

into the effects of DC electric fields on droplets with varying particle concentrations on different dielectric layer. We will better understand the effects of changing the variables (i.e., hydrophobicity ,polarity and particle concentration) under applied DC electric field.

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1.0 PROBLEM INTRODUCTION.

An understanding of the transport and deposition of particles in evaporating droplets is critical for a wide variety of applications, including ‘Lab-on-a-Chip’ devices [1,2], flexible/wearable electronics [3,4], printing [5,6], and nanoparticle assembly [7]. Microfluidics is a working principle besides all the above-mentioned applications. Fluids that are present in these applications usually range from a few microliters to picolitres. Particles contained inside them have dimensions ranging from a few micrometers to nanometers. In such quantities, the physical parameters like surface tension, electrostatic forces, van der walls force, capillarity, and contact angle come into play. A better understanding of microfluidics is crucial for the efficient working of the above-mentioned devices.

The main goal we are trying to achieve in our study is to understand the particle transport in evaporating a droplet over a dielectric surface when no electric field is applied, and particle transport in evaporating a droplet over a dielectric surface when DC field is applied. We are trying to deduce the trend of evaporation when a droplet is suspended over a surface with no external factor present by recording its evaporation time, contact angle, contact width and droplet height. Before we attempt to manipulate or control the particles inside the droplet or control the flow of fluid, it is important to understand how particles move and fluid flows during evaporation when no external factor is present. Previous research has been done to help understand the motions of fluid-containing particles which can be broadly classified under: 1) Convective Effects and 2) Interface Trapping.

1) Convective effect is crucial for better understanding the flow of particles inside an evaporating droplet. Deegan et al. [8] found that pinning of the contact line and evaporation flux at the contact line caused the evaporative flow, which drives the particle inside the droplet towards the periphery of the droplet and gives rise to coffee-ring stains (Figure 1). Hu & Larson’s [9] work found that 'Marangoni circulation' hinders the formation of coffee-ring stains. It drives the

particles inside the droplet towards the center of the droplet and hence coffee-rings stains are hindered [6], [10]. Both phenomena are termed under 'Convective effects'.

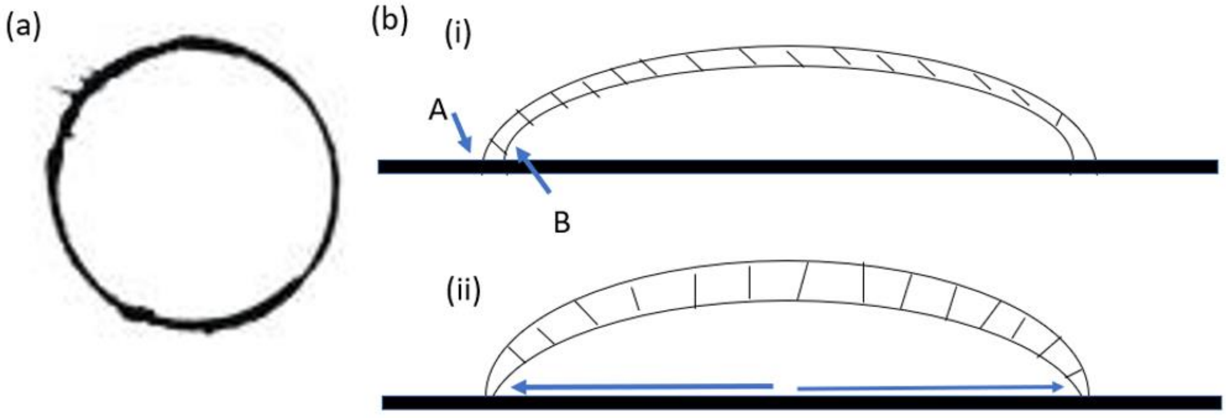

Figure 1 (a) Pattern left behind dried coffee drop adapted from Deegan et al. [8] *(b) (I) Imaginary condition when fluid flow is absent and contact line leaps from point A to point B. (ii) Real scenario where pinning of contact line forces the fluid towards the edge during evaporation and replaces the fluid which is lost during evaporation.*

2) Interface trapping is crucial for better understanding the pattern of deposition left beside an evaporating droplet. There are two kinds of interactions possible here: (a) Particles getting trapped on solid-liquid interface [2,11,12] and (b) Particles getting trapped on liquid-air interface [13,14]. Work done by Bhardwaj et al. [11] explains how the particles inside the droplet get stuck on the surface of the solid on which the droplet is suspended during evaporation. They talk about how the attractive DLVO forces (which is combination of van-der walls force and electrostatic force) pull the particles towards the solid surface and particles are trapped on that solid-liquid interface. Uniform deposition pattern is left behind as the result of this interaction when Marangoni flow is dominant and vice versa.

   Work done by Li et al. [14] & Burkhart et al. [13] explains how the particles inside the droplet are trapped on the liquid-air interface during evaporation. During evaporation, the liquid-air interface moves downwards. Due to this motion, the particles inside the droplet get stuck on the surface of the liquid-air interface and remain trapped till the end of evaporation. Uniform deposition pattern is left behind as the result of this interaction (Figure 2).

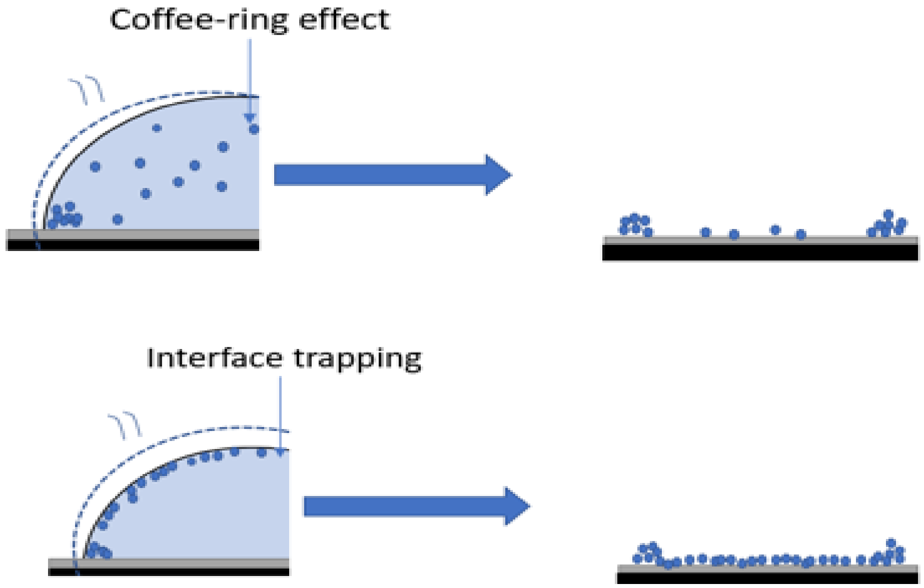

Figure 2 Pictorial representation of particle deposition under the coffee ring effect and interface trapping. More uniform deposition pattern is visible when particles are trapped on the interface. Adapted from Li et al. [14]

Many investigations have examined methods to control fluid flow and particle deposition in evaporating droplets by manipulating convective effects and interface trapping. Combined representation of all the convective and interfacing are shown in figure 3. Some of the ways of controlling and manipulating the particles were by adding a surfactant [15], altering the particle shape [16], changing the thermal gradient [9], and applying the electric field [12– 15].

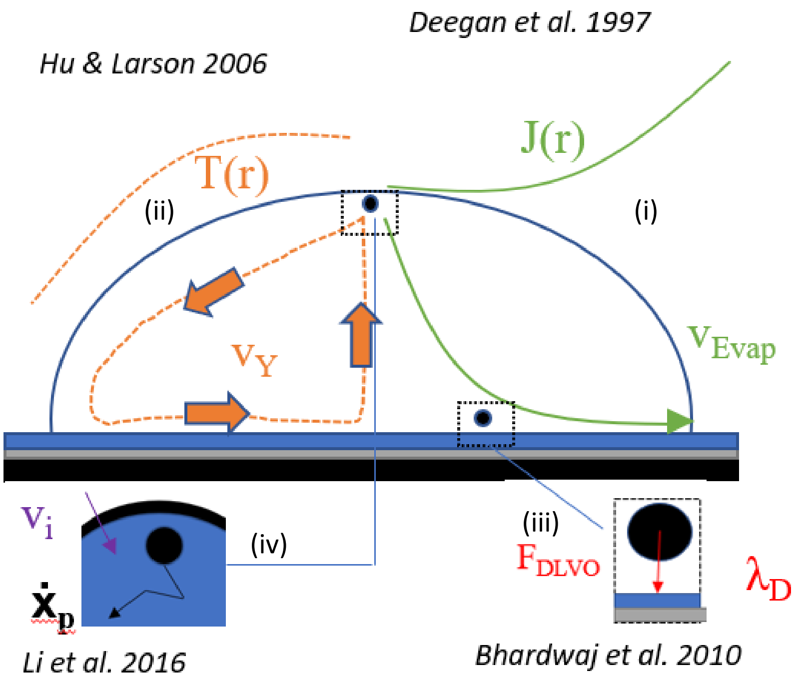

Figure 3 Representation for Convective effects (i) V_{Evap} is peripheral flow which gives rise to coffee-ring stains. (ii) Marangoni circulation (V_Y) drives particles to the center of the droplet. Interface trapping (iii) Due to attractive DLVO forces (F_{DLVO}) particles are trapped on the solid substrate. (iv) Due to descending interface (V_i) particles are trapped on Liquid-air substrate. Adapted from Schertzer et al.[13].

Morales et al. [15] introduced the surfactant to the droplet which altered the surface tension of the droplet. They found that by altering the concentration of the surfactant they can manipulate the surface tension and hence control the deposition pattern. Yunker et al. [16] modified the shape of particles inside the droplet from spherical to elliptical and achieved a uniform deposition pattern. Hu and Larson [9] created a thermal gradient which results in Marangoni circulation and drives the particle from the periphery to the center of the droplet and results in a uniform deposition pattern left behind by the evaporating droplet. All the above-mentioned methods had some limitations or disadvantages. Adding surfactant can alter the droplet's chemical or physical properties which is a matter of concern if we are dealing with biological applications. Changing the shape of particles is not always possible as it can be complex and expensive. Heating acts relatively slow and can result in a change of chemical and physical properties of the droplet or the particles.

Recent investigations have shown that the application of electric fields has the potential to alter the transport and deposition of particles in an evaporating droplet by changing the shape of droplet interface, increasing the surface area of the droplet, and reducing the evaporation time. We think that the application of electric field is very promising. Work done by Eral et al. [17] and Orejon et al. [19] show how the application of an electric field across the droplet helps in controlling the flow and manipulating the particles inside the droplet. Application of an electric field doesn't have the same limitations or disadvantages which adding surfactant possesses, as an electric field doesn’t typically change the chemical or physical attributes of the particle or the liquid. Even if it does, the effect is not permanent. We don’t have to change the shape of the particle as an electric field can act on particles of any shape and sizes.

Orejon's work talks about how they got rid of coffee-ring stains by manipulating the particles inside the droplet with the application of DC electric field [19]. Orejon et al. [19] tested their hypothesis with the application of DC electric field across the droplet of Deionized water (DI water) containing Titanium dioxide (TiO_2) particles suspended over a dielectric layer of SU-8 covering positive electrodes. They mentioned the presence of the electrophoretic force on negatively charged TiO_2 particles due to which they were able to get rid of the coffee ring stains. They argued the electrophoretic force dominated the flow inside the droplet which is usually governed by 'Convective effects' or 'Interface trapping'. They supported their hypothesis by a mathematical model to compare the velocities of particles under the influence of evaporative flow (advective velocity) and particles under electric field (electrophoretic velocity).

Lee et al. [21][22] demonstrated that during DC electrowetting the electric field doesn't penetrate the droplet or manipulate the particles inside the droplet. If work done by Lee et al. [21] holds correct, then one of the critical assumptions for Orejon et al's mathematical model will no longer be valid. To prove experimentally, it would be interesting to test Orejon's hypothesis if we reverse the polarity of electrodes and check for the consistency of the results. If Orejon's hypothesis is correct, we could get different results when the polarity of electrodes is reversed. The deposition pattern would be visually different/opposite to Orejon's results.

In our study, we will try to answer the questions about Orejon's hypothesis and design experiments to provide deeper insight into whether electrophoretic force acts on particles inside the droplet or some other factor is in play which can better explain the reason behind the uniform deposition pattern. We will first try to replicate Orejon's tests and then test their hypothesis under reversed polarity. We will aim to provide a hypothesis that would better explain the phenomenon behind unform deposition.

2.0 RESEARCH QUESTION

How does the DC electric field alter particle transportation and deposition in evaporating droplets?

Scope of Experiments:

- Control case: To determine the effect of an applied electric field on particle motion inside the droplet, we need to know the particle movement when there is no voltage applied.
- Observe the deposition pattern left behind the evaporated droplets, the evolution of contact angle and the interface shape of droplet during evaporation.
- The control experiments will involve contact angle readings that are taken on SU-8 coated devices and Teflon coated devices when no voltage is applied and across the droplet. These control cases would include readings from droplet with particle concentration at 0.01%, 0.05% and 0.1%. Microscopic Images taken just after the evaporation. Each test will be reapeted three times to check for repeatability.
- To determine the effect of applied voltage on deposition pattern left behind the droplet, another set of experiments would be done and contact angle readings taken on SU-8 coated devices and Teflon coated devices at application of appropriate voltage across the droplet with particle concentration 0.01%, 0.05% and 0.1%. Microscopic Images taken just after the complete evaporation. This will give us the visual and grapical comparison between the deposition pattern from control cases. Each test will be repeated three times to check for repeatability.

- We will study the effect of change of particle concentration and surface selection. We will compare our results to Orejon's hypothesis and try to give better explanation behind unform deposition pattern.

Expectations:

- Evaporation time of droplets with particles inside droplets should decrease when voltage is applied due to the instant change in the shape of the droplet, the surface area of the droplet would increase, and a faster rate of evaporation is expected.
- Deposition pattern left beside the droplet when voltage is applied would be more concentrated throughout the surface area of droplet due to interface trapping or Electrophoretic force.
- While replicating Orejon's experiments, we might see similar trend as he observed in his work.
- When the polarity of electrodes is reversed, deposition pattern would change as per Orejon's hypothesis the particles are negatively charged and the same polarities will repel each other. If not, then we will be able to support our competing hypothesis beside uniform deposition pattern.

3.0 LITERATURE REVIEW

3.1 Particle transport in evaporating droplets.

Deposition and transportation of particles in evaporating droplet is backbone of the applications that rely on coffee-ring stains. A wide variety of applications rely on better understanding of particle transport and deposition in evaporating droplets including 'Lab-on -a-Chip' devices [1], [23], [24] which are used in diagnostics, applications like flexible/wearable electronics [3], printing [5], and nanoparticle assembly [7] also use coffee ring effects.

All the above-mentioned applications works when coffee ring depositions are suppressed by manipulating particle transport inside the fluid during evaporation. Fluid's quantities here usually range from a few microliters (10^{-6} L) to picolitres (10^{-12} L). On microscale physical parameters such as surface tension, van der waals force, electrostatic force, surface roughness, height of droplet, the contact angle of the droplet at the interface, and droplet width come into play in this situation but it's often neglected when dealing with fluids at macro level. It is important to understand the effects of the physical parameters in microfluidics before we attempt on controlling or manipulating the fluid flow.

Particle transport and deposition in evaporating droplets is a complex phenomenon because there are several physical parameters are in play. The forces that are crucial for the better understanding of the fluid flow and particle transport can be categorized under two broad sections: 1) Convective Effects and 2) Interface Trapping.

An understanding of convective effects is crucial for better understanding the flow of particles inside an evaporating droplet. In 1997, Deegan et al. [8] found out that during evaporation the contact line gets pinned at a point and the flow is generated due to the evaporation which gives rise to the coffee-ring stains. He explained that particles get pinned at the periphery of the droplet due to evaporative flow which hindered the particle to be deposited on the center of the droplet. Those particles in the periphery of the droplet contribute towards the coffee-ring stains. His biggest contribution was the idea that evaporation happens at the contact line and when the contact line is pinned, we get the particle flow from the center of droplet towards the periphery of the droplet which results in the coffee-ring structures. This phenomenon has been studied extensively since then. Deegan's work explains the particle flow from the center to the periphery of the droplet during evaporation and how it is responsible for ring formation. Sometimes particle will travel inside the droplet to the center of the droplet which can lead to uniform deposition pattern.

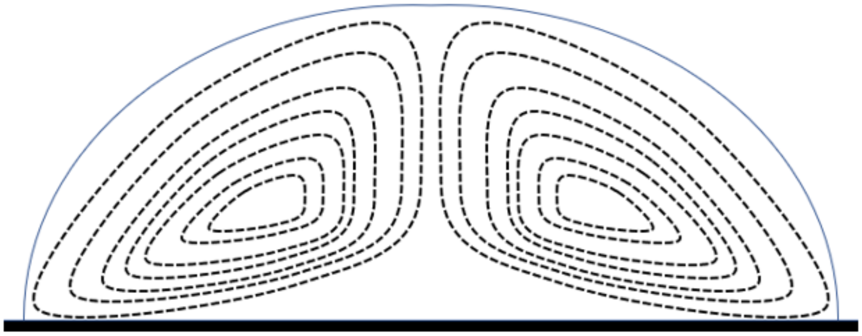

Figure 4 Marangoni Flow in an evaporating droplet. Particles travel to the center of the droplet which results in central deposition. Adapted from "Marangoni effect reverses coffee-ring depositions" [9].

Marangoni recirculation (Figure 4) in the droplet will hinder the formation of ring stains by driving particles inside the droplet towards the center of the droplet. Hu & Larson [9] depicted that during evaporation the 'Marangoni Flow' is generated due to the difference in temperature which also plays an important role in fluid flow and particle transportation. Their work shows that due to the presence of 'Marangoni Flow' the particles are transported to the center of the droplet which is complete opposite to the Deegan's. finding. The 'Marangoni Flow' hinders the coffee-ring stains and result in a more uniform deposition pattern throughout the surface area of the droplet. Work by Hu and Larson is also categorized under Convective effects. Both the convective effects gave us information about the particle flow inside the droplet. Now we will see how movement of contact line due to the combined effect of particles and convective effects occur.

Convective effect described by Deegan is dominant in evaporating droplet, but the flow due to evaporation and particle transport changes in the case where contact line is mobile. Unpinned contact line or moving contact line leads us to specify three modes of evaporation based on contact line mobility. These modes of evaporation are valid for droplets containing particles or no particles. The three modes/regime of evaporation are:

1. Constant Contact Radius (CCR) Regime - When contact width remains constant while height and contact angle decrease during the evaporation [25 – 27] .
2. Constant Contact Angle (CCA) Regime - When contact angle remains constant while height and contact width decrease during the evaporation [25 – 27].
3. Mixed Regime - When contact angle and contact width both decrease simultaneously during the evaporation [25 – 27].

Peripheral flow (transport of particles from center to periphery) responsible for coffee ring stains are prevalent when droplet evaporates in CCR regime. Peripheral flow which is responsible for coffee ring stains are less prevalent when droplet evaporates in CCA regime. Peripheral flow is dominated by the Marangoni recirculation in the mixed regime thus resulting in more uniform deposition. After learning about the particle transportation and movement of contact line under evaporation, now we will explain the effects of particle which gets stuck or latched to the solid-liquid and liquid-air interface.

An understanding of interface trapping is crucial for better understanding the pattern of deposition left beside an evaporating droplet. Bhardwaj et al.[11] shows that the presence of Derjaguin, Landau, Verwey, and Overbeek (DLVO) forces often trap the particle to the solid substrate on which they are suspended/spread. DLVO is the force that acts on charged particles. It is a combination of van der waals and electrostatic forces. Due to the attractive DLVO force, the particles cannot escape the solid interface and remain stuck to the surface until the end of evaporation. When particles get stuck on the solid-liquid interface, it results in a more uniform deposition pattern. They argued when attractive DLVO forces are dominant over other convective effects it results in more uniform deposition pattern. When the force driving the particles to periphery is less than the attractive DLVO force the particles are trapped over the solid-liquid surface which give rise to the uniform deposition. When the force driving the particles to the droplet periphery is more than the attractive DLVO force the particles no longer get trapped on solid-liquid interface but are transported to the periphery which gives rise to the coffee-ring stains. Work done by Bhardwaj is categorized under Interface trapping. This work told us about the trapping at solid-liquid interface now we will learn about the particles getting trapped in liquid-air interface.

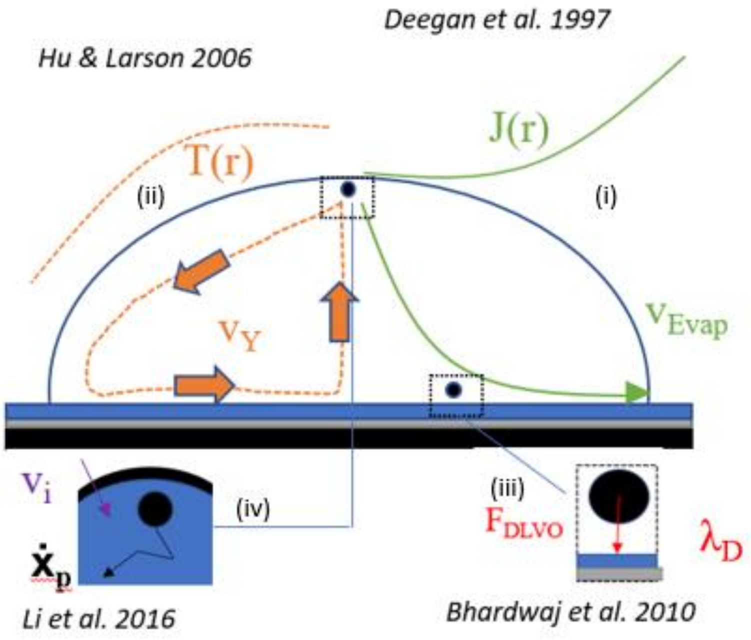

Figure 5 Representation for Convective effects (i) V_{Evap} is peripheral flow which gives rise to coffee-ring stains. (ii) Marangoni circulation (V_Y) drives particles to the center of the droplet. Interface trapping (iii) Due to attractive DLVO forces (F_{DLVO}) particles are trapped on the solid substrate. (iv)When rate of diffusion ($\dot{x}_p$) is higher than the interface velocity (V_i) particles are trapped on Liquid-air substrate. Adapted from Schertzer et al.[13].

Li et al. [14] & Burkhart et al. [13] show that particles can also be trapped on the liquid-air interface. When the rate of diffusion ($\dot{x}_p$) is higher than the interface velocity (v_i), the particles suspended inside the fluid get trapped on the liquid-air interface. They found that at low temperatures, the rate of diffusion is higher than the descending liquid-air interface and at higher temperatures, the rate of diffusion is less than descending liquid-air interface. They concluded that at lower temperatures particles migrated to the contact line which resulted in coffee ring stains and at higher temperatures due to interface trapping the particles are evenly distributed throughout the surface area of the droplet.

Many investigations have studied different methods to manipulate particle transport and deposition in evaporating droplets. Some of these methods include: adding surfactant [15], manipulating thermal gradient [9], changing the shape of the particles [16], and applying the electric field [17 – 20] across the droplet. All the above mentioned methods either change the droplet interface/shape of the particles or drive the particles away from the periphery of the droplet.

Morales et al. [15] introduced the nonionic surfactant to the droplet which altered the surface tension of the droplet. They found that by altering the concentration of the surfactant they can manipulate the surface tension and contact line behavior. They manipulated the surface tension and contact line behavior of the droplet by controlling the concentration of the surfactants. Then based on initial surface tension they categorized the contact line into three regimes which were slipping, pinned, and recurrent stick-slip which resulted in amorphous (irregular), coffee-ring and concentric ring stains respectively. They also mentioned it’s limitation as adding surfactant changes several physical properties it is not suited for the application which cannot withstand changes to those properties.

Hu and Larson [9,28,30] used a thermal gradient on surface that results in Marangoni circulation and drives the particle from the periphery of the droplet to the center of the droplet. They found that the Marangoni circulation generated due to thermal gradient dominates the evaporative flow and thus hinders the formation of coffee ring stains. They argued coffee ring is formed due to combined effects of pinned contact line, high evaporation and Marangoni flow. High evaporation at three-phase contact line and Marangoni flow generated due to temperature difference between substrate and liquid favors coffee ring formation. But if Marangoni flow overcomes the transportation of particles to the periphery (Marangoni flow is dominant), it gives rise to more uniform deposition. If Marangoni flow cannot overcome the transportation of particles towards the periphery (Marangoni flow is not dominant), then it gives rise to coffee-ring stains. When the particles Due to particles moving towards the center of the droplet from the periphery the resultant deposition pattern is uniform and spread throughout the surface area of the droplet.

Yunker et al. [16] modified the shape of the particles that are then introduced into the droplets. They changed the shape of the Polystyrene particles from spherical to elliptical in order to control the deposition pattern. They found that elliptical particles are trapped on liquid-air interface while spherical particles travel to the periphery. They made several inferences and compiled that deposition pattern left behind the droplet containing spherical particles leaves ring stains. The mixture of elliptical and spherical particles in the droplet leaves coffee-ring stains. The droplet containing elliptical particle will give rise to more uniform deposition pattern. They mentioned that sometimes modifying the shape may involve adding substances which have undesirable qualities like toxicity and flammability because of this disadvantage modification of shape of particles can’t be used in majority of applications.

Many researchers like Eral, Mampallil, Degaan and Orejon [17 – 20] showed how the applying electric field across the droplet helped in controlling the fluid flow and particle transportation inside the droplet. Orejon's work comprises of application of the DC electric field while Eral's work discusses particle manipulation with the application of AC electric fields.

While all the above-mentioned manipulation methods have been shown to be effective in achieving uniform deposition patterns or reducing coffee-ring stains, each option also had limitations or disadvantages. Like in case of adding surfactant it can alter the chemical properties within the droplet, application of thermal gradient can be slow, and it takes time for temperature to change. Modifying the shape of particles is not easy and can only be done in special cases and may not even be applicable in some cases as the changes are permanent and can't be toggled on and off. But the application of electric field doesn't have any such limitation or disadvantage. It can easily be applied across the droplet without changing the chemical or physical properties of the droplet or the particle. We don't even have to alter the particle shapes or sizes. Due to such advantages, the application of electric field possesses it has become the prime method of manipulation of particles inside the droplet.

Electric field cannot be directly applied to the droplet that is suspended over the metallic surface as it would cause the droplet to disintegrate (electrolysis) and just evaporate. For the manipulation to work, we introduce a dielectric layer over the metal electrode which prevents droplet from coming in contact with metal electrode and hence prevent electrolysis.

3.2 Electrowetting-On-Dielectric (EWOD)

All the manipulation of particle transport or fluid flow under the influence of an applied electric field can be grouped under the Electrowetting-over-a-dielectric (EWOD). Electrowetting over a Dielectric is a means of manipulating droplet and particles inside the droplet which was discovered by Lippmann in 1875 [29].

The electrowetting effect can be described by

$$cos\ \theta_U = cos\theta_O + \frac{C_H U^2}{2\gamma_{LM}}\ . \qquad \textit{Equation 1}$$

C_H is capacitance per unit area of the solid- liquid surface interface, *U* is the root mean squared (RMS) voltage, γ_{LM} is the surface tension between the liquid and air, θ_O and θ_U are the unactuated and actuated contact angles respectively.

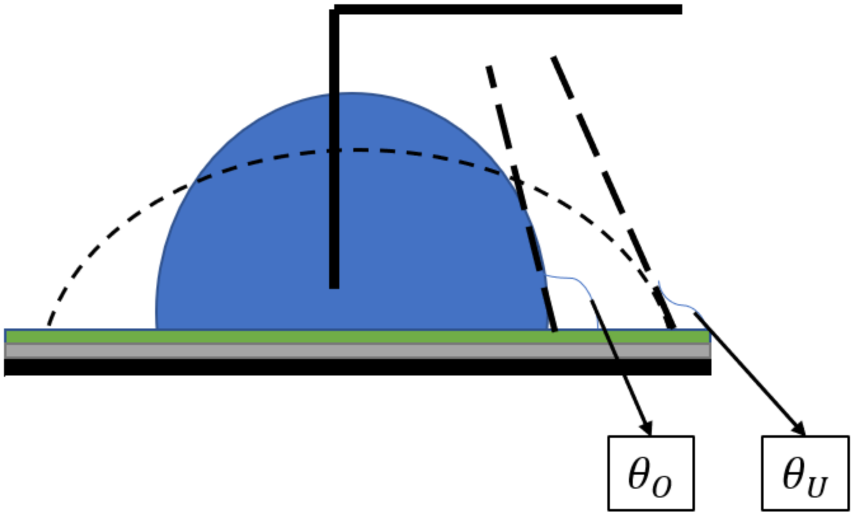

Figure 6 Graphical representation of a droplet over a dielectric layer experiencing electrowetting. Dotted line shows the change in the droplet shape once voltage is applied [28].

When an electric field is applied across the droplet, the shape of the droplet interface is changed. This force overcomes the pinning force which hinders the formation of coffee ring stains [17,19]. When electric field is applied, it gives rise to electrothermal effects which creates difference in temperature at the contact line [31]. The higher temperature at the contact line means that the density of the fluid at the contact line is lower than the fluid in the upper part of the droplet. Due to this temperature difference, the particles inside the droplet start to circulate and in the presence of electrowetting force contact angle of the droplet also decreases.

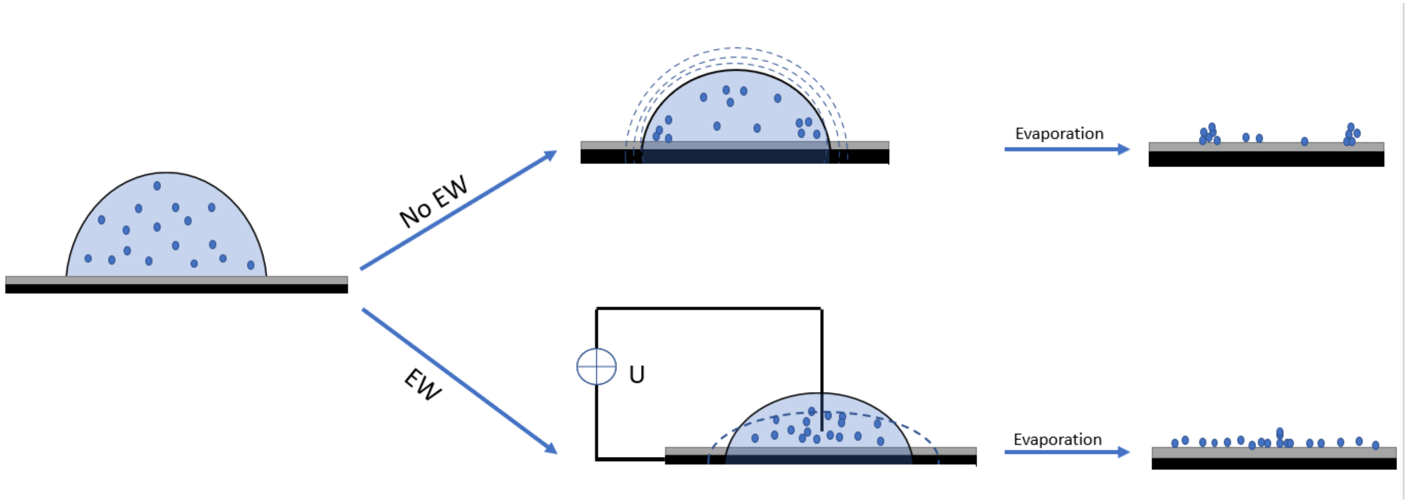

Figure 7 Schematic of Drop evaporation process. Top row is evaporation without Electrowetting. Bottom row illustrates the Evaporation with Electrowetting [17].

One investigation suggests that an applied DC field provides the opportunity for electrophoretic manipulation of particle in the evaporating droplet [19]. Orejon et al. [19] argued that they were able to control the fluid flow and manipulate negatively charged TiO_2 particles over a SU-8 coated device and thus getting rid of the coffee stains. They applied the DC electric field across the droplet and argued that electrophoretic force on negatively charged TiO_2 particles is responsible for absence coffee ring stains.

Orejon's hypothesis was that electrophoretic forces pulls the particle down to the surface faster than they are transported to the periphery. They supported their hypothesis by comparing the velocities due to radial convection (that drives particles to the periphery) and electrophoretic migration (that drives particle to the center of the droplet). Radial convection or advective speed is speed of particles that travel from center to the three-phase contact line (periphery). They calculated the maximum advective speed to be as 3 µm/s and validated it with the work done by Marin et al. [32]. Electrophoretic migration is calculated under DC actuation. It is speed of the particles by which they deposit over electrode.

$$V_{ep} = \mu_{ep}\frac{V}{h}, \qquad \text{Equation 2}$$

where V_{ep} is electrophoretic speed, μ_{ep} is electrophoretic mobility, V is applied voltage and h is distance between the electrodes.

Upon substituting the values for electrophoretic mobility as 1.6 µm/s/V/cm from their pre-calculated values, Voltage = 18 V and distance between electrodes as 0.14 cm they got V_{ep} as 200 µm/s. Upon comparison they found that electrophoretic migration velocity is much higher than the radial convection velocity for TiO_2 particles. This made them conclude that particles will be deposited over the electrode rather than transported towards the periphery. This would result in a more uniform deposition pattern and get rid of ring stains. Their hypothesis could be correct as the particles were negatively charged and the electrode below was at positive polarity and they also assumed that electric field is present inside the droplet.

Lee et al. [21] found that DC electric fields do not penetrate the droplet. If DC electric field don't penetrate the droplet it means that electrophoretic forces won't play any role in the particle transportation. And in Equation 2 the value of applied voltage inside the droplet would be zero which would mean that particles are not driven by electrophoretic force.

In our study, we test Orejon's hypothesis. We think that electrophoretic force might not be acting on the TiO_2 particles. It can be the case of interface trapping where the majority of TiO_2 particles suspended in the fluid get trapped on the liquid-air interface and due to the electrowetting force rapidly changing the interface shape of the droplet. We design experiments where we replicate Orejon's work to test the hypothesis about the electrophoretic force on negatively charged TiO_2 particles. We would also change the polarity of the electrodes and if Orejon's hypothesis is correct we would observe different deposition patterns from their work. Orejon’s work is the case where particles are attracted towards the electrode. To prove our hypothesis, we will investigate the repulsive case: where the polarity of electrodes would be reversed and if Orejon’s hypothesis is correct it would be applicable for the repulsive case as well.

4.0 EXPERIMENTAL METHODOLOGY

This chapter describes the components that are used in the investigation to answer the research question. Creation process of droplets and device are explained. All the equipment used for capturing data and analyzing data are mentioned in this section.

4.1 Droplets

The fluid for all droplets used for this study was deionized (DI) water purchased from Sigma Aldrich. The particles mixed in all droplets were spherical shaped 25nm TiO_2 particles inside the droplet. These particles were used for our study because we are testing Orejon's hypothesis, thus we want to replicate their results for unactuated and attractive case. Then we will be testing their hypothesis if polarity is reversed (repulsive case). Particle concentrations examined included of 0.01%, 0.05% and 0.1% . These were the same concentrations that were used in Orejon's work.

Droplets for all experiments were prepared using the same methodology. The concentrated solutions were created by weight. We first prepared the large stock quantity of 1% concentrated solution and then kept diluting the stock solution as required. Before each test, the solution was put in a glass container and a sonicator was used to keep the concentration uniform. Droplet volume of $3\mu L$ was used for all the cases that were done on the SU-8 coated surface. Droplet volume of $5\mu L$ was used for the cases that were done on the Teflon coated surfaces.

4.2 Devices

Two types of devices were fabricated for the experimentation: (1) SU-8 coated device and (2) Teflon coated device. The process of the fabrication is adapted from Bernetski et al. [33] and Burkhart et al. [13]. The coating process is the same for SU-8 and Teflon devices with an extra last step performed to deposit a Teflon layer on top. Glass slides with aluminum deposited on top were purchased from Sigma Aldrich and used for making these SU-8 and Teflon devices. For this study, these devices will be referred to as SU-8 coated or Teflon coated devices.

SU-8 was deposited to obtain a dielectric thickness of approximately $5\mu\mathrm{m}$. Films were deposited using a two-stage spin coating process. The first step consists of spinning the device at 500 rpm for 10 seconds. Next is the spinning of device at 4000 rpm for 30 seconds with acceleration of 300 rpm per second. The next step was baking the device at 95°C for two and a half minutes, followed by curing in an Electro-lite EC-500 (UV rays) for 30 seconds. The final step was baking at 150°C for 3 minutes. This process is consistent and adapted from Bernatski et al. [33] and Burkhart et al. [13].

For Teflon coated devices, the device pre-coated with SU-8 is taken and one additional layer of Teflon is deposited (referred as Teflon coated devices) to act as the hydrophobic layer. Teflon layers were deposited over the pre-existing SU-8 dielectric layer. Teflon films were spun onto devices for one minute at 2000 rpm then hard baked for ten minutes at 160°C. This process is also consistent and adapted from Bernatski et al. [33] and Burkhart et al. [9].

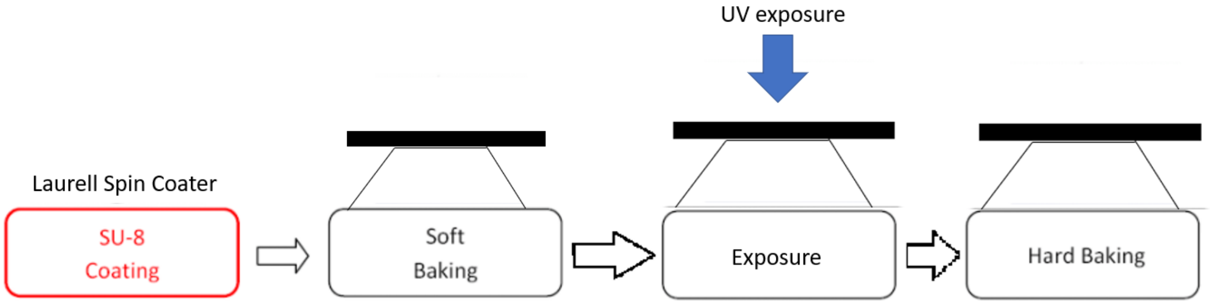

Figure 8 Schematic flowchart of stages of SU-8 coating.

4.3 Observation of droplet interface

Droplet profiles were imaged using the Ramè-Hart model 250 goniometer. Devices are positioned on the holder where glass devices were placed with droplets deposited on the top (Figure 10).

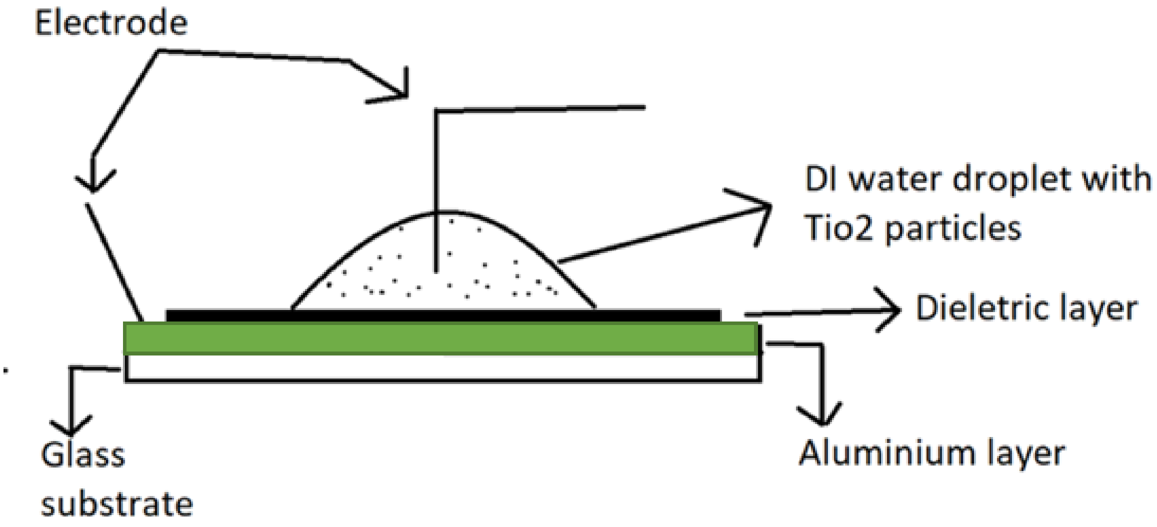

Figure 9 Schematic drawing for the general setup of droplet for over a device.

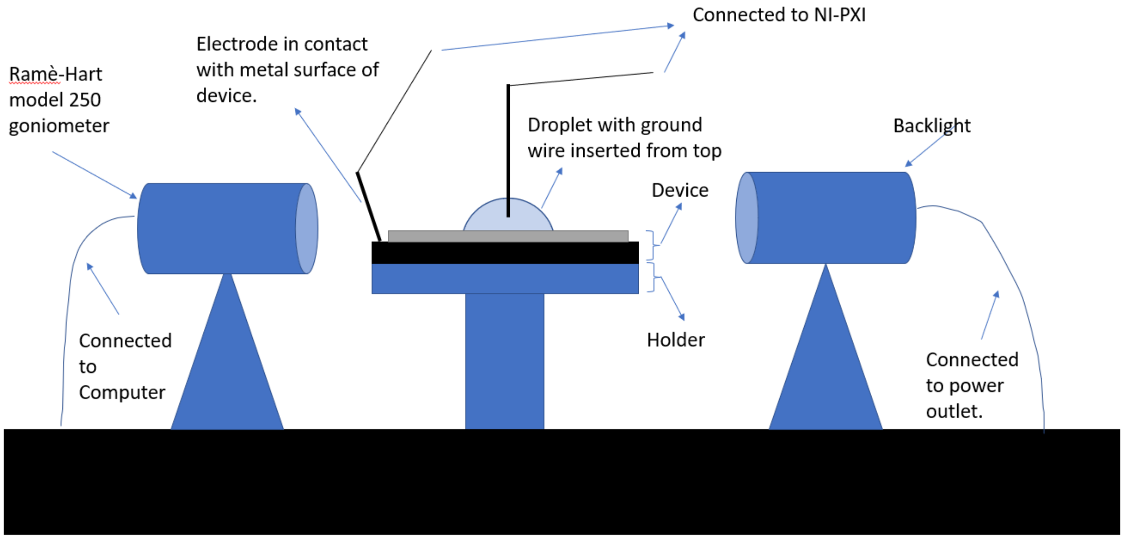

Figure 10 Sketch of the general experimental setup for contact angle readings.

The imaging system consists of a camera and a backlight. Before the experiments, the goniometer is calibrated and the surface is levelled to avoid distortion. Frequency of the image capture can be manually set. In our case, droplets over SU8 devices were recorded at one frame per second and for Teflon devices one frame per two seconds.

During tests 'Rame-Hart DROPimage Advanced' software is used to analyze and compile images per frame. Software measures contact angle, contact width and contact height through visual input from the goniometer. We get output in the form of text files which is then imported into excel separately for creating graphs which help us numerically analyze the data to study deposition pattern. Each experiment set was repeated three times to check for repeatability.

A Zeiss Stereo Discovery v12 microscope (Figure 11) was used for the analysis of the deposition pattern left behind by the evaporating droplets. Images were taken by the Carl-Zeiss camera that was mounted over the microscope. Two types of imagery were used for the study: (1) Dark (with no additional light) and (2) Bright (with additional lights) images. Both images were significant in studying the deposition pattern and predicting the stick- slip behavior. Dark images gave us a better idea of the central deposition and how particles are accumulated on the substrate. Bright images gave us the idea of the peripheral deposition (rings) and how droplets shrunk over the course of time (Figure 12). Images taken under microscope was calibrated with software 'ImageJ'. Scale bars were added to images by the help of the software.

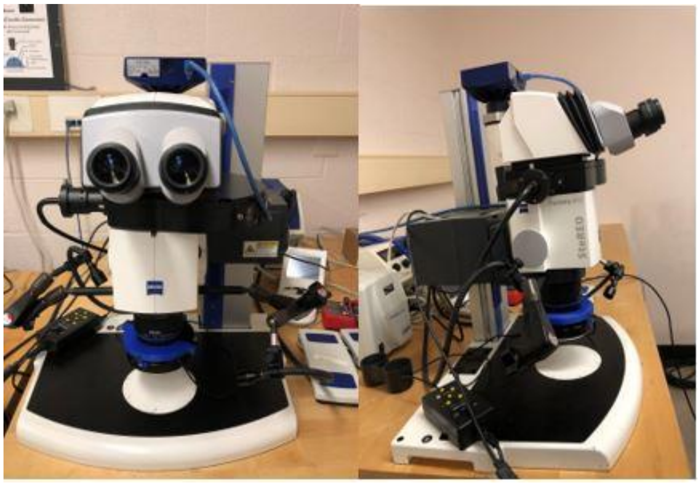

Figure 11 A Zeiss Stereo Discovery v12 Microscope.

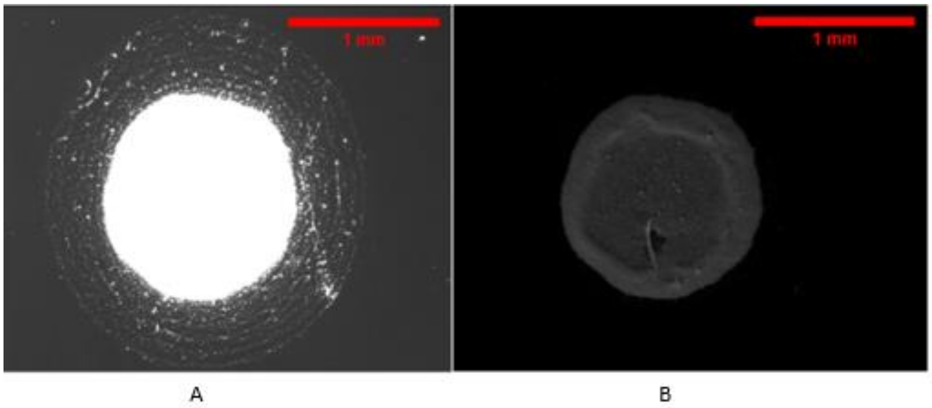

Figure 12 Example of Bright(A) taken when LED is switched on and Dark(B) images when LED is switched off.

4.4 Actuation

Droplets were actuated both on DC signal produced by an NI PXI-5402 . PXI system consists of three main parts which are Chassis, Signal generator and external amplifier. It is all driven by its respective software: Software 'FGEN soft front panel' for signal generation and 'NI PXI amp panel' for amplifier. Droplets were actuated at voltages ranging from 20 V to 200 V. The signal was applied to the electrodes with the ground wire inserted on top aimed at the center of the droplet. A general schematic and devices can be seen in the figure 16. For the polarity reversal, a value of "-1" was multiplied while generating DC signals.

5.0 RESULT AND DISCUSSION

5.1 Determining an appropriate applied voltage for evaporation testing.

All the devices after fabrication with SU-8 and Teflon were checked for consistency and at what voltage we should run our test. To check for consistency we compared the experimental value to the theoretical value calculated by the electrowetting equation. The electrowetting performance of the devices used in this investigation was examined prior to performing droplet evaporation tests. In addition to demonstrating that the devices are performing as expected, these experiments also give us the opportunity to determine a reasonable maximum voltage to apply during the evaporation tests.

The electrowetting equation is given as:

$$\cos\theta_U = \cos\theta_O + \frac{C_H U^2}{2\gamma_{LM}}. \qquad \text{(Equation 3)}$$

where C_H is capacitance per unit area of the solid- liquid surface interface, U is the root mean squared (RMS) voltage, γ_{LM} is the surface tension between the liquid and air, θ_O and θ_U are the unactuated and actuated contact angles respectively.

We wanted to apply maximum voltage which our device can sustain without causing it to fail on a long run. This will maximize the effects of applied voltage and it will be easier for us to observe the changes. For deciding on the maximum voltage there are two limiting factors. 1) Saturation Point and 2) Electrolysis point.

The Saturation point is defined as when the experimental value of contact angle to the corresponding particular voltage starts to deviate from the Electrowetting curve (Theoretical value). The point at which this deviation happens is termed as the saturation point. Saturation point is also the voltage after which the increase in voltage doesn’t impact the shape of the droplet interface but can still affect and Electrophoretic force on particle. The theoretical values of contact angle were deduced from the electrowetting equation (Equation 4).

Electrolysis point can be defined as voltage when the device fails. Device failure can occur in many ways such as, rupture of dielectric layer, bubble formation inside the droplet, and smoke formation at droplet interface. Electrolysis is unfavorable case for us as it could happen in the middle of the test and it also ruins the device. This point should be avoided and never be reached.

In order to decide the maximum voltage for the experimentation where device was stable and also gave maximum response. We decided to run the device under several voltage ranging from 0 V to 160 V. We were looking for the point where device would fail or electrolysis point is reached. Reason behind opting for maximum voltage was that these tests lasts for 30 to 40 minutes and if we apply voltage above the threshold then, dielectric layer ruptures and bubbles are formed inside the droplet which is indication of electrolysis. The theoretical value curve on graph was introduce to check if the experimental values of electrowetting followed the same trendline or not.

For SU-8 surface that point was decided after analysis to be at 140 V for both AC (rms) and DC (Figure 14 & 15). This was the maximum voltage where we didn’t see any bubble formation or any rupture of the dielectric layer. At 160 V we saw some bubbles and decided to not test the device on higher voltages. This voltage is for long cycle evaporation tests, and we don’t want our device to fail in the middle of test.

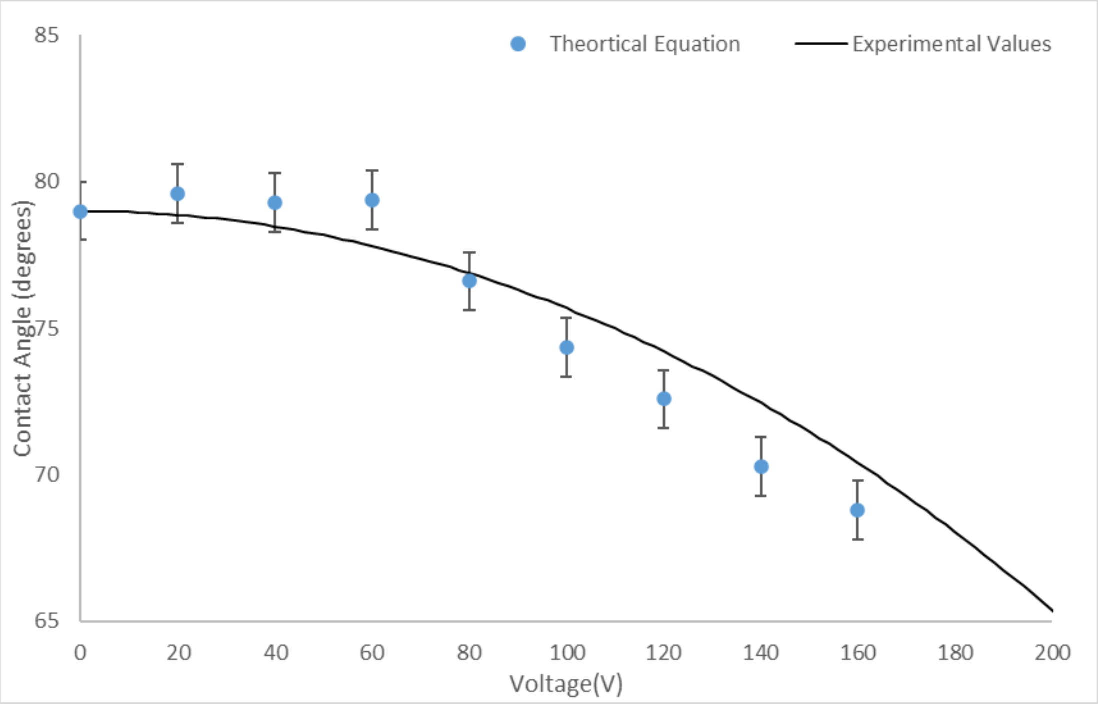

Figure 13 Experimental and Theoretical values of Electrowetting over SU-8 surface under DC electric field.

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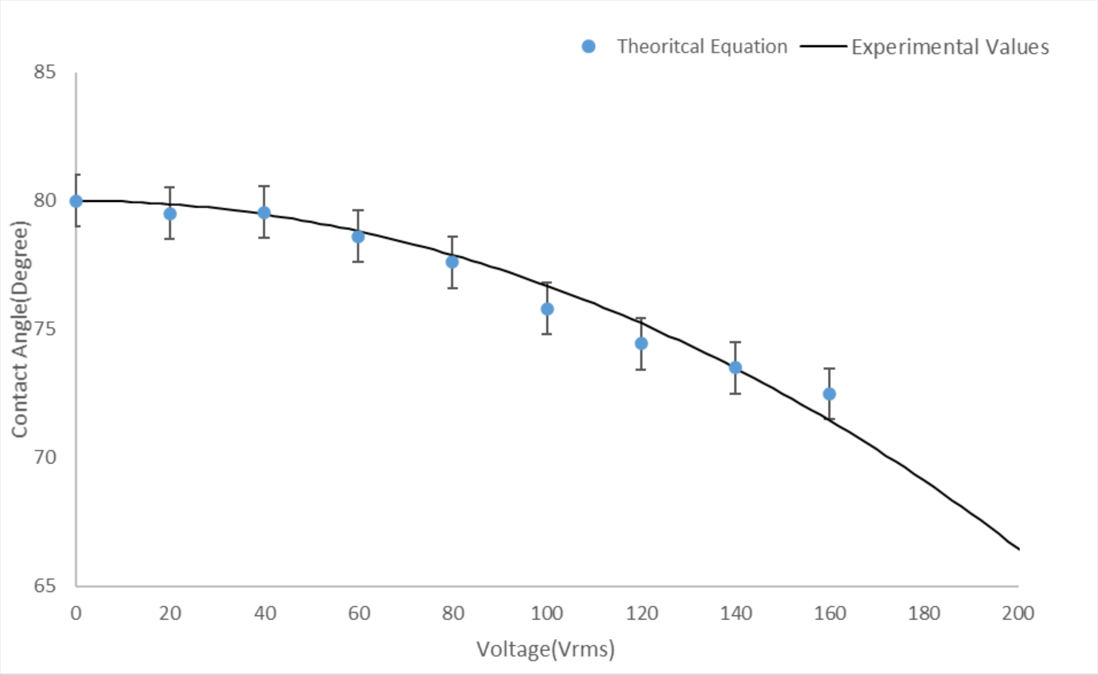


Figure 14 Experimental and Theoretical values of Electrowetting over SU-8 surface under AC electric field.

For the selection of maximum voltage for Teflon coated devices same process as mentioned above was done. After the same graphical result (Figure 15 & 16), 140 V (AC rms and DC) was chosen for the experimentations. At 160 V we saw some bubbles and decided to not test the device on higher voltages.

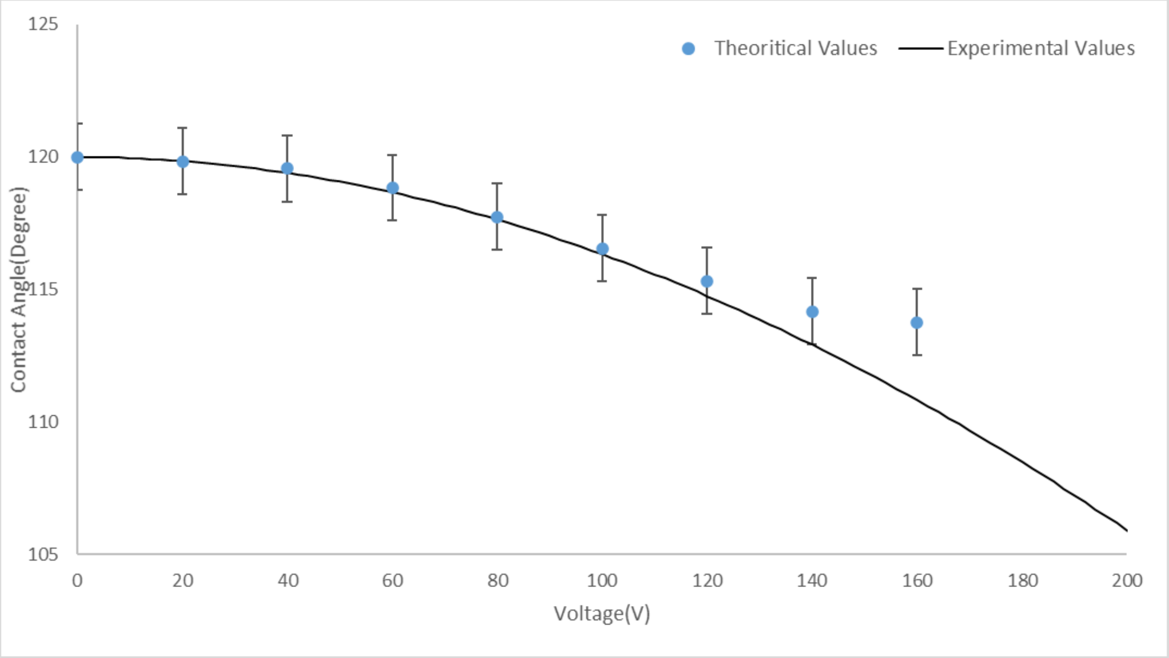


Figure 15 Experimental and Theoretical values of Electrowetting over Teflon under DC electric field.

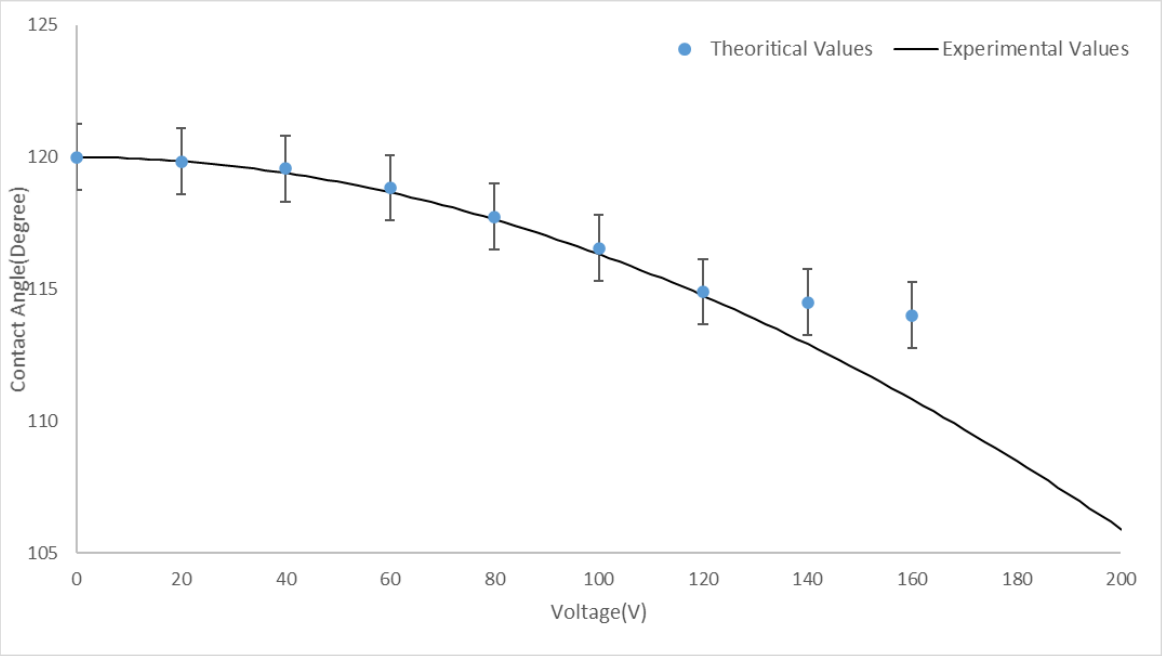


Figure 16 Experimental and Theoretical values of Electrowetting over Teflon under AC electric field.

To answer our research question, we split up the further chapters under three sections:

1. Effect of DC polarization, where we will compare the result of unactuated and actuated cases of SU-8 coated devices at 0.05% particle concentration.
2. Effect of DC polarization with change in Particle concentration, where we will compare the result of unactuated and actuated cases of SU-8 coated devices between 0.01% and 0.1% particle concentration.
3. Effect of DC polarization with change is surface selection, where we will compare the results of unactuated and actuated cases of SU-8 and Teflon coated devices at 0.05% particle concentration.

5.2 Effect of DC polarization.

SU-8 coated devices & Droplet Particle concentration at 0.05%.

Droplet under free evaporation (Unactuated):

Before we can understand the effects of applied electric field in suppressing ring structures, we examined a control case with no electric field. In control case we are trying to study how droplet containing particles react under evaporation under no electric field. Comparing actuated results to control case will give us sense of effect that the applied electric field has. Performing this case also provides an opportunity to confirm the results presented by Orejon for the same control case.

For flat surfaces, there are three modes of evaporation. First is constant contact radius, where height and contact angle of the droplet decreases but the width of the contact line remains constant. Contact angles continue to decrease till the end of first phase. Second phase is constant contact angle, where height and contact angle remain constant (or very slight change) but contact diameter keeps on decreasing. Droplet diameter continue to decrease till the end of second phase. Third phase is where both contact angle and contact diameter decreases. The transition between Constant contact angle and Constant contact diameter occur due to loss of the liquid and high number of particles inside the droplet. This transition happens because of the force balance at the contact line. The contact line starts to move when the contact angle decreases and stick-slips when contact diameter is decreasing.

In control case, we observe that the particle accumulates at the contact line and stays pinned. The contact line could not recede due to the particle accumulation at the point of three-phase interphase. During evaporation liquid is lost from the edges of droplet. Those edges are termed as three-phase interface. According to mass conservation, liquid that is lost during evaporation from three-phase interface is replaced by the particles inside the droplet to make up for the lost mass of liquid. This particle transportation from center to periphery results in particle accumulation at the edges and cause contact line to pin [18]. This induced transportation drives solute towards the contact line. Increase in solute concentration that leads to more viscous droplet. The accumulated solute further increase the pinning force, and it ultimately forms the solid residue that constitute the ring stain depending on the initial contact angle and the rate at which the pinning force increases the contact line either remains stuck during entire evaporation time or display a stick-slip behavior involving one or more pinning and depinning cycles.

For analysis of deposition patterns, we used external LED lights so that we can observe the periphery of droplet deposition very clearly because in the absence of LED light we weren’t able to see the ring stains as the particles were not visible in low-lighted surrounding. To observe center of the droplet deposition, we omitted the use of external LED lights because we can observe the center of the droplet because under the presence of LED light the center of the deposition is hidden or just appears to be a white mass. So, we decided to put both images for comparison to have a better understanding of the deposition. When we take images under external LED light are termed as “Light” and “Dark” when images are taken with external LED is off.

The results shown in Figs 17 & 18 are consistent with the Orejon’s observation. We can see evidence of rings and stick-slip behavior as per the figure 18. The appearance of concentric rings is evidence of slip stick behavior. For the initial phase the (till 1000th second) evaporation takes place with almost constant width (2.1 mm) and decreasing contact angle (from 80° to 65°).This is characteristic behavior of the constant contact diameter. For the next phase(from 1000th to 2000th second) both contact width(from 2.1mm to 1.7mm) and contact angle (from 65° to 50°) keep on decreasing. This is characteristic behavior of the mixed regime. For the remainder of the time (from 2000th to 3000th second), certain spikes in contact angle (around 50°)and decrease in contact width (1.3mm to 1mm) is observed till the end. This is also a characteristic behavior of mixed regime where contact diameter and contact angle fall more dramatically. Peripheral deposition is visible in the deposition pattern image (Fig. 17).

Deposition pattern in figure 17 contains evidence of slip-stick and ring pattern. More deposition at the periphery and less towards the center of the droplet. We can clearly see from figure 17 that concentric rings are visible over the periphery of the droplet. This is what was expected by us, and it also agrees with Orejon's observations. They also observed the rings pattern for unactuated cases. Results of repeated trials can be seen in the Appendix 1.

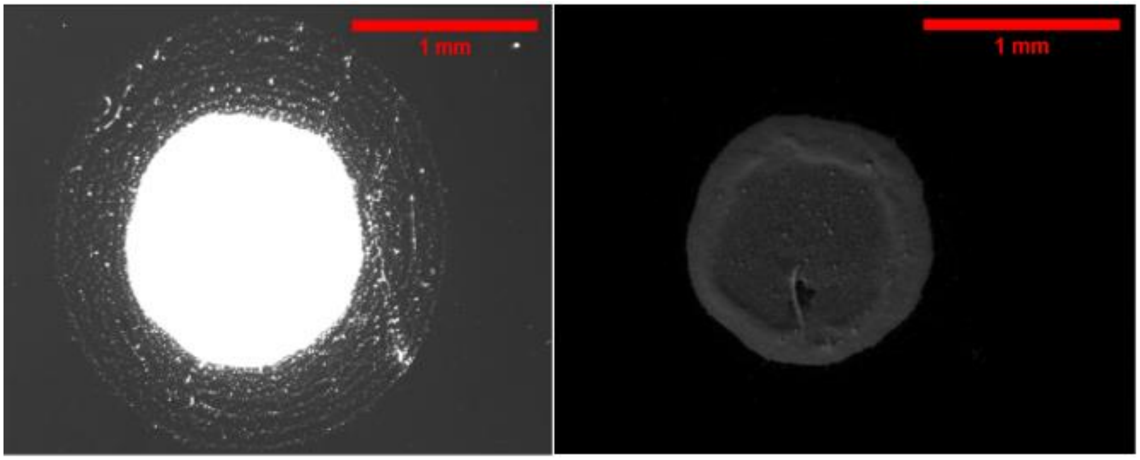


Figure 17 Deposition pattern left behind the evaporating droplet under evaporation with particle concentration at 0.05% over a SU-8 device.

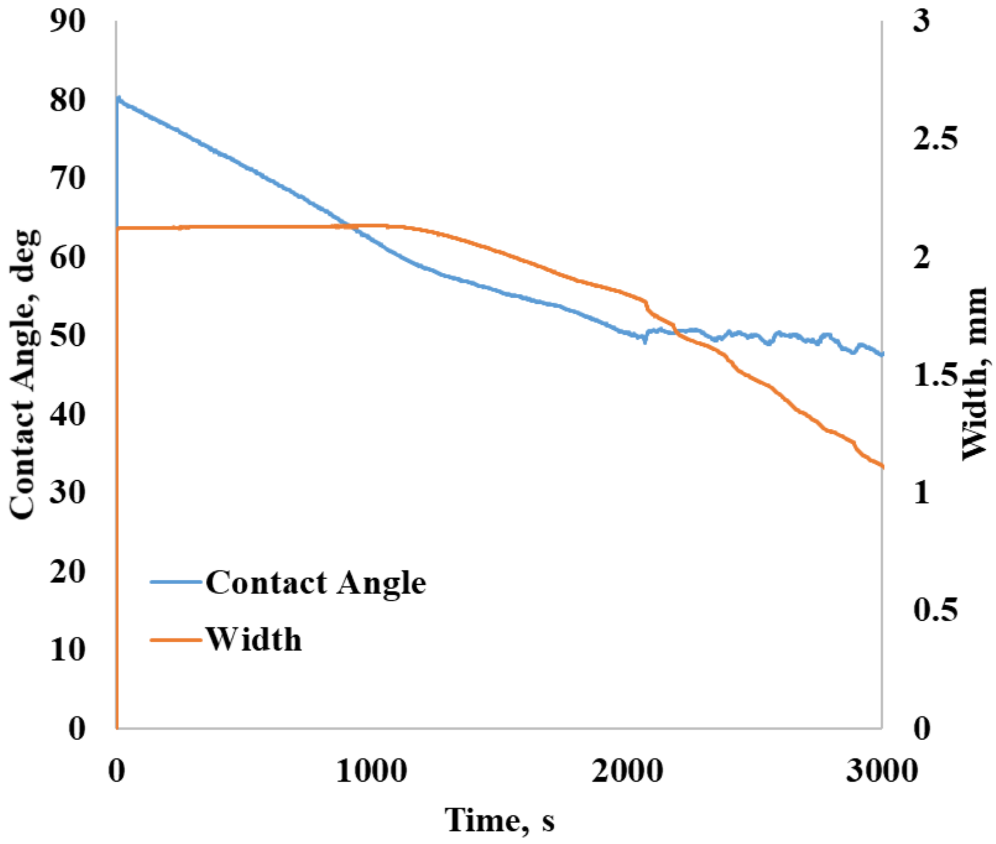


Figure 18 Evolution of contact angle and contact width for the Control Case with 0.05% concentration over SU-8 device.

Droplet evaporation under an applied electric field.

Results of these experiments agrees with Orejon's observations, an increase in the deposition area and reduction in the slip-stick are observed when voltage is applied across the droplet-containing particles over the device.

Orejon et al. argued that rings were not present when DC voltage was applied. They argued that electrophoretic force might be acting on the particles inside the droplet due to which they observe don't observe ring stains. They explained that electrophoretic force pull the particles down to the surface faster than they are transported to the periphery which results in uniform deposition. But according to Lee et al. [21], DC electric field doesn’t penetrate the droplet. If Lee et al. is correct, then no electrophoretic force can act on the particles inside the droplet. One way to test the Orejon’s hypothesis is to examine how the deposition patterns change in the repulsive case (when polarity of electrodes is reversed). Since electrophoresis depends upon the polarity, Orejon’s hypothesis suggests that the deposition pattern would be different in this case. Their hypothesis suggests that particles would be repelled if polarity is reversed because the charge on the particle and the electrode would be same and the electrode would repel the same charged particles. But they only examined one polarity where the ground wire was with negative polarity, and the metal surface covered with dielectric layer was at positive polarity. We believe we can further test their hypothesis by examining both polarities one similar to Oregon's setup and another where polarities are reversed. They mentioned that electrophoretic force was acting upon the particle inside the droplet and as the TiO_2 particles are negatively charged they would be attracted towards the positive electrode (which in their case was device surface coated with Su-8). But we think the interface trapping might be happening there instead of particles driven under electrophoretic force. The change in the shape of the droplet is very instantaneous that particles are trapped on the liquid-air substrate and thus giving us the uniform deposition pattern. To test their hypothesis, we decided to split up the DC actuation into two, Attractive DC(DC+) and Repulsive DC(DC-).

Attractive DC(DC+)

When voltage is applied, electrowetting causes a very rapid increase in the contact diameter and reduction in contact angle (Figure 19 & 20). When actuated: the droplet diameter increased from 2.1 mm to 2.7 mm (29%); the contact angle decreased from 75° to 65°(13%); and the droplet height decreased from 1.3mm to 1mm (23%). As per the graphical data the contact line recedes with the no leaps for almost till complete droplet evaporation (2511th second). Contact angle kept on decreasing till the end of the evaporation while diameter was decreasing but at very slow rate. Evaporation time for Attractive DC(DC+) is 2511 seconds which is 20% less than the unactuated case.

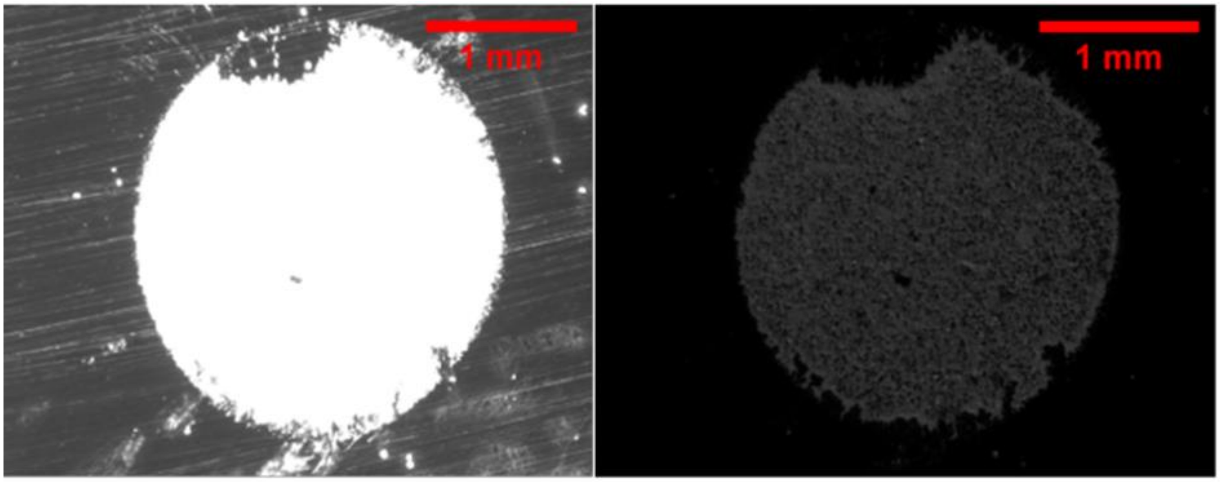


Figure 19 Deposition pattern left behind the evaporating droplet under attractive DC over SU-8 device with particle concentration at 0.05%.

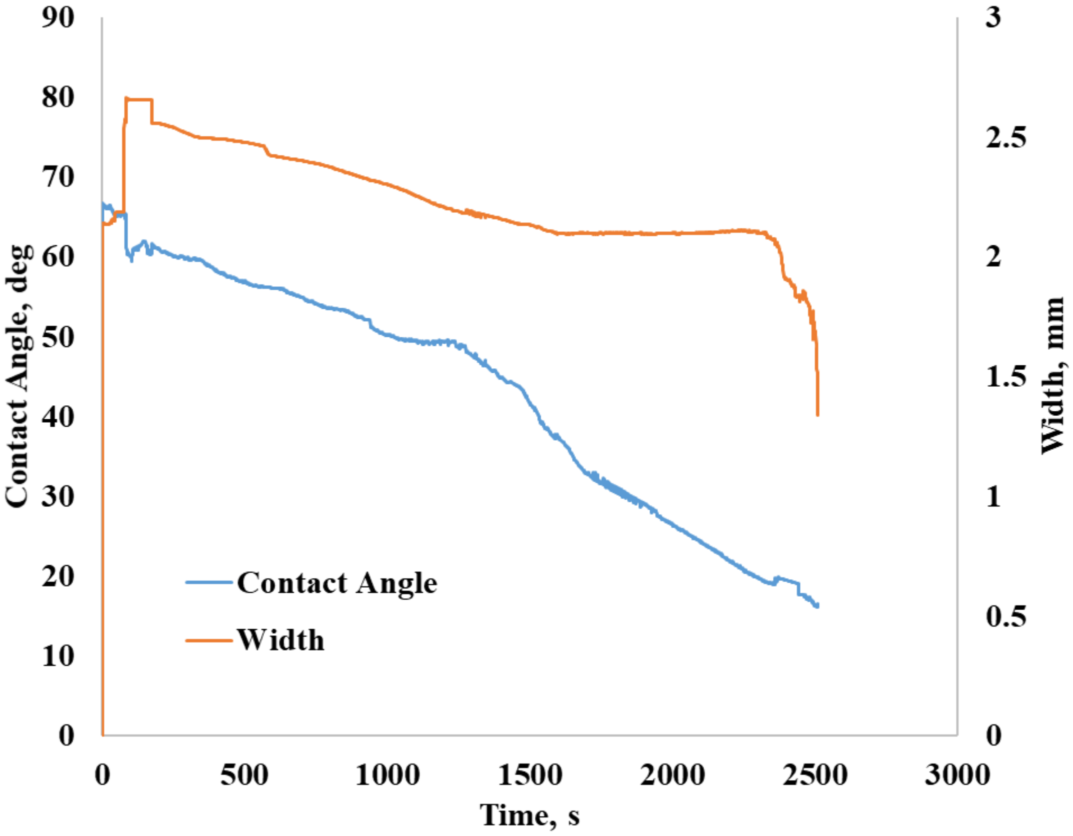


Figure 20 Evolution of contact angle and contact width for the DC+ with 0.05% concentration over SU-8 surface.

When we compare actuated and unactuated case we observe that evaporation time is decreased by 20%. According to the graphical data (Figure 20) we don't see any evidence of stick slip behavior. The deposition pattern in the actuated case (Figure 19) has no ring or evidence of slip-stick deposition and the diameter of the deposition is bigger than that of unactuated case (Refer to figure 21). We can see the uniform deposition over the entire surface area of droplet which is not present in the unactuated case. Deposition of particles are more uniform in the actuated case throughout the area. For comparison of unactuated and actuated cases refer to Figure 21. All the repeated trials are in Appendix 2.

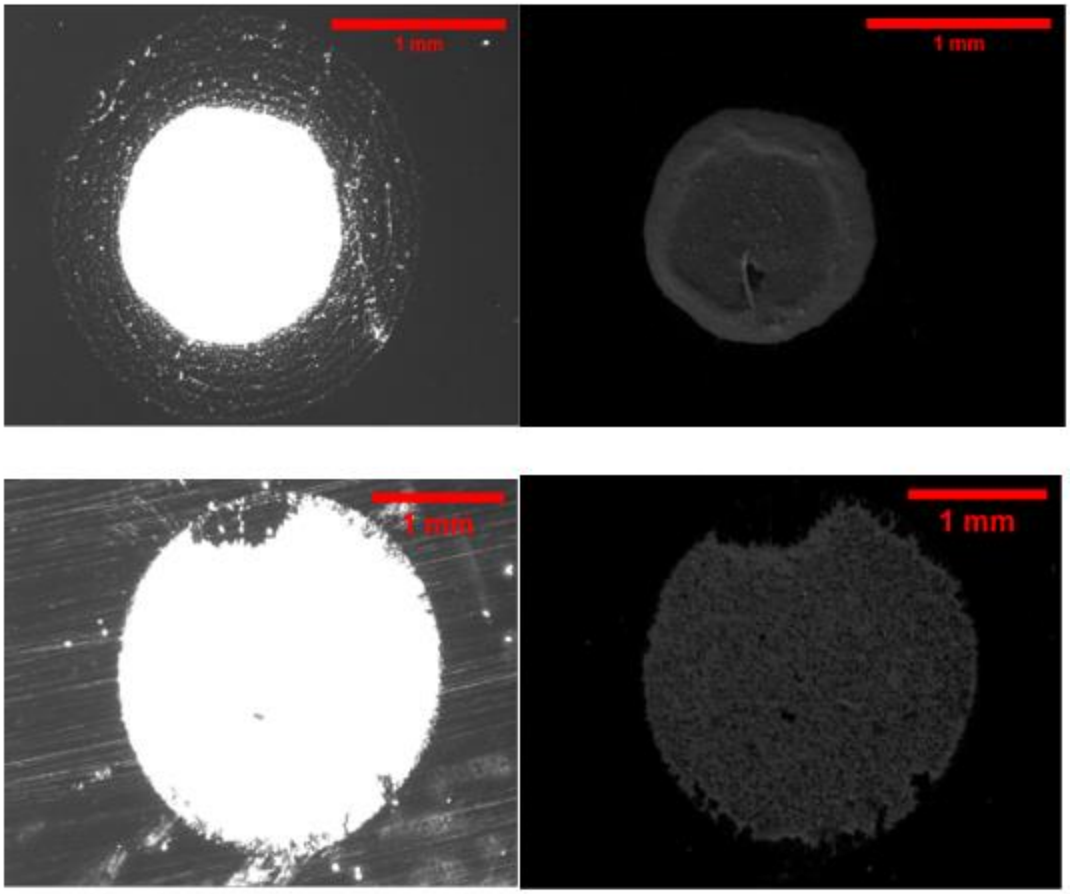


Figure 21 Deposition pattern under no actuation(above) and attractive DC (below) over SU-8 surface with particle concentration at 0.05%.

Under attractive DC actuation, Orejon observed that rings and stick-slip behavior was absent. They attributed this to electrophoretic force on the negatively charged TiO_2 particles. They argued that particles under electrophoretic force travelled towards the positive electrode instead of travelling towards the periphery. Particle transportation towards the periphery leads to ring stains or slip-stick behavior and due to particles migrating away from periphery they didn't observe ring stains.

However according to our hypothesis, it is also possible that due to interface trapping we might not be seeing any slip-stick or ring stains. When electric field is applied the liquid-air interface lowers/drops instantaneously which makes particle stuck to the interface. Reduction in slip-stick phenomenon occur due to particles getting trapped in liquid-air interface and by the end of evaporation those particles deposit over the SU-8 surface uniformly. Due to being trapped on the interface they are unable to travel towards the periphery which eventually resulted in uniform deposition. We used same setup for the experiments as Orejon used for their studies. We still think that our result is consistent with their hypothesis for Attractive DC(DC+) but real reason behind the consistency can still be different.

Repulsive DC(DC-)

To test the Orejon's hypothesis we decided to reverse the polarity of electrode and verify if the repulsive electrophoretic force would alter or change the deposition pattern observed in Attractive DC (which is similar to the setup as Orejon's). If Orejon's hypothesis is correct we would expect to see the particles to be deposited away from the center. As per their hypothesis, electrophoretic force was acting on the negatively charged particles which resulted in uniform deposition pattern. They argued that particles under electrophoretic force were attracted to the opposite polarized electrode and those particles instead of travelling towards the periphery they were deposited over the SU-8 layer. Due to this particle transportation they didn’t see any ring or slip-stick behavior. If that holds correct then we might see particles repelled away from the electrode as we reversed the polarity.

When voltage was applied, electrowetting caused a very rapid increase in the contact diameter and reduction in contact angle (Figure 22 & 23). When actuated: the droplet diameter increased from 2mm to 2.6mm (30%); the contact angle decreased from 83° to 74° (14%) of its initial value when the voltage is applied; and droplet height decreased from 1.3mm to 1mm (23%). The contact line receded with no slip-stick for almost till completion of droplet evaporation. During evaporation, contact angle kept on decreasing as well as diameter was decreasing at very slow rate after initial increment. Evaporation time for Repulsive DC(DC-) is 2400 seconds which is 23% less than the unactuated case.

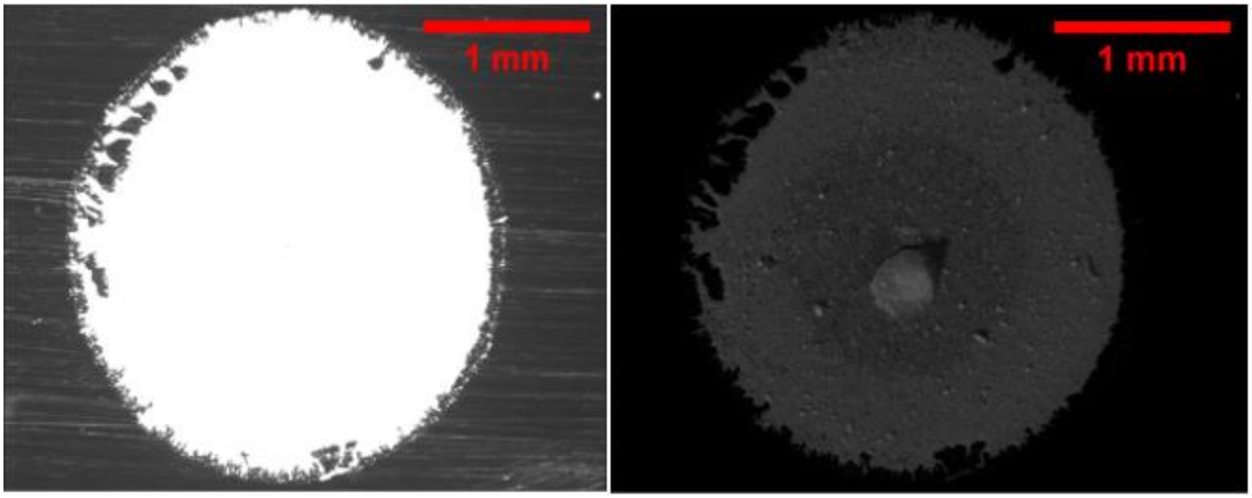


Figure 22 Deposition pattern left behind the evaporating droplet under Repulsive DC over SU-8 devices with particle concentration at 0.05%.

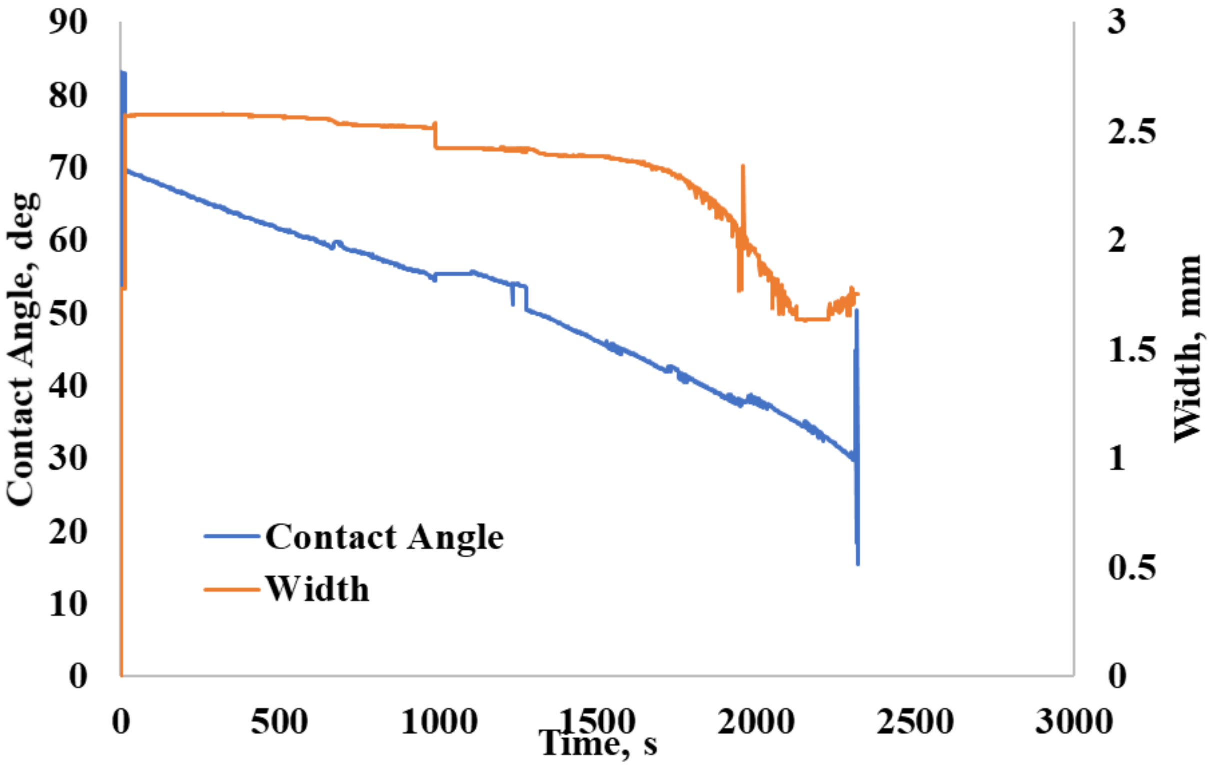


Figure 23 Evolution of contact angle and contact width for the DC- with 0.05% concentration over SU-8 surface.

The deposition pattern for Repulsive DC(DC-) (Figure 22) has no ring stains, diameter of the deposition is bigger than that of unactuated case. In the unactuated case (Figure 17), we can see the ring stains but here we see uniform deposition of the particles in DC- case. Deposition of particles are more uniform in the DC- throughout the area of droplet. Results of repeated trials are shown in Appendix 3.

Deposition pattern of attractive DC(DC+) and repulsive DC(DC-) cases are nearly similar(Refer to Figure 24). Increase in the contact width is 29%-30% in both cases, decrease in contact angle is 13%-14%, decrease in droplet height from 1.3mm to 1mm. The evaporation time for DC+ and DC- is 2511 and 2400 seconds.

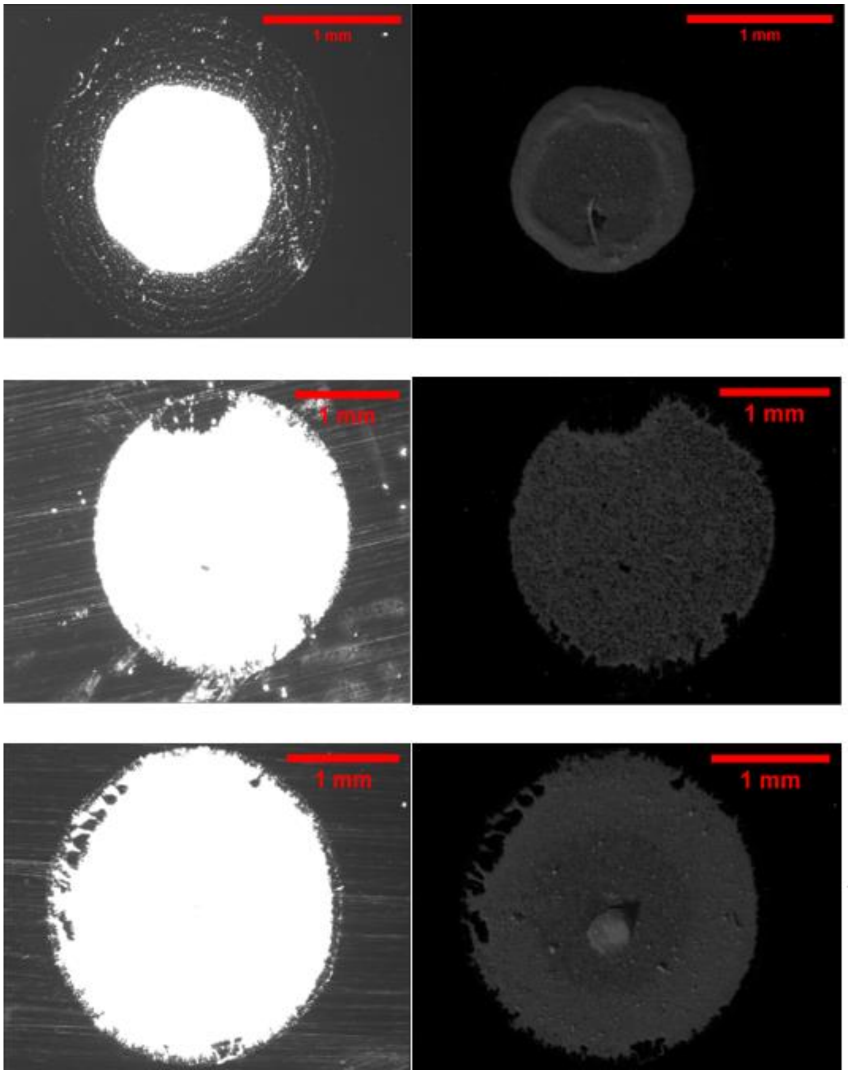


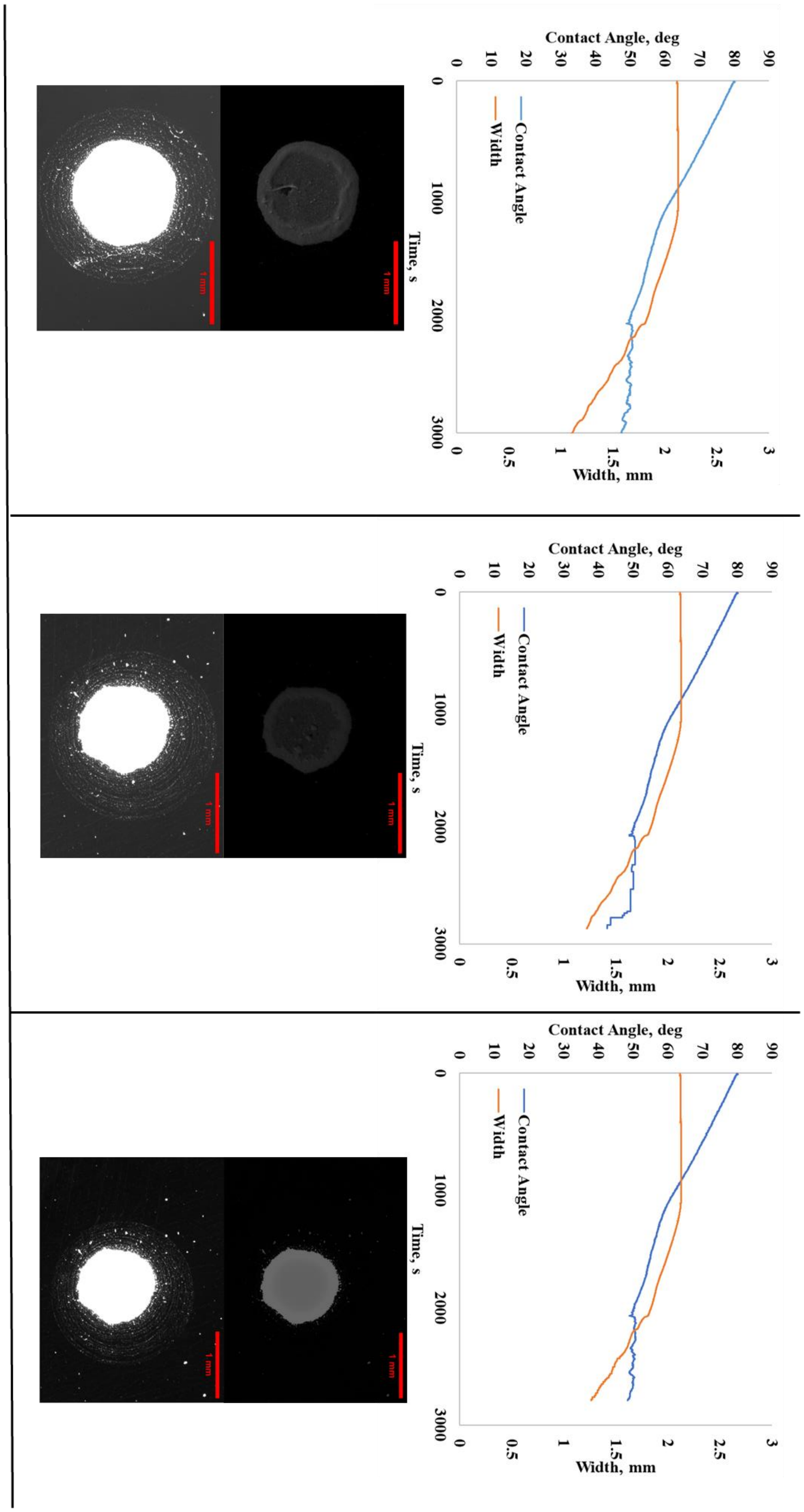
Figure 24 Deposition pattern: Unactuated case(top), Attractive DC (middle), and Repulsive DC (bottom) for SU-8 devices at 0.05% concentration.

Orejon's hypothesis was that electrophoretic forces pulls the particle down to the surface faster than they are transported to the periphery. They supported their hypothesis by comparing the velocities due to radial convection (that drives particles to the periphery) and electrophoretic migration (that drives particle to the center of the droplet). Radial convection is calculated under no actuation. It is speed of particles from center to the three-phase contact line (periphery). Electrophoretic migration is calculated under DC actuation. It is speed of particles at which they will travel and deposit over electrode. Upon comparison they found that electrophoretic migration velocity is much higher than the radial convection velocity. This made them conclude that particles will be deposited on the center of the droplet rather than transported towards the periphery. This would give us a more uniform deposition pattern and get rid of ring stains. Their hypothesis could be correct as the particles were negatively charged and the electrode below was at positive polarity.

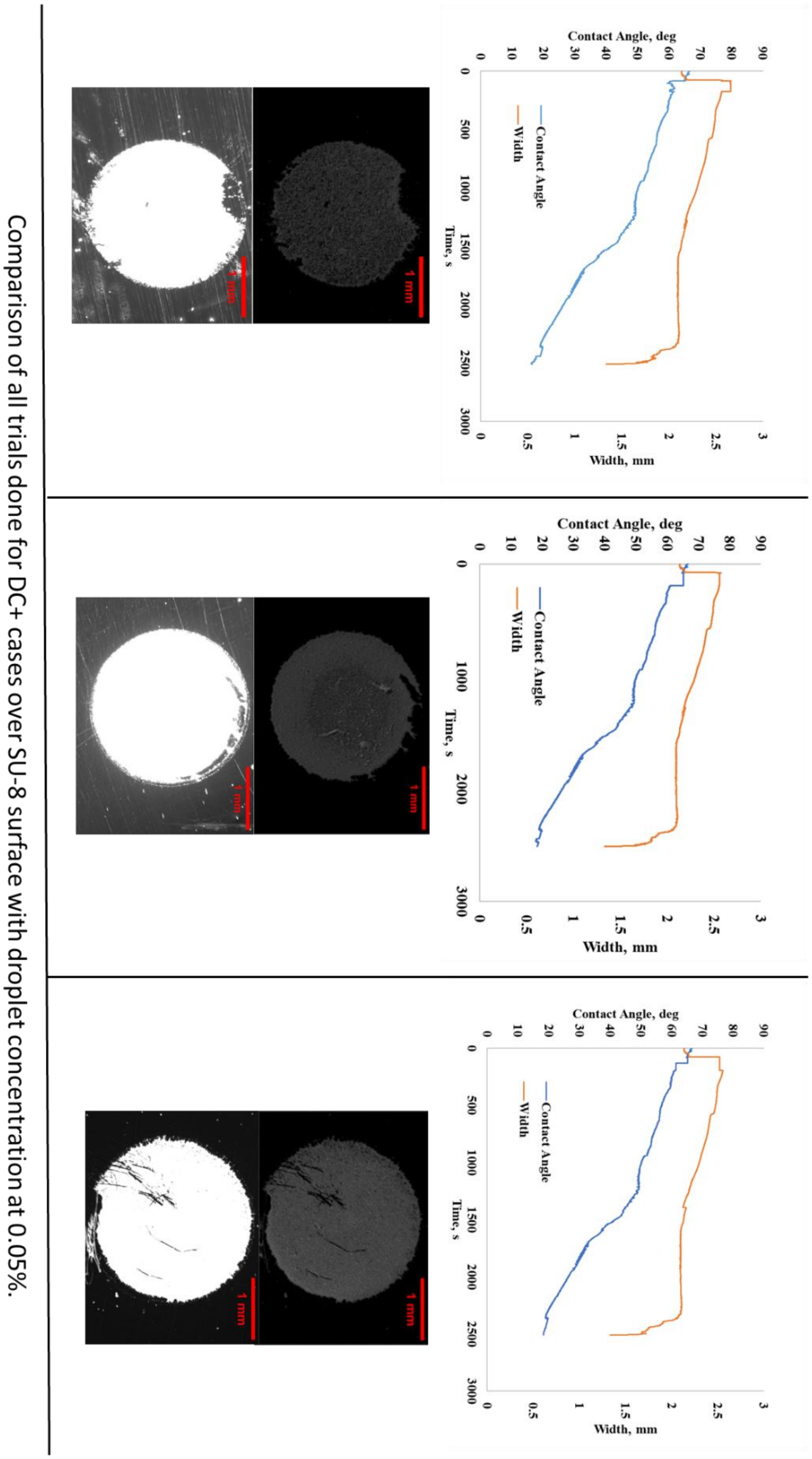
Electrophoretic manipulation of particles could have been present. It means when we reverse the polarity of the electrodes and keep the rest of the same setup, we expect to get the deposition pattern opposite to what we observe in the Attractive DC(DC+) (Same setup as Orejon's). But our experimental data doesn't support their hypothesis. The electrophoretic migration should be away from the surface which mean they have to either travel towards the periphery of the droplet or towards other electrode and giving us more of a ring like pattern but we don't observe that.

The similarities between DC+ and DC- cases suggest that electrophoresis is not the mechanism that causes uniform deposition pattern and the actual mechanism should be independent of the polarity. A competing hypothesis could be that the large downward interface velocity at the beginning of the EW process make the particles stuck on the interface. This means fewer particles are free floating in the droplet as most of the particles are stuck on the interface. Due to particles stuck on the interface, less particles would be floating and migrating towards the periphery which means less stick-slip phenomenon. If this was the mechanism beside uniform deposition, it would fit what Orejon saw from the control to attractive DC. And the similarities we see between attractive and repulsive DC strengthen our competing hypothesis.

Comparison of all trials done for unactuated cases over SU-8 surface with droplet concentration at 0.05%.

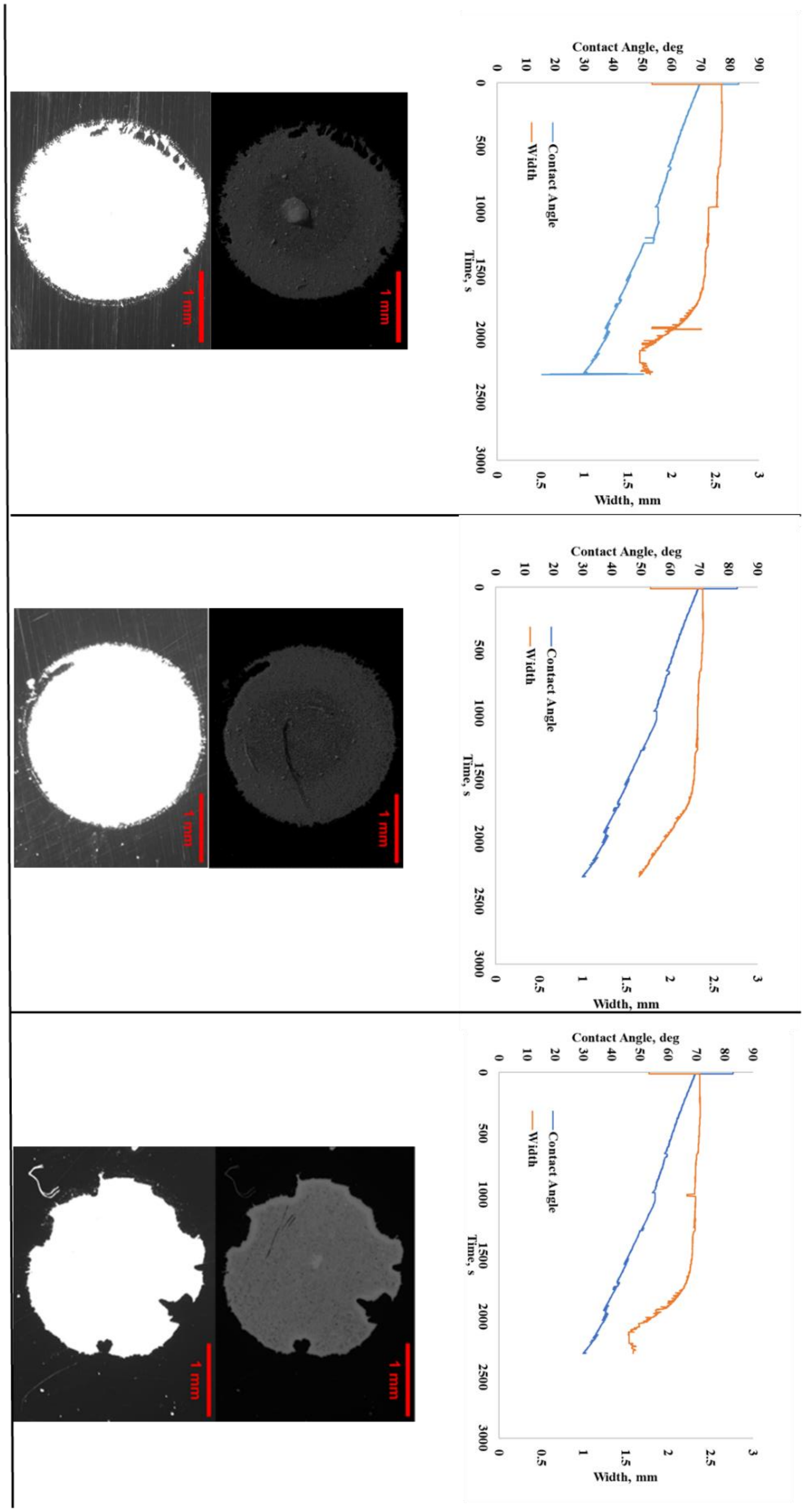


Appendix 1 Results from the repeated trials of unactuated cases with concentration at 0.05%.



Appendix 2 Results from the repeated trials of DC+ cases with concentration at 0.05%.

Comparison of all trials done for DC- cases over SU-8 surface with droplet concentration at 0.05%.



Appendix 3 Results from the repeated trials of DC- cases with concentration at 0.05%.

5.3 Effects of DC polarization with change in Particle concentration.

SU-8 coated devices & Droplet concentration at 0.01 & 0.1%.

Droplet under free evaporation (Unactuated):

We are going to consider tests done on SU-8 surface with particle concentration 0.05% as base case. For our study we decided to run the experiment over SU-8 surface with droplet concentration 0.01% (lower than base case) and 0.1% (higher than base case) to observe the effects of DC polarization with change in particle concentration. We are going to perform similar experiments on these droplets. First, we are going to study the control case for droplet with 0.01% and 0.1% and compare the results with base case (Droplet with 0.05% concentration over SU-8 surface). After comparing the results of control cases we will run our experiments similarly under attractive and repulsive dc and compare them to base case.

For initial phase of droplet at 0.01% concentration, evaporation (till 500th second) takes place at constant contact width (2.8 mm) and decreasing contact angle (from 75° to 60°). For next phase both contact angle (from 60° to 50°) and contact width decreasing (from 2.8 mm to 2.4 mm). For the remainder of the time, certain spike at the beginning of the phase and then gradual decline for both contact angle (57° to below 40°) and contact width (from 2.4 mm to 2.2 mm). High peripheral deposition is visible in the deposition pattern image (Figure 25).

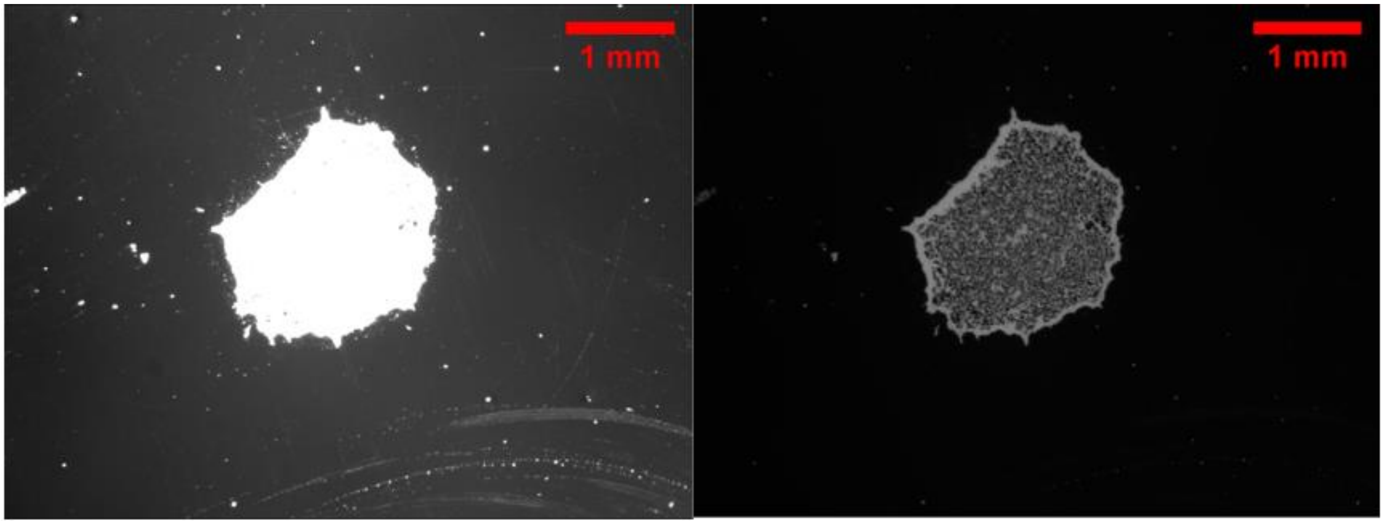


Figure 25 Deposition pattern left behind the evaporating droplet under evaporation over SU-8 device with particle concentration at 0.01%.

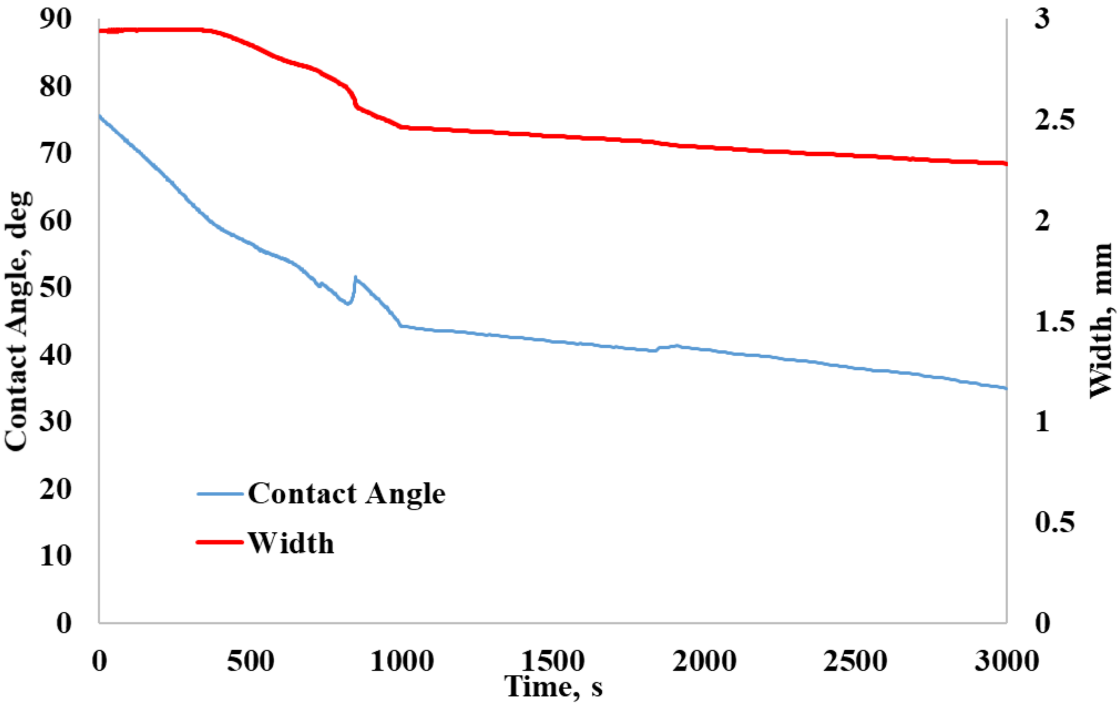


Figure 26 Evolution of contact angle and width under no actuation over SU-8 device at 0.01% concentration.

For initial phase of droplet at 0.1% concentration, evaporation (till 500th second) takes place at constant contact width (2.5 mm) and decreasing contact angle (from 75° to 60°). For next phase both contact angle (from 60° to 50°) and contact width decreasing (from 2.5 mm to 2.1 mm). For the remainder of the time, certain spike at the beginning of the phase and then gradual decline for both contact angle (57° to below 40°) and contact width (from 2.1 mm to 1 mm). But due to high concentration of the particles inside the droplet the deposition pattern appears to be all uniform (Figure 27).

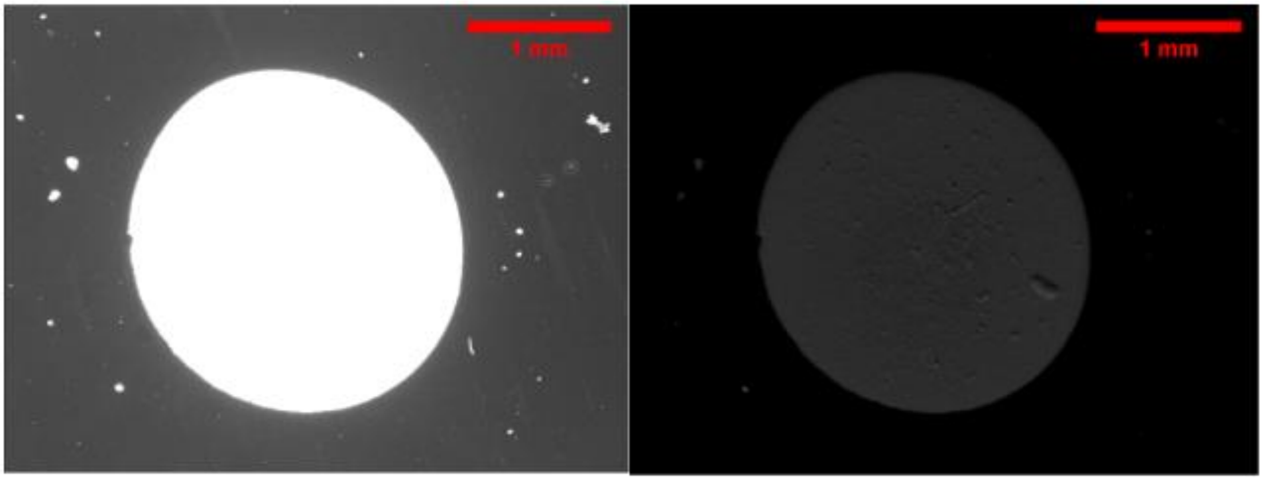


Figure 27 Deposition pattern left behind the evaporating droplet under evaporation over SU-8 with particle concentration at 0.1%.

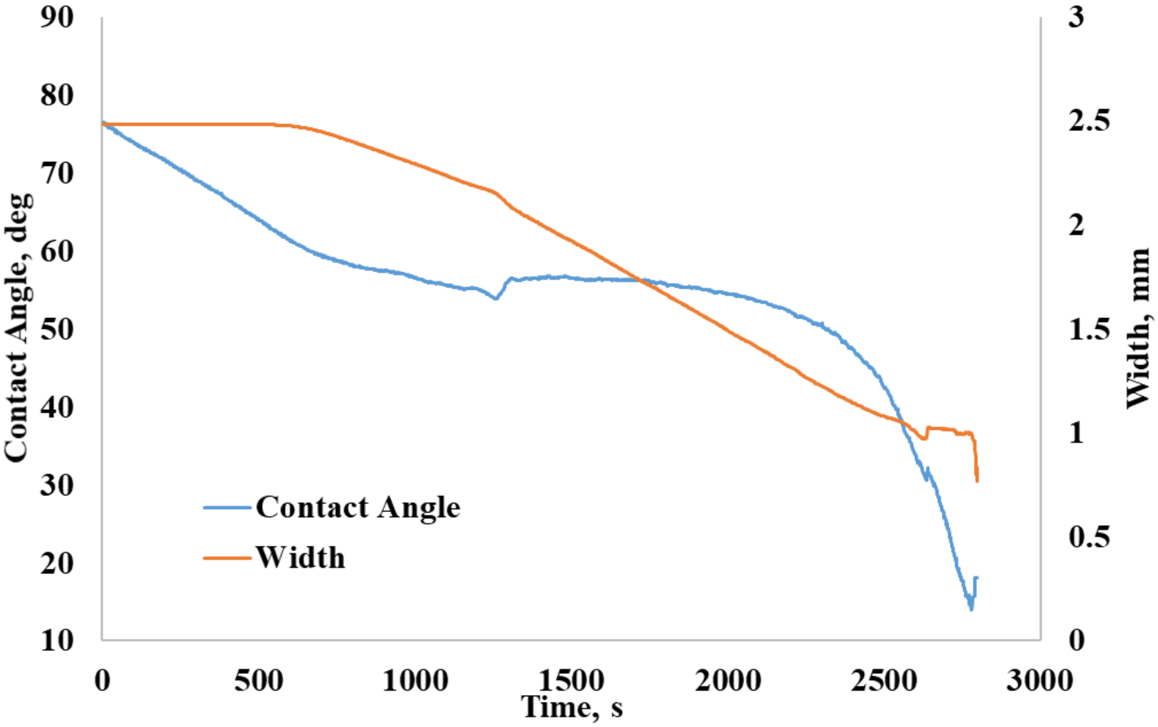


Figure 28 Evolution of contact angle and width under no actuation over SU-8 device at 0.1% concentration.

The results shown in Figs 26 & 28 are consistent with the Orejon's observation. We can see evidence of stick-slip behavior as per the figure 26 and 28. Due to such low particle concentration we can't observe the clear rings in the microscopic images (Figure 25) and similarly due to high particle concentration we can't observe the rings in the microscopic images (Figure 27). We also observe the three regimes of evaporation which we saw in the base case. The presence of three-regimes gives us the enough evidence that these two cases (droplet at 0.01% and 0.1% concentration) agrees with the base case which also makes it agreeable to Orejon's observation. Result from repeated trials can be seen in the Appendix 4 and 5.

Attractive DC(DC+)

After comparing the results of control cases with increase and decrease of particle concentration we are now going to compare the effect of increase and decrease of particle concentration (0.01% and 0.1%) under actuation (Attractive DC) with the base case. We are going to study the effect of increasing and decreasing the concentration under attractive DC. We will also compare the results of attractive DC with their respective unactuated case. We will also test Orejon's hypothesis here.

At droplet concentration 0.01% we observe: When voltage is applied, electrowetting causes a very rapid increase in the contact diameter and reduction in contact angle (Figure 30). When actuated: the droplet diameter increased from 2.1 mm to 2.8 mm (33%); the contact angle decreased from 78° to 68° (13%); and the droplet height decreased from 1.3mm to 1mm (23%). As per the graphical data the contact line recedes with the few jumps in between till complete droplet evaporation. Contact angle kept on decreasing till the end of the evaporation while diameter was decreasing but at very slow rate. Evaporation time for Attractive DC (DC+) is 2420 seconds which is 20% less than the respective unactuated case. Deposition pattern for this case can be seen in figure 29.

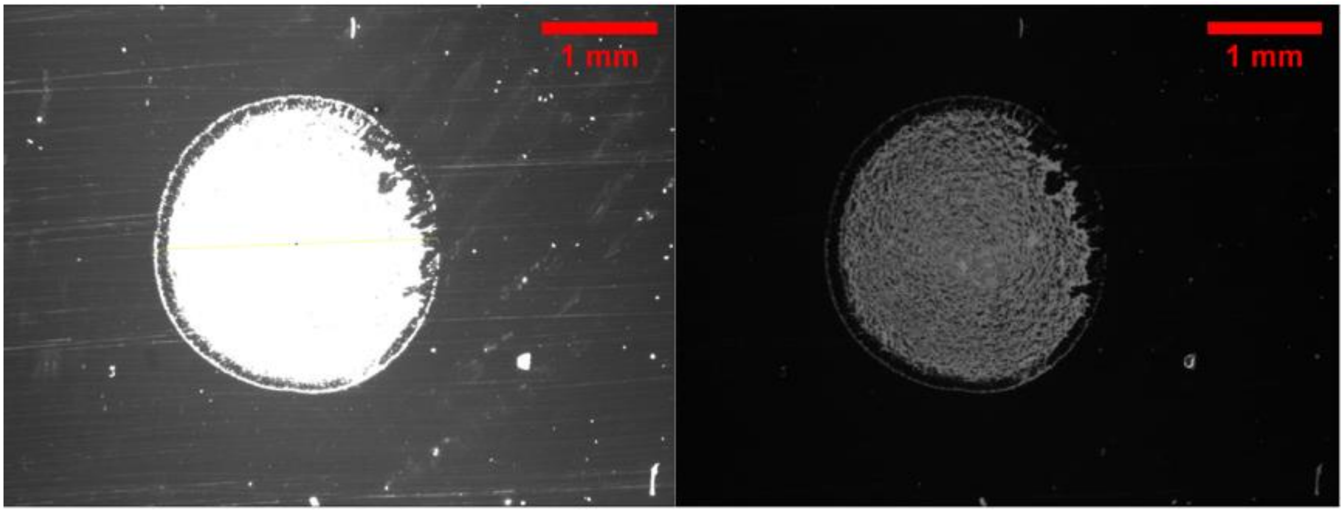


Figure 29 Deposition pattern left behind the evaporating droplet under DC+ over SU-8 device with particle concentration at 0.01%.

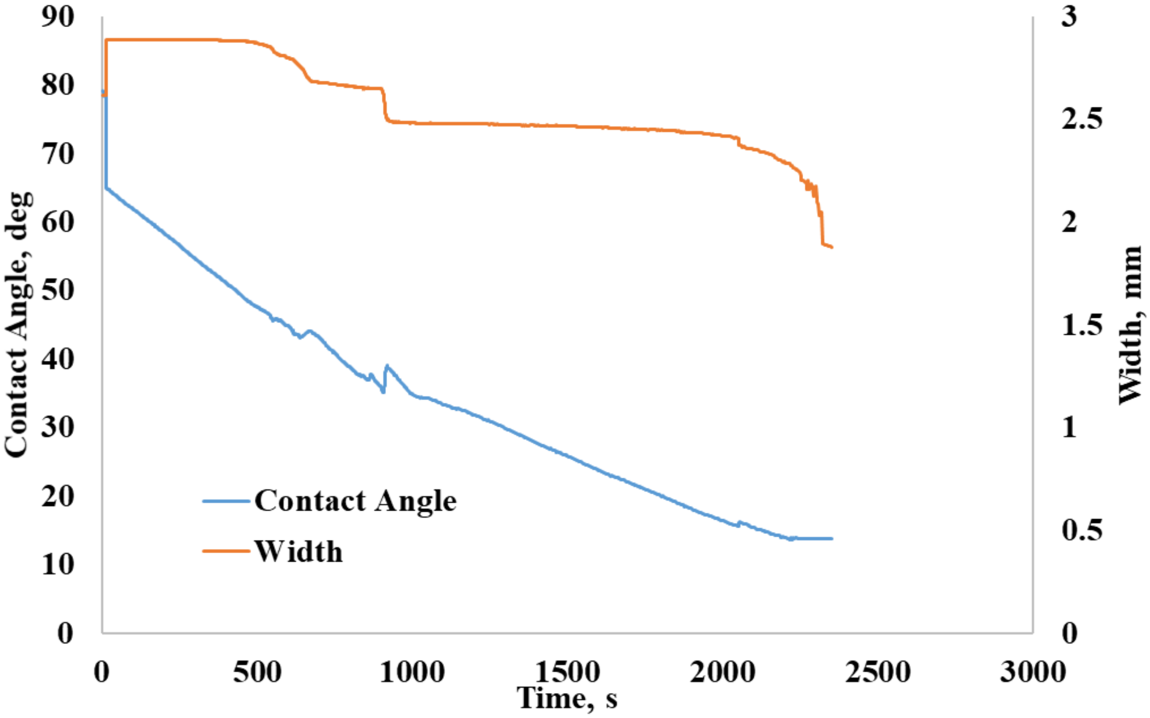


Figure 30 Evolution of contact angle and width under DC+ over SU-8 device at 0.01% concentration.

At droplet concentration 0.1% we observe: When voltage is applied, electrowetting causes a very rapid increase in the contact diameter and reduction in contact angle (Figure 32). When actuated: the droplet diameter increased from 2.5 mm to 3.0 mm (20%); the contact angle decreased from 75° to 65° (13%); and the droplet height decreased from 1.3mm to 1mm (23%). As per the graphical data the contact line recedes with the no jumps for almost till complete droplet evaporation. Contact angle kept on decreasing till the end of the evaporation while diameter was decreasing but at very slow rate. Evaporation time for DC+ is 2300 seconds which is 22% less than the respective unactuated case. Deposition pattern can be seen in figure 31. Result from the repeated trials can be seen in the Appendix 6 and 7.

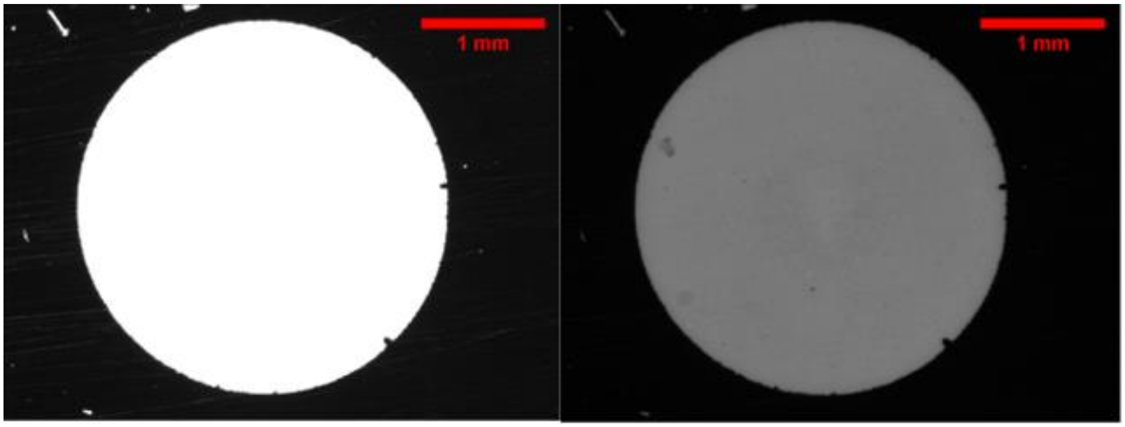


Figure 31 Deposition pattern left behind the evaporating droplet under DC+ over SU-8 with particle concentration at 0.1%.

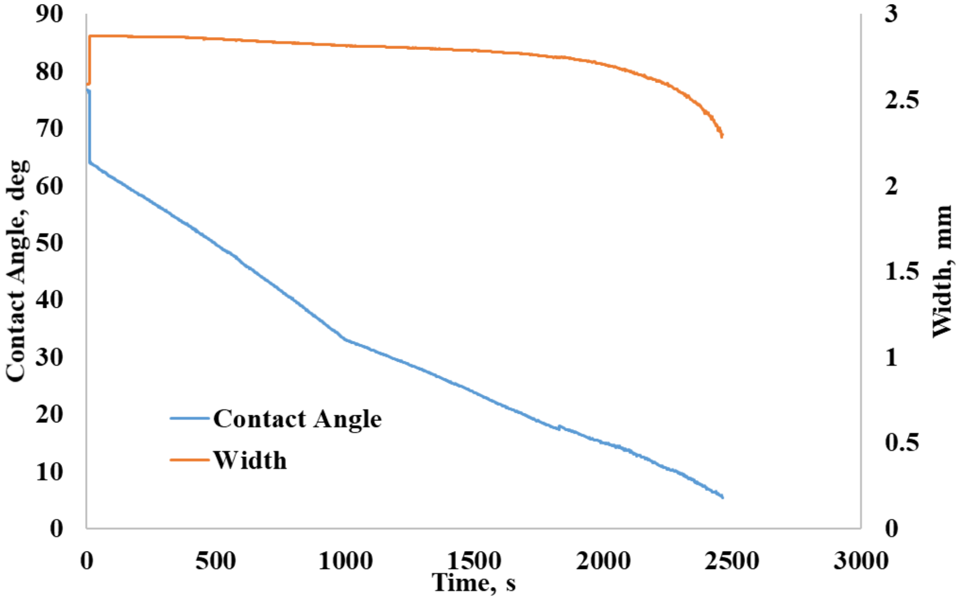


Figure 32 Evolution of contact angle and width under DC+ over SU-8 device at 0.1% concentration.

When we compare the DC+ cases at different concentrations we see the similar trend from the graphical data, the evaporation time is for 0.05%, 0.01%, and 0.1% concentration are 2511,2420 and 2300 seconds. The initial increase in contact diameter is 29%, 33% and 20%. The decrease in contact angle is 13% for all the given concentrations. The decrease in height is 23% which is constant among all the concentrations.

Under attractive DC actuation, Orejon observed that rings and stick-slip behavior was absent. They attributed this to electrophoretic force on the negatively charged TiO_2 particles. They argued that particles under electrophoretic force travelled towards the negative electrode instead of travelling towards the periphery. Particle transportation towards the periphery leads to ring stains or slip-stick behavior and due to particles migrating away from periphery they didn't observe ring stains.

However according to our hypothesis, it is also possible that due to interface trapping we might not be seeing any slip-stick or ring stains. When electric field is applied the liquid-air interface lower/drops instantaneously which makes particle stuck to the interface. Reduction in slip-stick phenomenon occur due to particles getting trapped in liquid-air interface and by the end of evaporation those particles deposit over the SU-8 layer uniformly. Due to being trapped on the interface they are unable to travel towards the periphery which eventually resulted in uniform deposition. We used same setup for the experiments as Orejon used for their studies. We still think that our result is consistent with their hypothesis for Attractive DC(DC+) reason behind the consistency can still be different.

We think these results follow the same trend as results from base case. It means that the change in particle concentration doesn't have much effect on deposition pattern or particle transportation. Orejon's hypothesis is also relevant for attractive DC at both higher and lower concentrations case as well. Our hypothesis gives common reasoning for all the attractive DC cases and we believe that it is the better explanation beside the uniform deposition pattern rather than acting of electrophoretic force on the particles inside the droplet.

Repulsive DC(DC-)

Now we are going to compare the results of repulsive DC for base case (0.05% concentration) with higher/lower concentrations (0.01% and 0.1% concentration). Similarly to the base case, In order test Orejon's hypothesis we decided to reverse the polarity of electrode and verify if the repulsive electrophoretic force would alter or change the deposition pattern observed in Attractive DC (which is similar to the setup as Orejon's). If Orejon's hypothesis is correct we would expect to see the particles to be deposited away from the center. As per their hypothesis, electrophoretic force was acting on the negatively charged particles which resulted in uniform deposition pattern. They argued that particles under electrophoretic force were attracted to the opposite polarized electrode and those particles instead of travelling towards the periphery they were deposited over the SU-8 layer. Due to this particle transportation they didn't see any ring or slip-stick behavior. If that holds correct then we might see particles repelled away from the electrode as we reversed the polarity. We are going to study the effect of increasing and decreasing the concentration in repulsive DC. We will also compare the results of repulsive DC with their respective unactuated case. We are going to see if the change in concentration have any effect on the repulsive case.

At droplet concentration 0.01% we observe: When voltage was applied, electrowetting causes a very rapid increase in the contact diameter and reduction in contact angle (Figure 34). When actuated: the droplet diameter increased from 2.1 mm to 2.7mm (29%); the contact angle decreased from 78° to 68° (13%) of its initial value when the voltage is applied; and droplet height decreased from 1.3mm to 1mm (23%). As per the graphical data the contact line receded with no leaps for almost till completion of droplet evaporation. Contact angle kept on decreasing while diameter was decreasing at very slow rate/almost constant after initial increment. Evaporation time for DC- is 2450 seconds which is 20% less than the respective unactuated case. Deposition pattern for Repulsive DC(DC-) can be seen in figure 33.

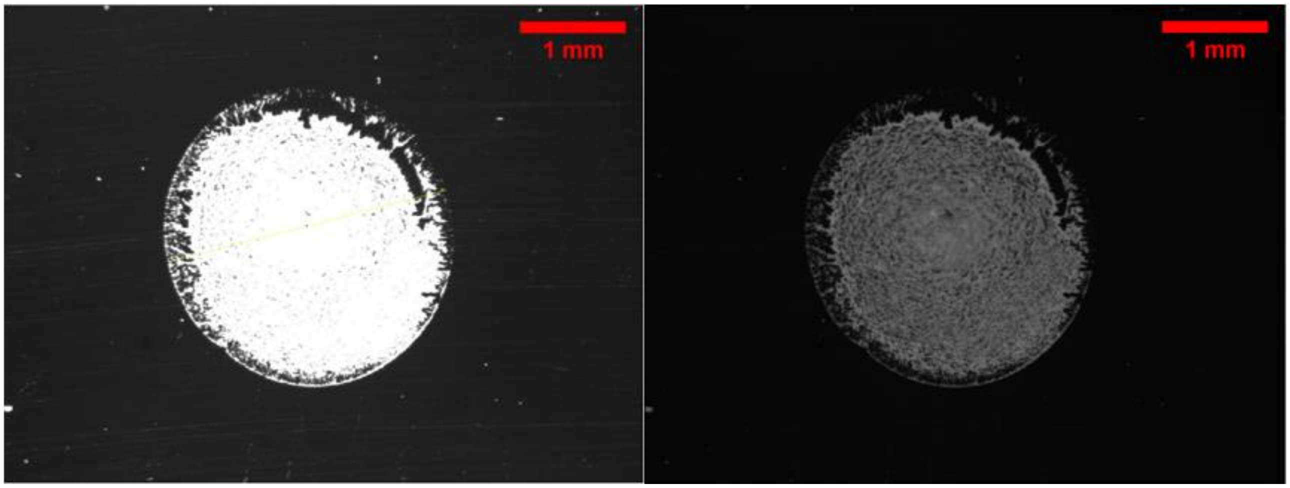


Figure 33 Deposition pattern left behind the evaporating droplet under DC- over SU-8 device with particle concentration at 0.01%.

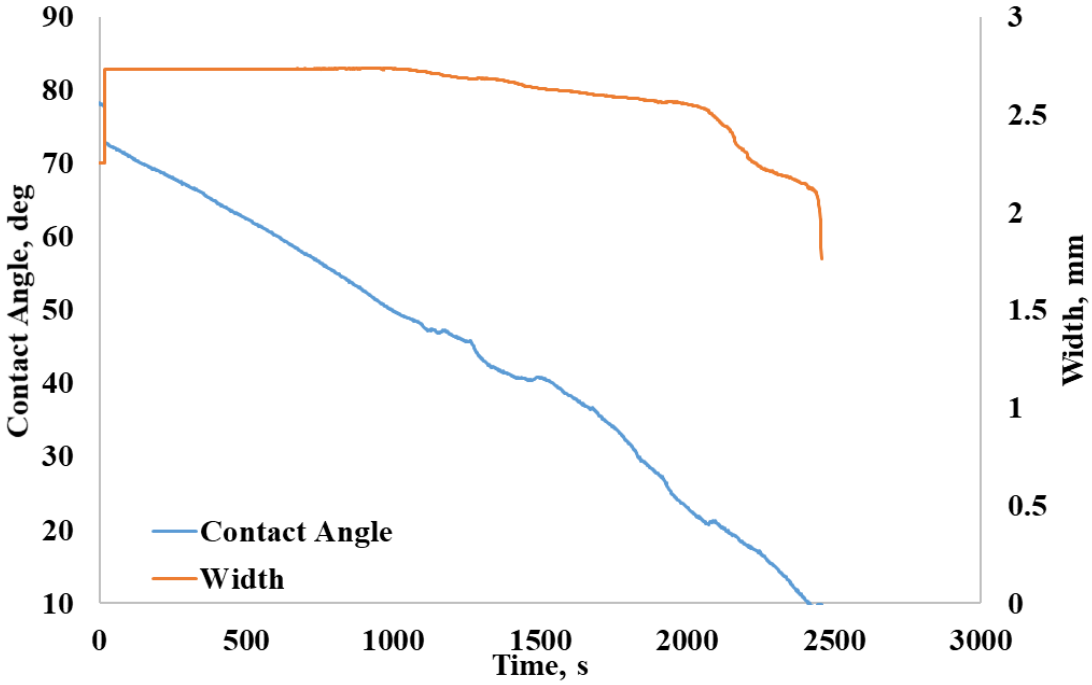


Figure 34 Evolution of contact angle and width under DC- over SU-8 at 0.01% concentration.

For droplet concentration 0.1% we observe: When voltage was applied, electrowetting causes a very rapid increase in the contact diameter and reduction contact angle (Figure 36). When actuated: the droplet diameter increased from 2.5 mm to 2.9 mm (16%); the contact angle decreased from 78° to 68° (13%) of its initial value when the voltage is applied; and droplet height decreased from 1.3mm to 1mm (23%). As per the graphical data the contact line receded with no leaps for almost till completion of droplet evaporation. Contact angle kept on decreasing while diameter was decreasing at very slow rate/almost constant after initial increment. Evaporation time for DC- is 2250 seconds which is 20% less than the respective unactuated case.

When we compare the DC- cases at different concentrations we see the similar trend from the graphical data, the evaporation time is for 0.05%, 0.01%, and 0.1% concentration are 2400,2450 and 2250 seconds.

The initial increase in contact diameter is 30%, 29% and 16%. The decrease in contact angle is 13% for all the given concentrations. The decrease in height is 23% which is constant among all the concentrations. Deposition pattern for DC- can be seen in figure 35. Results from the repeated trials can be seen the Appendix 8 and 9.

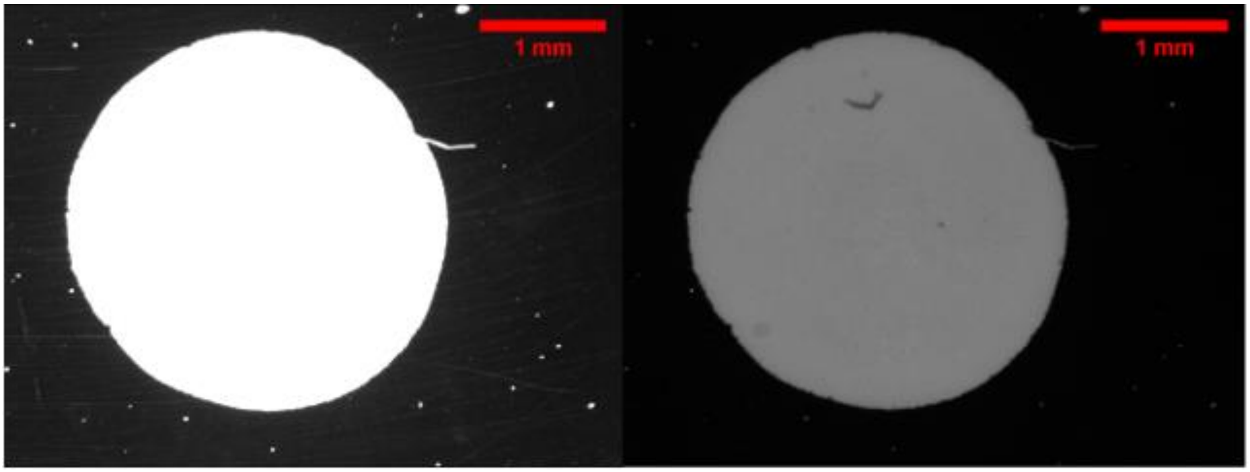


Figure 35 Deposition pattern left behind the evaporating droplet under DC- over SU-8 device with particle concentration at 0.1%.

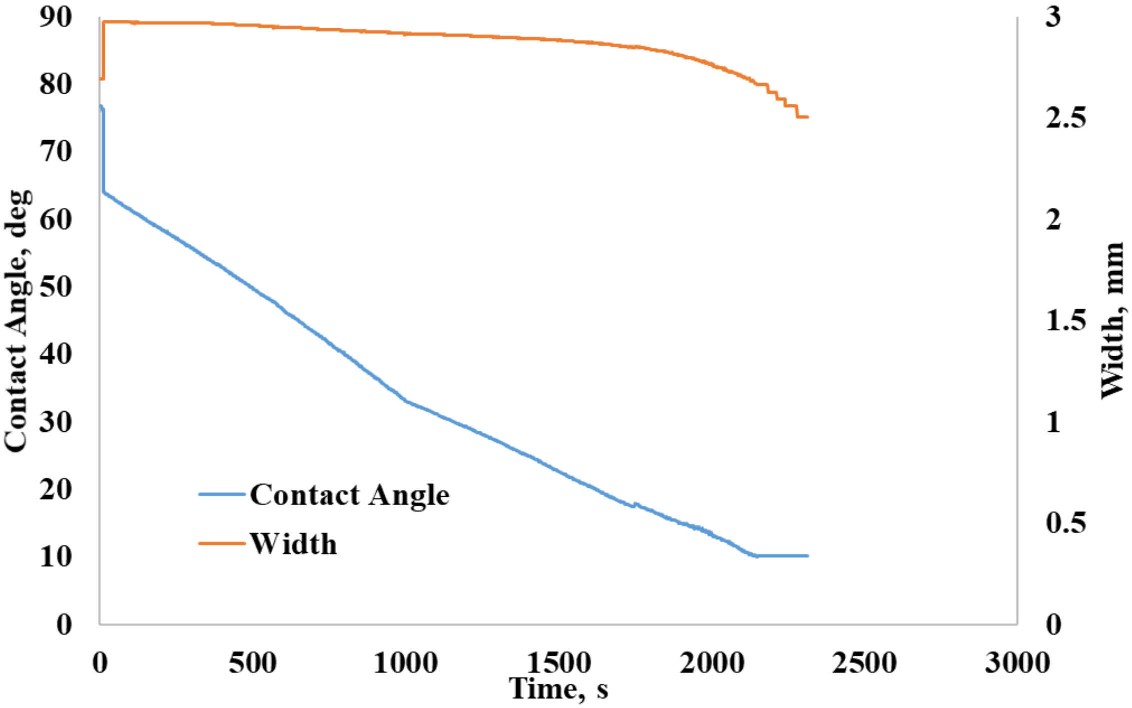


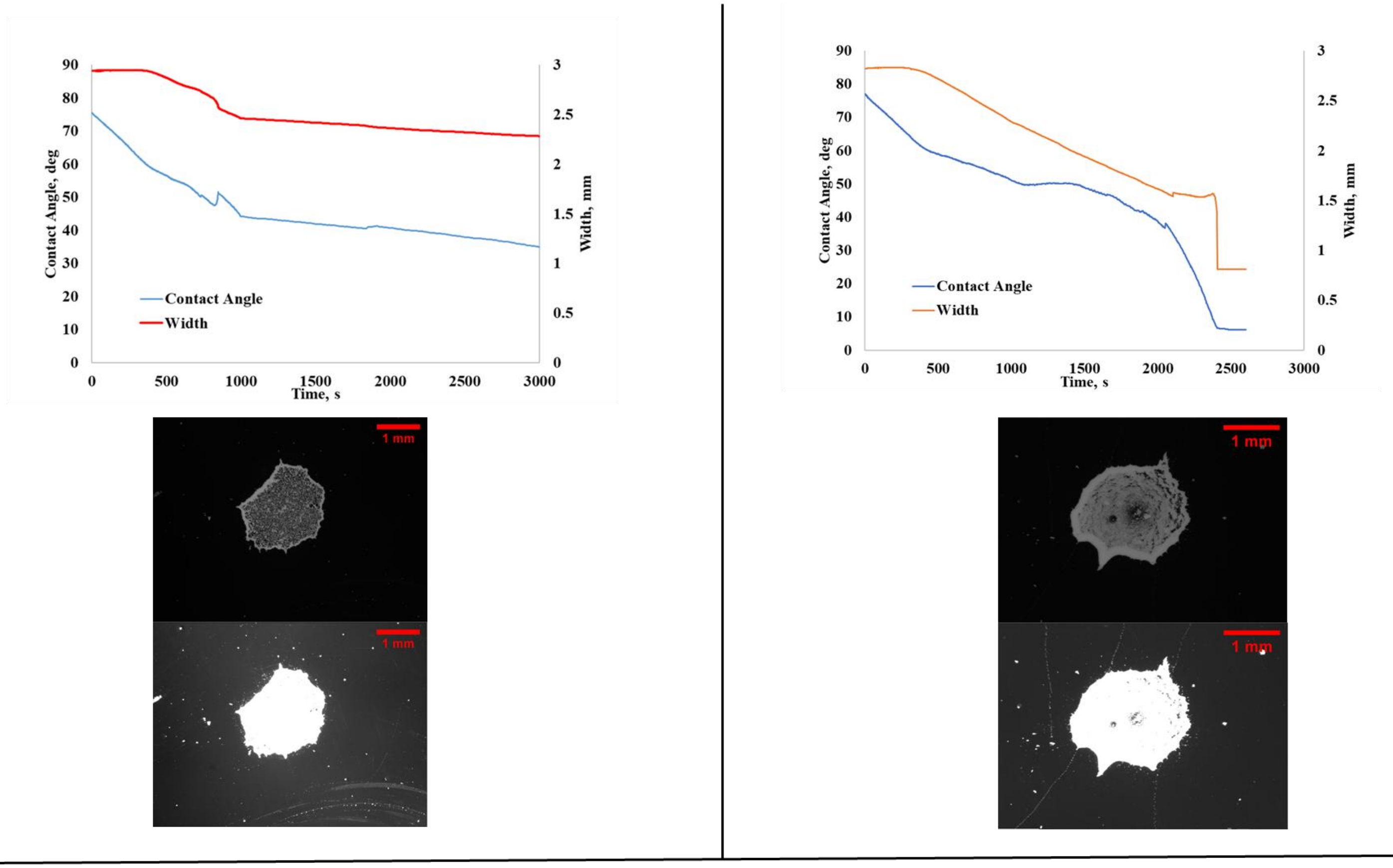
Figure 36 Evolution of contact angle and width under DC- over SU-8 device at 0.1% concentration.

The deposition pattern for Repulsive DC(DC-) (Figure 33 & 35) has no ring shapes, diameter of the deposition is bigger than that of their respective unactuated cases. In the unactuated case, we can see the ring stains but here we see uniform deposition of the particles in DC- case for both concentrations. Due to lack of particles the deposition pattern is not as dense (for 0.01%) as base case but it is still uniform throughout the surface area of droplet and graphical data shows that there is no significant slip-stick behavior. And due to abundance of particles in the 0.1% concentrated droplet there is no visual difference in deposition pattern but according to graph there is no presence of slip-stick behavior. We can conclude just like attractive DC, the change in concentration doesn’t have any significant effect on deposition pattern or particle transportation in the case of repulsive DC.

Orejon's hypothesis was that electrophoretic forces pulls the particle down to the surface faster than they are transported to the periphery. They supported their hypothesis by comparing the velocities due to radial convection (that drives particles to the periphery) and electrophoretic migration (that drives particle to the center of the droplet). Radial convection is calculated under no actuation. It is based on how much time liquid and particles take to travel from center to the three-phase interface(periphery). Electrophoretic migration is calculated under DC actuation. It is based on how much time particles will take to deposit over electrode. Upon comparison they found that electrophoretic migration velocity is much higher than the radial convection velocity. This made them conclude that particles will be deposited on the center of the droplet rather than transported towards the periphery. This would give us a more uniform deposition pattern and get rid of ring stains. Their hypothesis could be correct as the particles were negatively charged and the electrode below was at positive polarity.

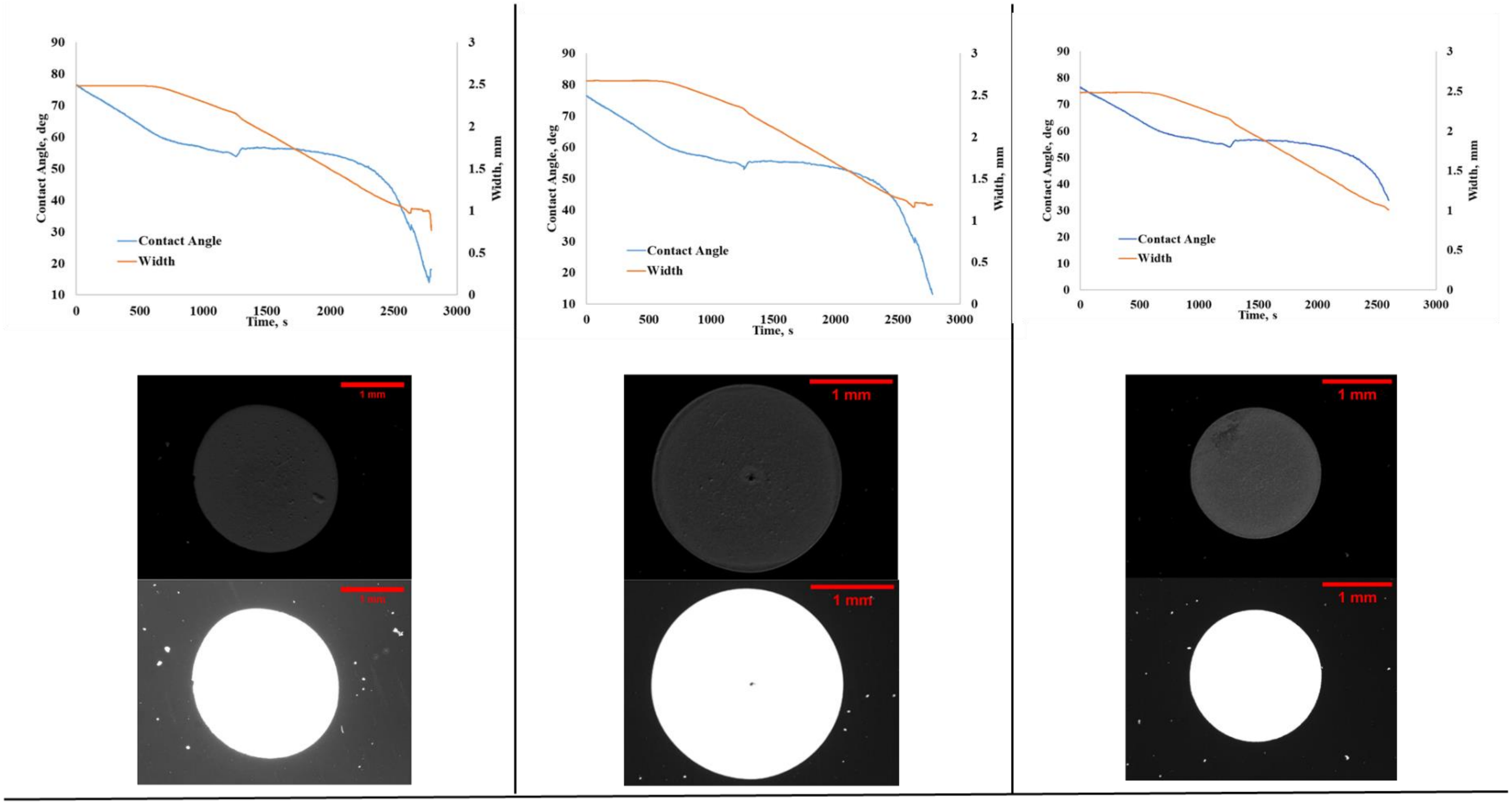
Electrophoretic manipulation of particles could have been present. It means when we reverse the polarity of the electrodes and keep the rest of the same setup, we expect to get the deposition pattern opposite to what we observe in the Attractive DC(DC+) (Same setup as Orejon's). But our experimental data doesn't support their hypothesis (for all concentrations). The electrophoretic migration should be away from the surface which mean they have to either travel towards the periphery of the droplet or towards another electrode and giving us more of a ring like pattern but we don't observe that.

The similarities between DC+ and DC- cases suggest that electrophoresis is not the mechanism beside uniform deposition pattern and the actual mechanism should be independent of the polarity. A competing hypothesis could be that the large downward interface velocity at the beginning of the EW process make the particles stuck on the interface. This means fewer particles are free floating in the droplet as most of the particles are stuck on the interface. Due to particles stuck on the interface, less particles would be floating and migrating towards the periphery which means less stick-slip phenomenon. If this was the mechanism beside uniform deposition, it would fit what Orejon saw from the control to attractive DC and repulsive DC. And the similarities we see between attractive and repulsive DC strengthen our competing hypothesis.



Comparison of all trials done for unactuated cases over SU-8 surface with droplet concentration at 0.01%.

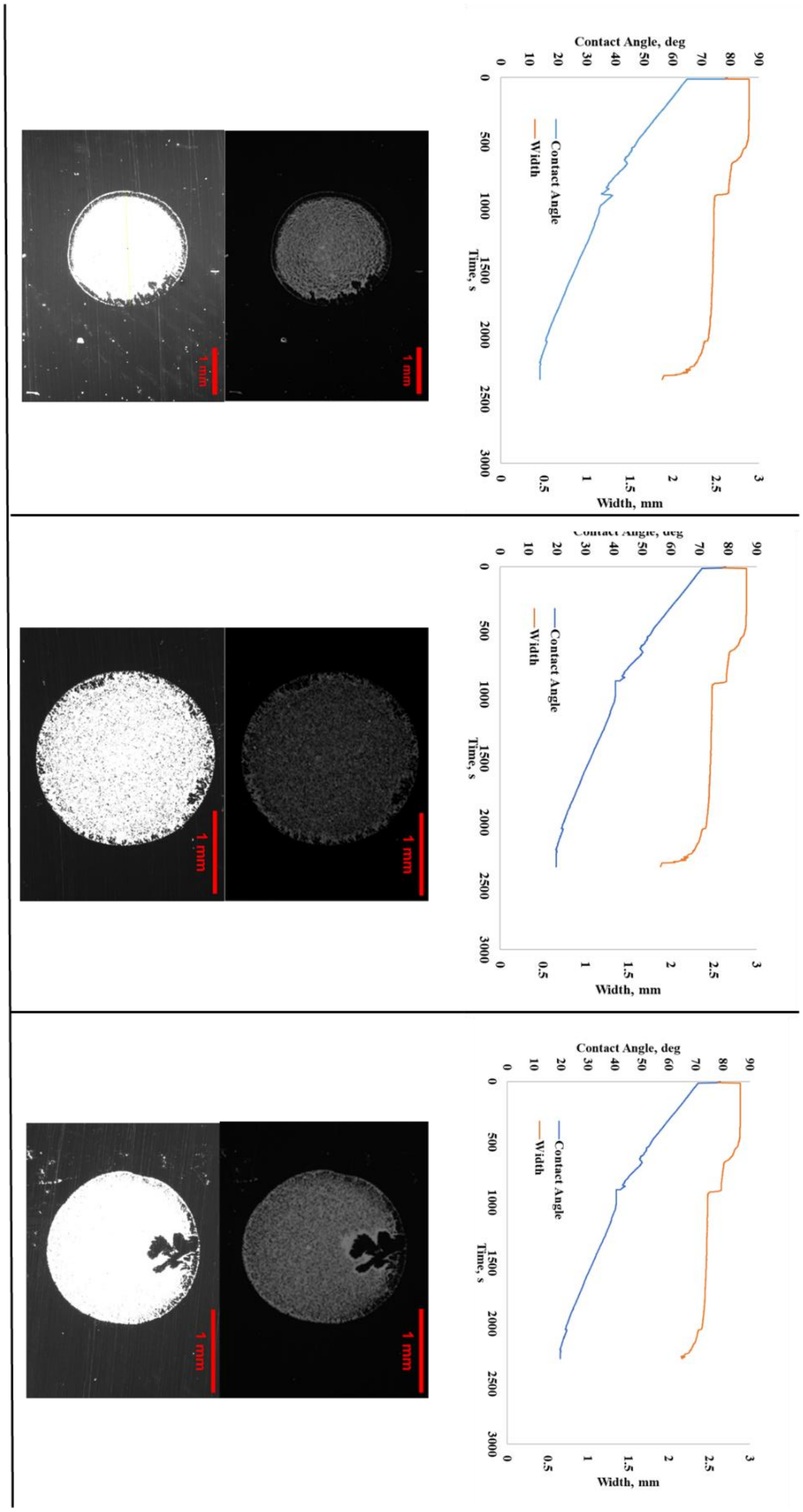
Appendix 4 Results from the repeated trials of unactuated cases with concentration at 0.01%.



Comparison of all trials done for unactuated cases over SU-8 surface with droplet concentration at 0.1%.

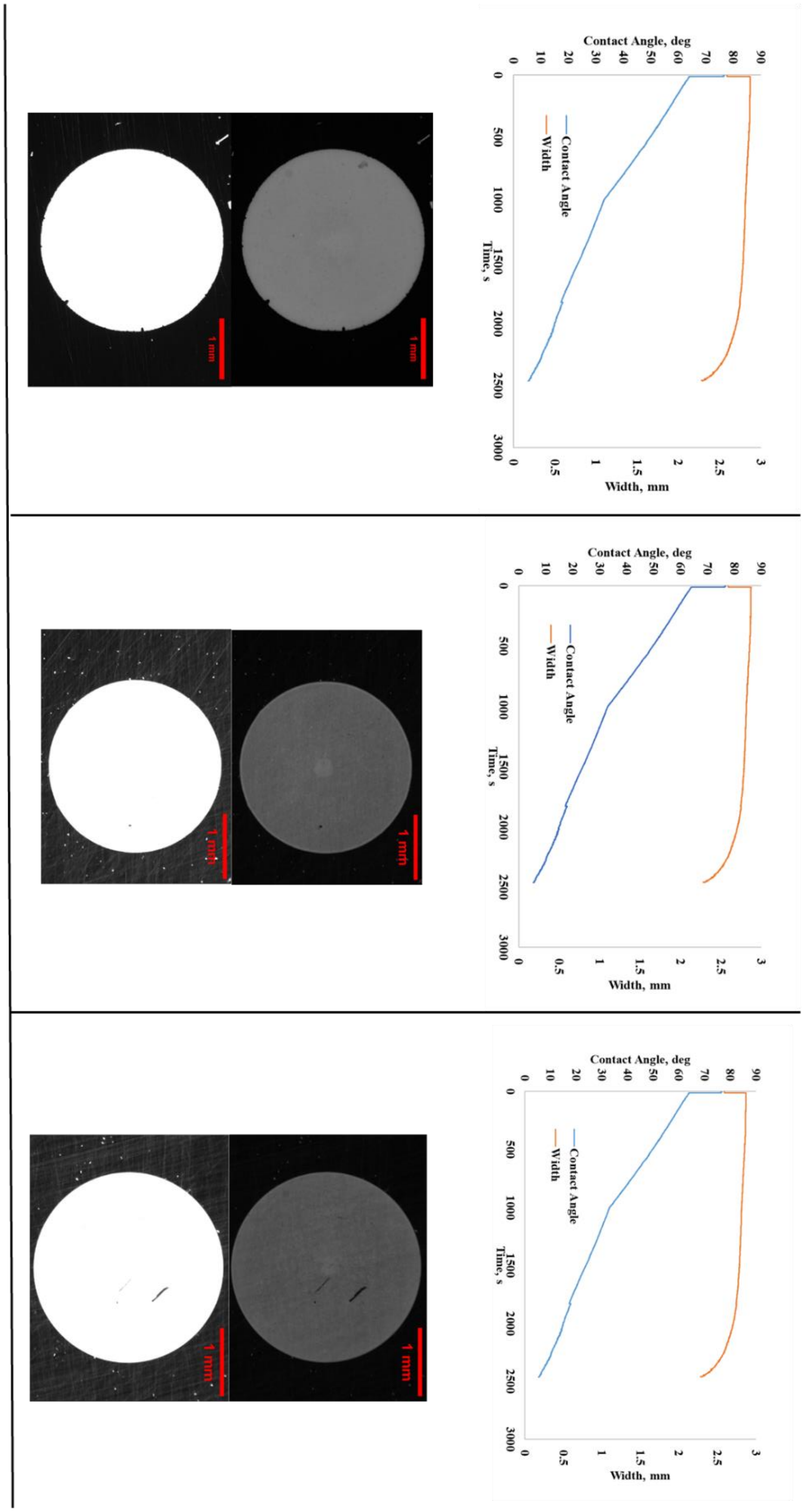
Appendix 5 Results from the repeated trials of unactuated cases with concentration at 0.1%.

Comparison of all trials done for DC+ cases over SU-8 surface with droplet concentration at 0.01%.

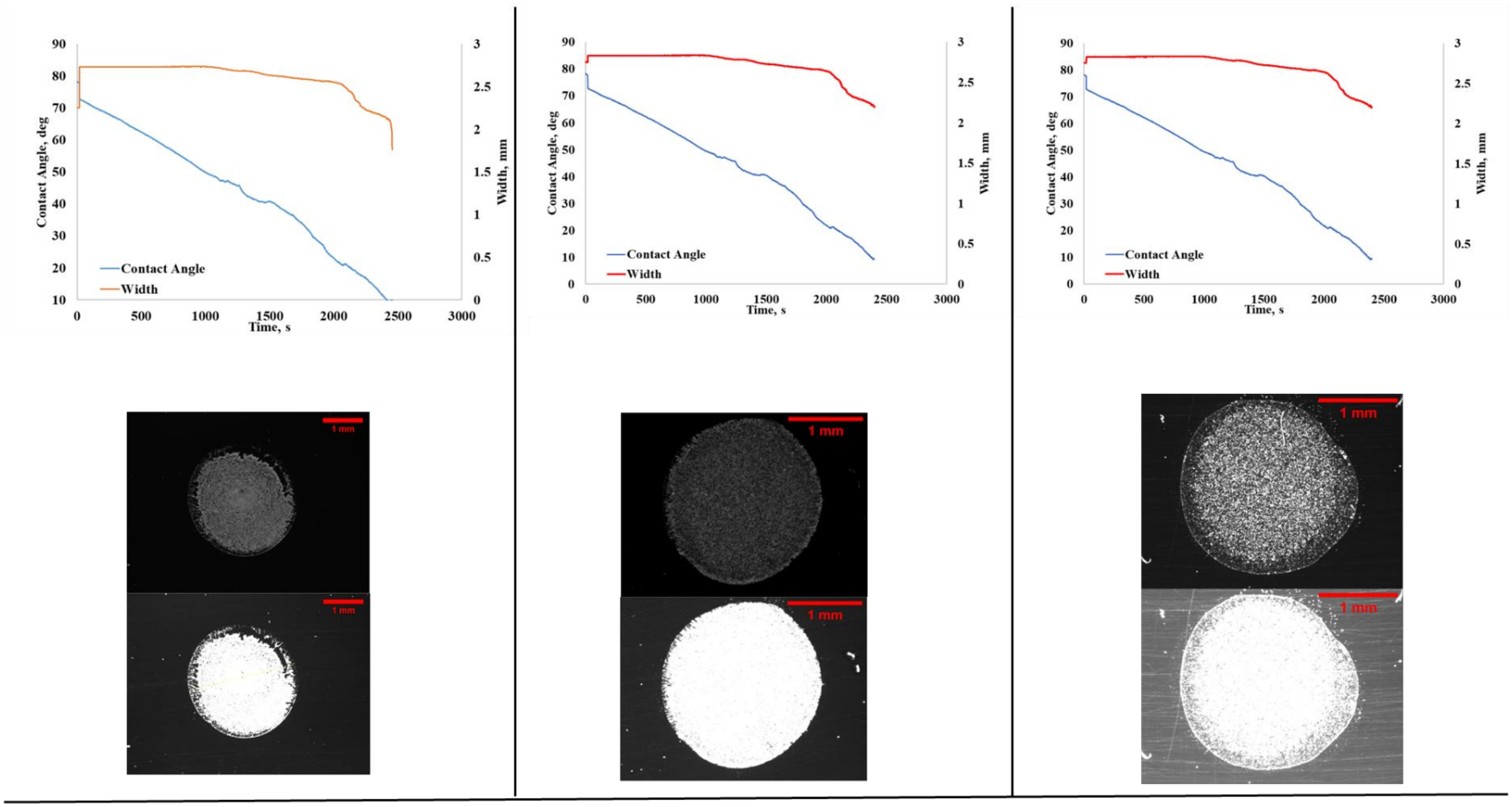


Appendix 6 Results from the repeated trials of DC+ cases with concentration at 0.01%.

Comparison of all trials done for DC+ cases over SU-8 surface with droplet concentration at 0.1%.

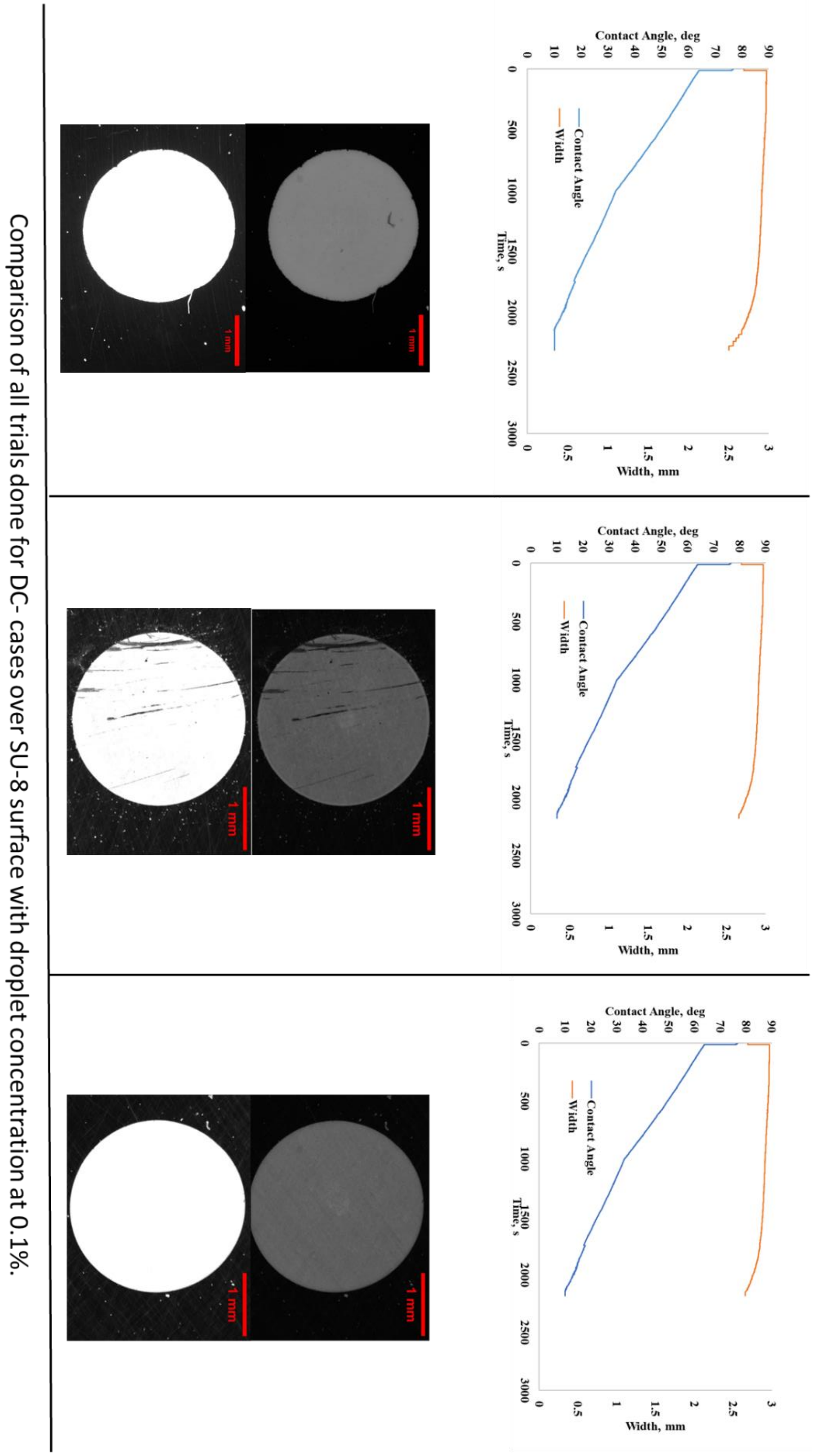


Appendix 7 Results from the repeated trials of DC+ cases with concentration at 0.1%.



Comparison of all trials done for DC- cases over SU-8 surface with droplet concentration at 0.01%.

Appendix 8 Results from the repeated trials of DC- cases with concentration at 0.01%.



Appendix 9 Results from the repeated trials of DC- cases with concentration at 0.1%.

5.4 Effects of DC polarization with change in surface selection.

Teflon coated devices & Droplet concentration at 0.05%.

Droplet under free evaporation (Unactuated):

For studying the effect DC polarization with change in surface we decided to do tests on hydrophobic surface (Teflon devices). This will give us insight of how droplet reacts on the hydrophobic surface. We will compare results of control cases, attractive DC, and repulsive DC with base case (Droplet over SU-8 with particle concentration at 0.05%).

We are first going to study the control case over Teflon devices and compare with control base case (SU-8 device with particle concentration 0.05%). Evaporation takes place in mixed regime for the entire time. Contact angle and contact width decreased simultaneously (Figure 38). Initial contact width was 1.9 mm, contact angle was 115° and contact height was 1.4mm. No rings were observed as there was no slip-stick of the contact line. Evaporation time is 7600 seconds. For data collection contact angle and contact width readings were taken once every two seconds. Deposition pattern can be seen in figure 37. Results from repeated trials can be seen in the Appendix 10.

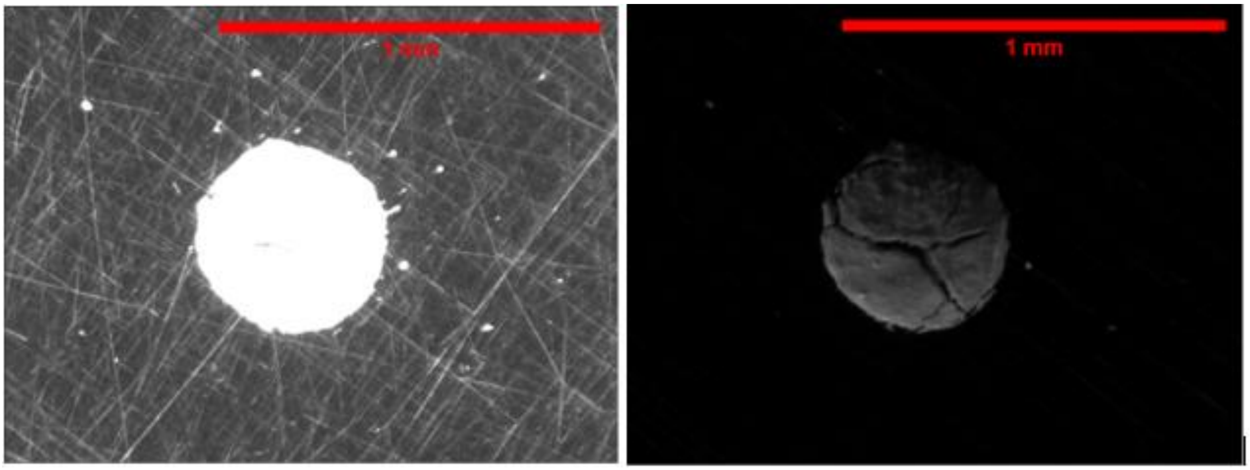


Figure 37 Deposition pattern left behind the evaporating droplet under evaporation over Teflon device with particle concentration at 0.05%.

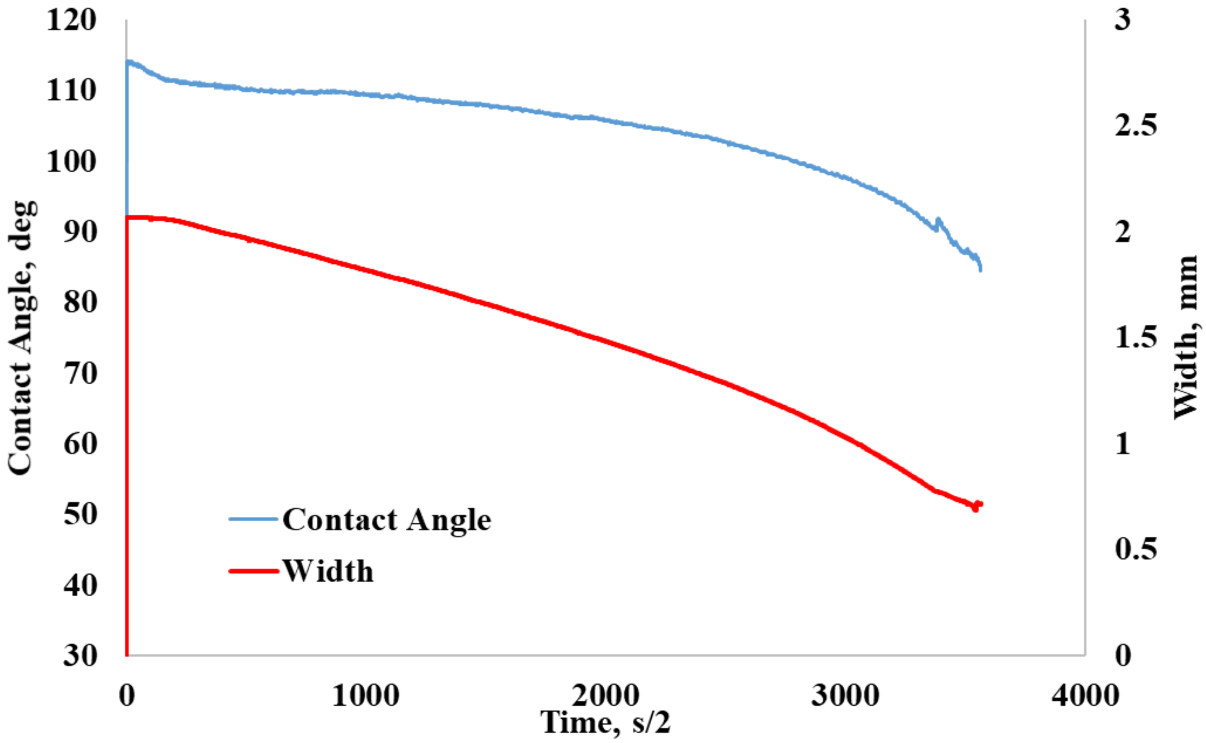


Figure 38 Evolution of contact angle and width under no actuation over Teflon device at 0.05% concentration.

While comparing the results of unactuated Teflon and SU-8 coated devices, we don't observe any similarities. Teflon is a hydrophobic surface due to which contact line is naturally too mobile and it never stays pinned. Due to unpinned contact line, we don't observe any rings or slip stick. Evaporation time increased by 153% when compared to evaporation over SU-8 surface. Which is a normal observation for any hydrophobic surface. Due to less surface area of droplet spreading over the solid layer, the evaporation time increases. We also don't observe the presence of evaporation regimes as we observed in SU-8 unactuated cases.

Attractive DC (DC+)

When voltage is applied, electrowetting causes a very rapid increase in the contact diameter and reduction in contact angle (Figure 40). When actuated: the droplet diameter increased from 2 mm to 2.6 mm (30%); the contact angle decreased from 115° to 100° (13%); and droplet height is decreased from 1.4mm to 1mm (23%). As per graphical data the contact line recedes but certain stick-slip are observed which is indicator of ring stains but when we see the deposition pattern the rings aren't visible. Contact line is naturally mobile over hydrophobic surfaces, we don't observe any ring stains over these surfaces. The evaporation times tends to be higher for hydrophobic surfaces because the droplet makes less surface contact, and which eventually hinders evaporation. Total evaporation time is 4250 seconds which is 44% less than the unactuated cases for Teflon coated devices. Deposition pattern for attractive DC(DC+) can be seen in figure 39. Results from the repeated trials can be seen in the Appendix 11.

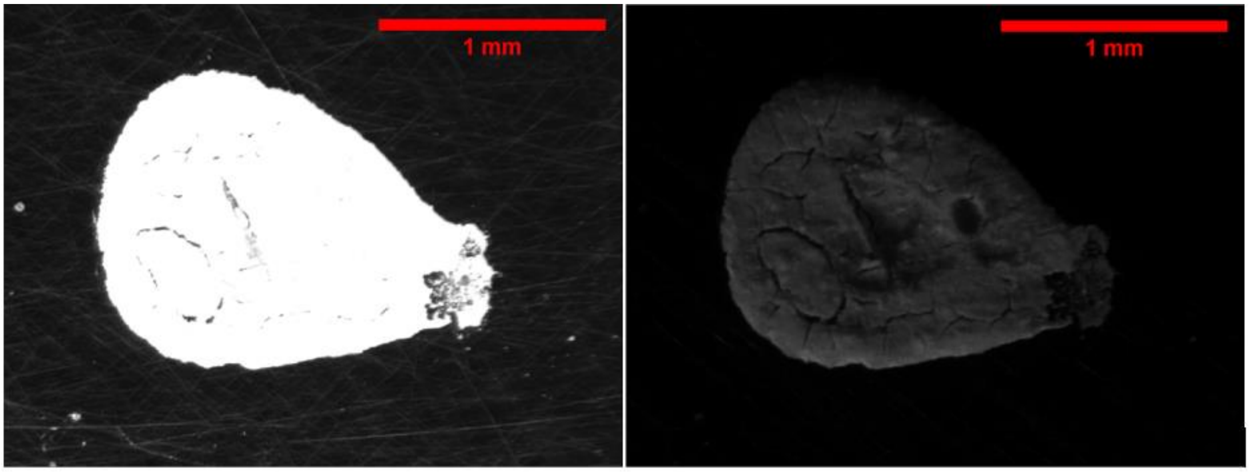


Figure 39 Deposition pattern left behind the evaporating droplet under DC+ over Teflon device with particle concentration at 0.05%.

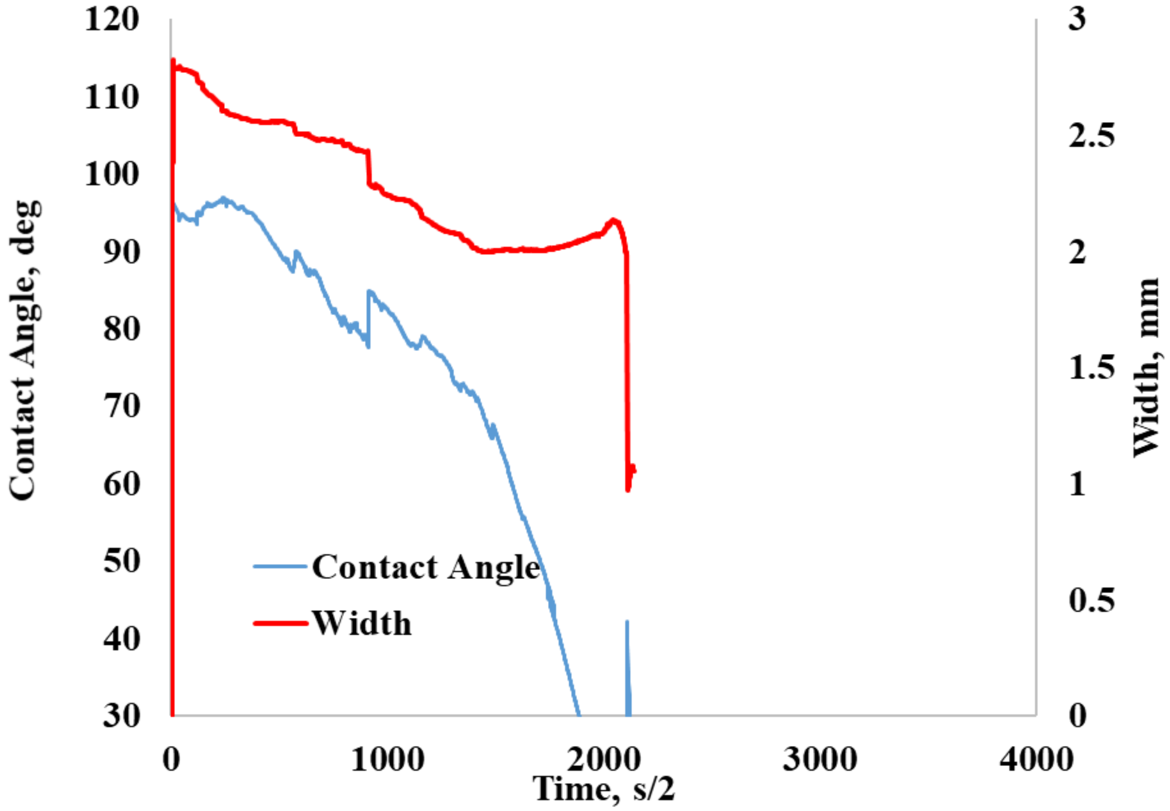


Figure 40 Evolution of contact angle and width under DC+ over Teflon device at 0.05% concentration.

When comparing the unactuated and actuated case for Teflon devices, we observe that contact width increases, and contact angle and droplet height decreases instantaneously due to electrowetting force. Deposition pattern left behind the unactuated and attractive DC is not very distinct than one another.

When we compare attractive DC for SU-8 and Teflon device, we don't observe any similar trend in deposition pattern. When we look at Figure 39 & 40, we observe that stick-slip behavior is still present in attractive DC actuation on Teflon coated device. On SU-8 surface, we don't observe any stick-slip behavior.

We don’t observe uniform deposition in Teflon coated devices, but we do observe uniform deposition in attractive DC on SU-8 devices.

Due to no significant similarities between the attractive DC for SU-8 and Teflon coated devices we can conclude that neither Orejon’s hypothesis nor our competing hypothesis holds true in this case. It is possible that hydrophobic surfaces might not conform with the hypothesis that applies to hydrophilic surfaces like SU-8.

Teflon is a hydrophobic surface due to which contact line is naturally too mobile and it never stays pinned. Under attractive DC we neither observe uniform deposition nor ring stains. We think due to naturally mobile contact line in these tests the effect of attractive DC doesn’t make much impact on deposition pattern or particle transportation.

Repulsive DC(DC-)

When voltage is applied, electrowetting causes a very rapid increase in the contact diameter and reduction in contact angle (Figure 42). When actuated: the droplet diameter increased from 2.2 mm to 2.8 mm (27%); the contact angle decreased from 115° to 100° (13%); and droplet height is decreased from 1.4mm to 1mm (23%). As per graphical data the contact line recedes but certain stick-slip are observed which is indicator of ring stains but when we see the deposition pattern the rings aren’t visible. Contact line is naturally mobile over hydrophobic surfaces, we don’t observe any ring stains over these surfaces. The evaporation times tends to be higher for hydrophobic surfaces because the droplet makes less surface contact, and which eventually hinders evaporation. Total evaporation time is 4400 seconds which is 42% less than the unactuated cases for Teflon coated devices. We observe that contact width increases, and contact angle and droplet height decrease instantaneously due to electrowetting force. Deposition pattern left behind the unactuated and Repulsive DC(DC-) is not very distinct than one another. Deposition pattern left behind the DC- can be seen in figure 41. Results from the repeated trials can be seen in the Appendix 12.

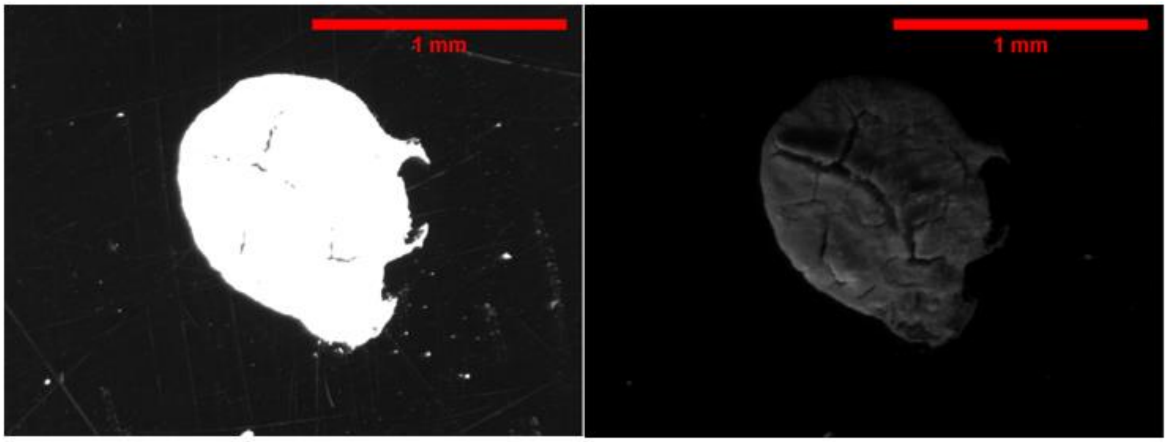


Figure 41 Deposition pattern left behind the evaporating droplet under DC- over Teflon device with particle concentration at 0.05%.

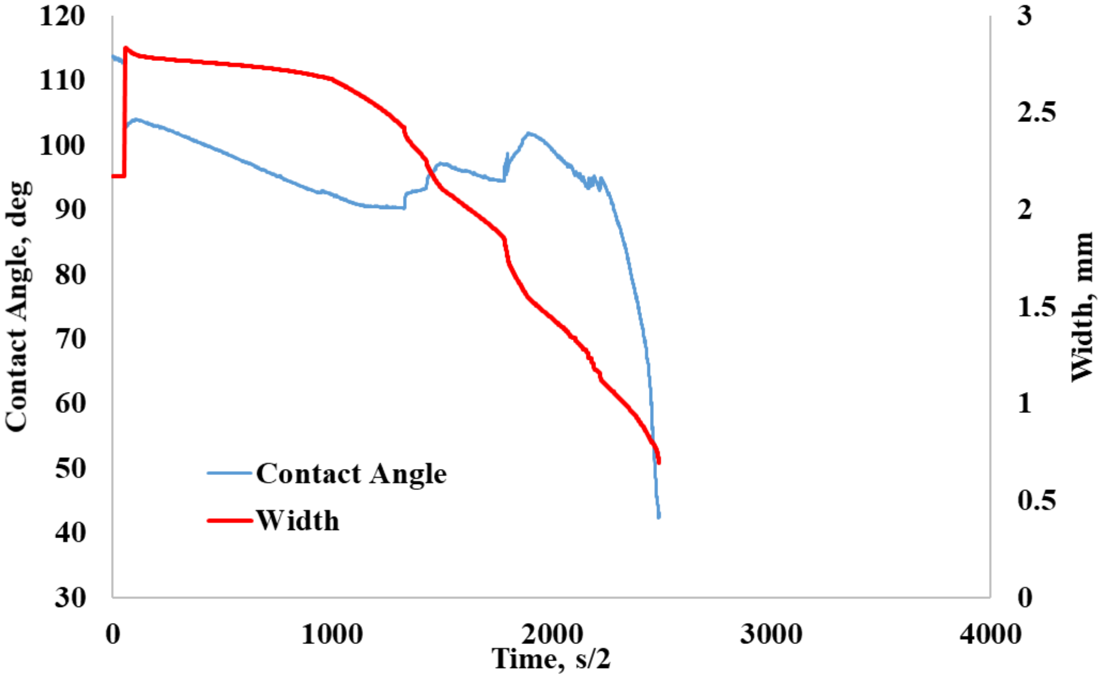
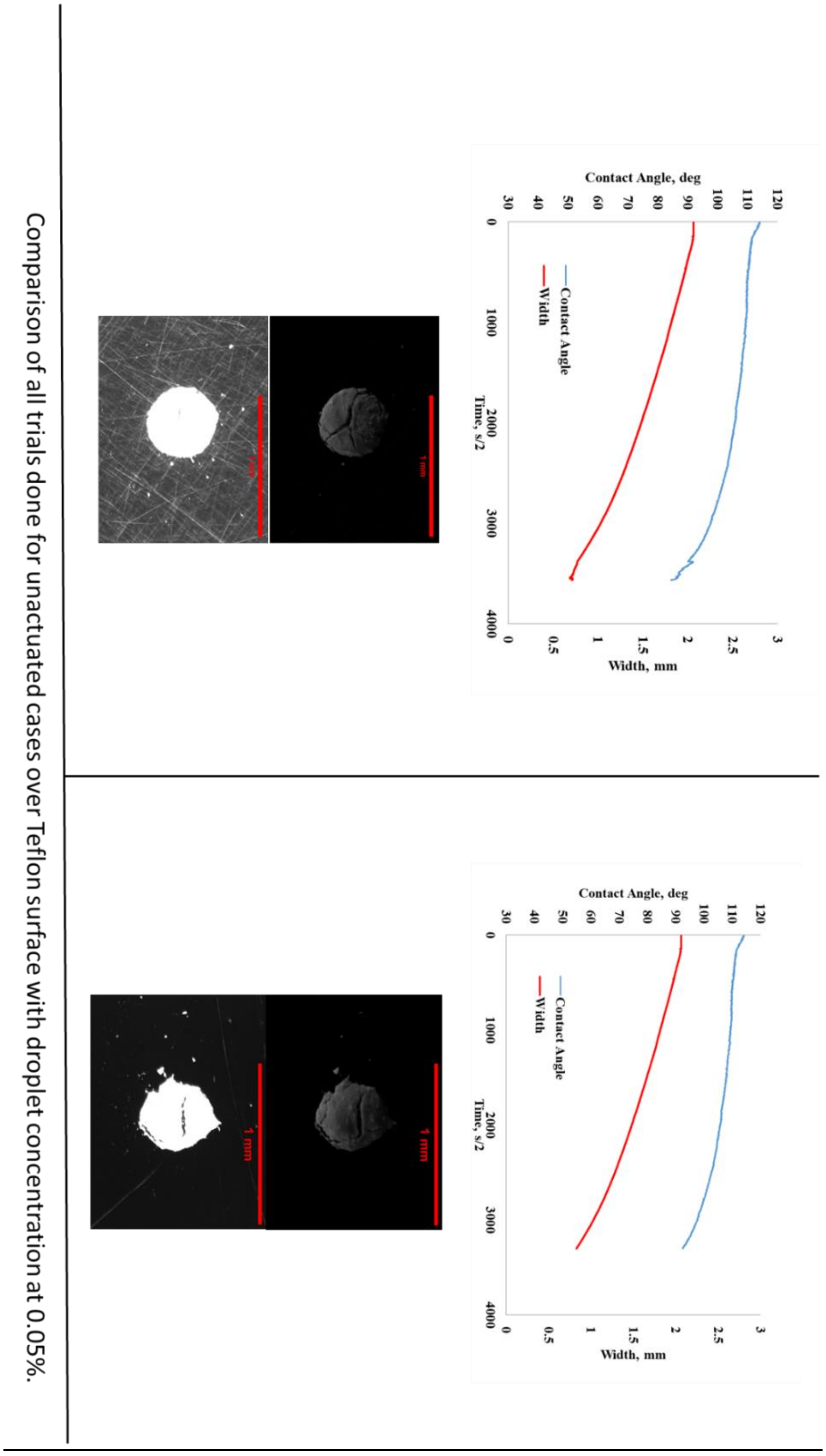


Figure 42 Evolution of contact angle and width under DC- over Teflon at 0.05% concentration.

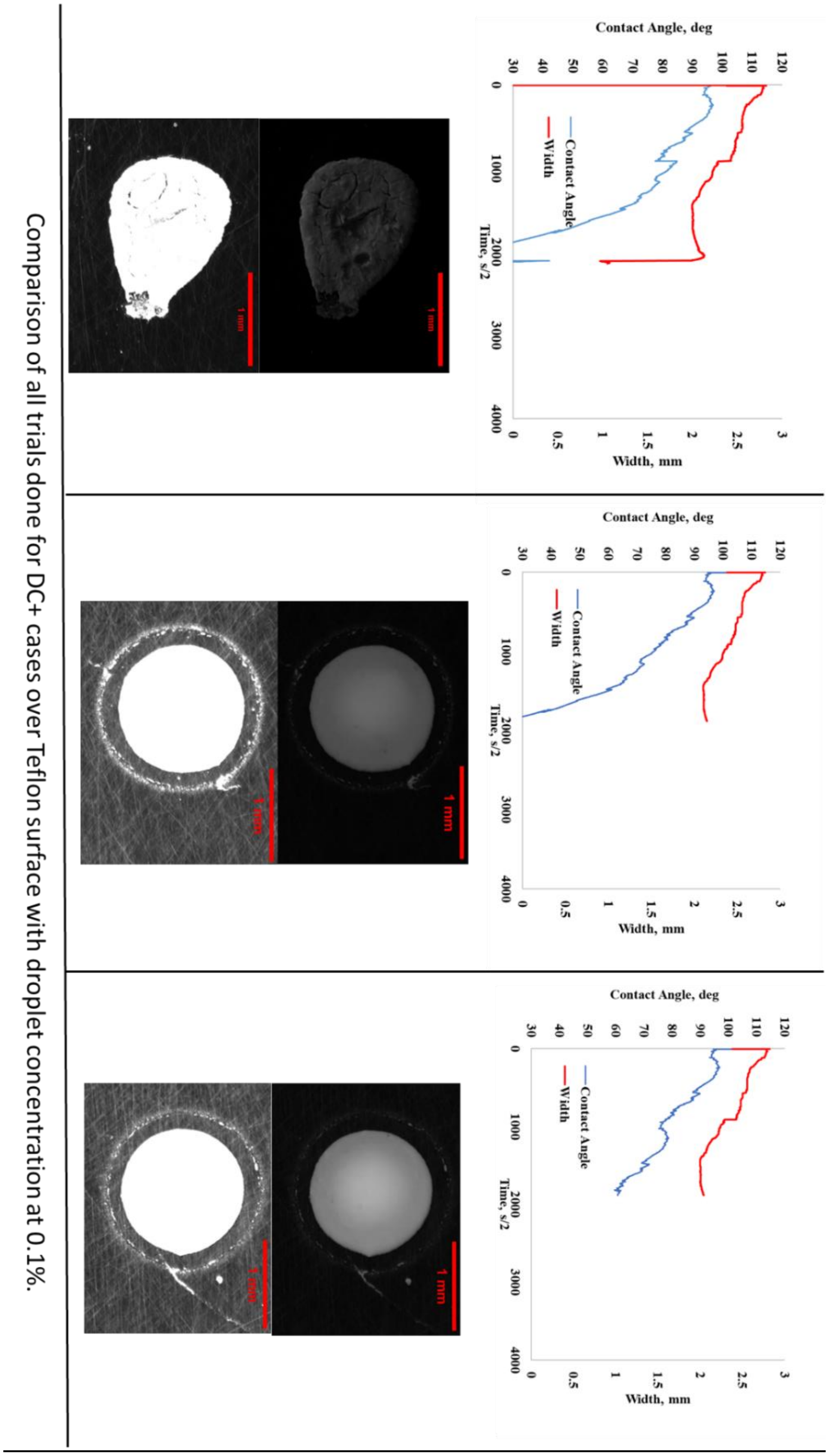
When we compare Attractive DC and Repulsive DC, we don't observe any difference in the deposition pattern left behind the droplet. We think that Teflon coated devices is not well suited for testing Orejon's hypothesis because we don't see any major difference between unactuated and actuated (DC+ &DC-) cases. This explains why Orejon chose SU-8 surface for their study.

These set of results provide no proof to strengthen or weaken our hypothesis as well. We are not able to observe any evidence of interface trapping because we never got to see uniform central deposition for either of actuated cases (i.e., Attractive and Repulsive DC).



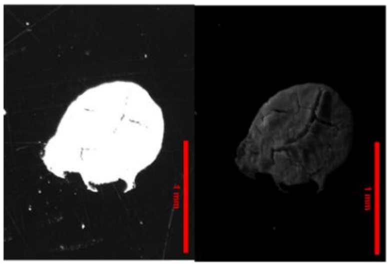
Comparison of all trials done for unactuated cases over Teflon surface with droplet concentration at 0.05%.

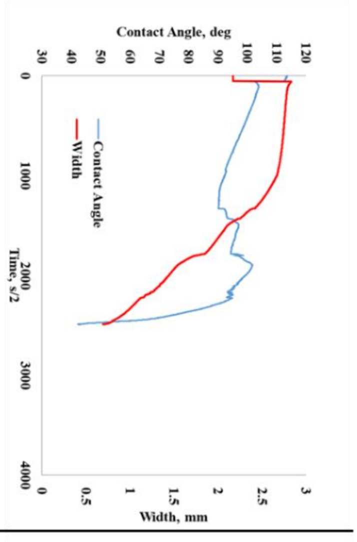
Appendix 10 Results from the repeated trials of unactuated cases with concentration at 0.05% over Teflon coated devices.

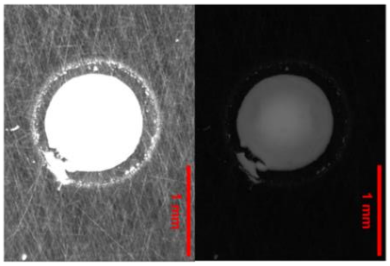


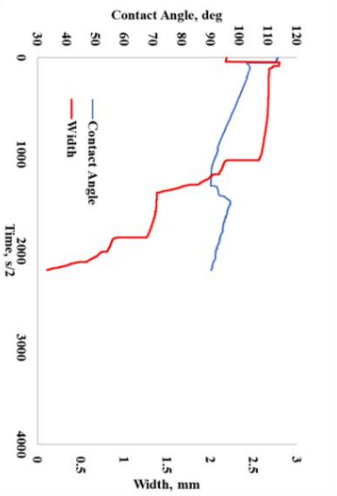
Appendix 11 Results from the repeated trials of DC+ cases with concentration at 0.05% over Teflon coated devices.

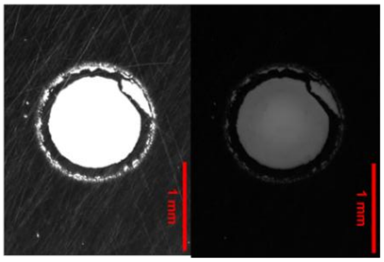
Comparison of all trials done for DC- cases over Teflon surface with droplet concentration at 0.05%.

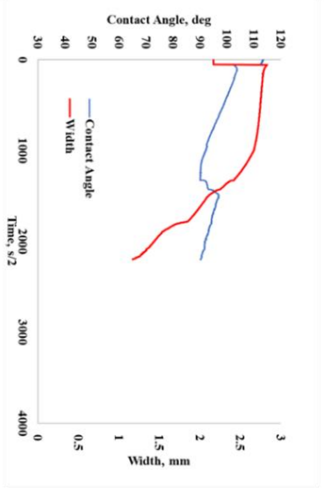












Appendix 12 Results from the repeated trials of DC- cases with concentration at 0.05% over Teflon coated devices.

6.0 CONCLUSIONS

Determining an appropriate applied voltage for evaporation testing:

All the devices after fabrication with SU-8 and Teflon were checked for consistency and at what voltage we should run our test. We wanted to apply maximum voltage which our device can sustain without causing it to fail on a long run. This will maximize the effects of applied voltage and it will be easier for us to observe the changes.

For SU-8 surface that point was decided after analysis to be at 140 V for both AC (rms) and DC. This was the maximum voltage where we didn’t see any bubble formation or any rupture of the dielectric layer. At 160 V we saw some bubbles and decided to not test the device on higher voltages. This voltage is for long duration evaporation tests, and we don’t want our device to fail in the middle of test.

For the selection of maximum voltage for Teflon coated devices same process as SU-8 was done. After analysis, 140 V (AC rms and DC) was chosen for the experimentations. At 160 V we saw some bubbles and decided to not test the device on higher voltages.

Effects of DC polarization:

While comparing the unactuated and actuated (attractive DC) cases, we can say that results were consistent with Orejon’s observation.

The similarities between DC+ and DC- cases suggest that Orejon’s hypothesis is not the mechanism that causes uniform deposition pattern and the actual mechanism should be independent of the polarity. A competing hypothesis could be that the large downward interface velocity at the beginning of the EW process make the particles stuck on the interface. This means fewer particles are free floating in the droplet. If this was the mechanism, it would fit what Orejon saw from the control to attractive DC. And the similarities we see between attractive and repulsive DC strengthen our competing hypothesis.

Effects of DC polarization with change in particle Concentration:

While comparing the effects of changing particle concentration, we can say that results were consistent throughout all the actuated and unactuated cases with our proposed hypothesis. All the concentrations followed the same trend as 0.05% concentration droplet results. We think that due to the very less concentration of particles at 0.01%, we see unclear ring stains in unactuated cases and for 0.1% concentration, we see nothing but a uniform deposition. Evaporation times for all the unactuated cases are similar. Contact width was also very similar in all the unactuated cases for SU-8 coated devices.

For actuated cases (attractive and repulsive DC), for 0.01% concentration we see a similar trend as 0.05% concentration, which strengthens our hypothesis. But for 0.1% as the concentration was very high, we weren't able to differentiate between them on the basis of microscopic images, but graphical data supported our competing hypothesis. Interestingly, we didn't notice any supporting proof of electrophoretic manipulation of TiO_2 particles throughout our experiments. We can say that our competing hypothesis is applicable when particle concentrations are changed. It gives better explanation to the deposition pattern left behind the evaporating droplet.

The similarities between DC+ and DC- cases suggest that electrophoresis (Orejon's hypothesis) is not the mechanism that causes uniform deposition pattern and the actual mechanism should be independent of the polarity. A competing hypothesis could be that the large downward interface velocity at the beginning of the EW process make the particles stuck on the interface. This means fewer particles are free floating in the droplet as most of the particles are stuck on the interface. Due to particles stuck on the interface, less particles would be floating and migrating towards the periphery which means less stick-slip phenomenon. If this was the mechanism beside uniform deposition, it would fit what Orejon saw from the control to attractive DC. And the similarities we see between attractive and repulsive DC strengthen our competing hypothesis. We can conclude that with change in concentration our competing hypothesis holds true.

Effects of DC polarization with change in surface selection:

While comparing the results of SU-8 and Teflon coated devices, for unactuated cases increased evaporation time (due to the hydrophobic nature of Teflon) for Teflon coated devices and smaller contact width was observed for Teflon coated devices. We expected that we won't observe the rings in Teflon coated devices and we didn't see any ring stains in Teflon devices. Ring stains were present in the unactuated SU-8 devices but not in Teflon coated devices. There was a complete change in deposition pattern in SU-8 devices for actuated and unactuated cases. But for Teflon there wasn't much of a difference between unactuated and actuated cases. Teflon is a hydrophobic surface due to which contact line is naturally too mobile and it never stays pinned. Due to unpinned contact line, we don’t observe any rings or slip stick.

When we compare attractive DC for SU-8 and Teflon device, we don’t observe any similar trend in deposition pattern. We observed that stick-slip behavior is still present in attractive DC actuation on Teflon coated device. On SU-8 surface, we don’t observe any stick-slip behavior. We don’t observe uniform deposition in Teflon coated devices, but we do observe uniform deposition in attractive DC on SU-8 devices. For SU-8 devices upon actuation the deposition pattern had significant changes in width and no ring stains. Due to hydrophobic nature of Teflon and naturally mobile contact line we couldn't get the different result in deposition pattern when electric field was applied.

When we compare Attractive DC and Repulsive DC, we don't observe any difference in the deposition pattern left behind the droplet. We think that Teflon coated devices is not well suited for testing Orejon's hypothesis because we don't see any major difference between unactuated and actuated (DC+ &DC-) cases. This explains why Orejon chose SU-8 surface for their study.

These set of results provide no proof to strengthen or weaken our hypothesis as well. We are not able to observe any evidence of interface trapping because we never got to see uniform central deposition for either of actuated cases (i.e., Attractive and Repulsive DC).

Other possible hypotheses:

Interface trapping is one of the reasons due to which uniform deposition pattern is obtained but there can be several other physical phenomena due to which uniform deposition pattern is obtained.

1. Due to instantaneous change in the shape of the droplet interface, it is high possibility that particles are pushed down on the substrate and due to the higher density of particles they never go back into the droplet and recirculate till the end of evaporation.
2. Attractive DLVO forces might be acting on the particles and due to decrease in the droplet height the particles migrate easier towards the electrode. DLVO force is inversely proportional to the distance between the particles and the solid surface.
3. Particle inside the droplet might rearrange themselves during the combined effects of the EW and evaporation. Due to high concentration of particles, it will hinder the free motion of the particles as they will collide with each other more as concentration increases. Particle motion inside the droplet under combined effect of EW and evaporation is still debated.

7.0 FUTURE WORK

Based on the other possible hypotheses and combination of physical parameters like size of particles, electric field we came up with some suggestions that might help future researchers.

Our other suggestion for further research would be: -

- Particles sizes can be changed. - One of the methods of particle manipulation was changing the orientation of the particles and we think that it is something that could give interesting results in this field.
- Particles can be changes from titanium dioxide to polystyrene. The density of polystyrene is much lower than the titanium dioxide particles and we think that evidence for interface trapping can be further proved this is taken into consideration.
- Particles can we changed to self-illuminating. - Our particles were not bright at all. We had to take photographs with LED lights on and off in order to observe the ring pattern and deposition pattern. It would be interesting if future work would be carried out with some self-illuminating particles.
- Particle motion inside the droplet can be studied with the mathematical model and can be checked experimentally. It will give an idea about how valid a mathematical model is when compared to actual flow of particles inside the droplet.
- To test our hypothesis of interface trapping, experiments can be carried out with supplied voltage at the start and removed in the middle of the evaporation. If interface trapping is not the driving principle beside the uniform deposition pattern, then we will see ring patterns again.
- Side view of the deposition pattern might give some interesting information – This would be the most challenging task to do in the future as it involves two camera setups and two readings of

contact angle. Compilation of the results would be challenging as well. But if it is done, we would get deeper insight into interface profile of the droplet.

- Different metallic surfaces can be used. - We used aluminum as metallic substrate. We think it might be interesting to check the results on some higher or lower conductive surfaces.
- Transparent metal (Aluminum treated with the UV rays) could be used in future.- The most interesting of all the future scope would be this. If achieved, we would be able to see the deposition pattern from beneath the metal surface and that would give us exact idea of the particle deposition which is sometimes lost when viewed from top view.
- Infrared lights can be used to study the particle motion inside the droplet and flow of particles can be further observed with the combined effect of EW and evaporation.
- AC electric field can be studied instead of DC electric field. AC electric field can manipulate the particles inside the droplet due to electrophoretic forces as it is known by previous research that when AC electric field is applied the electric field actually penetrates the droplet. It would be interesting to check the results of deposition pattern when AC electric field is applied.

8.0 SOCIETAL CONTEXT

With technological advancements the need for things such as flexible electronics, ‘Lab on a chip’ that can be used for easy diagnostics would become standard use in upcoming days. Though the concept used behind both processes is still under study by many scholars worldwide. Such research would help in better understanding of the phenomenon used in these processes. Some study also suggests that the concepts behind particle transport and deposition can also help with some major world issues like water treatment, oil spills and waste management.

Quite a lot of research has been done within past decade regarding particle transport and how to manipulate and control the deposition patterns left behind the evaporating droplets. Application of electric field is one of the ways to gain control over the particle transport and control deposition pattern. But scholars have conflicting thoughts and uncertainties regarding the actual behavior of the process and the key elements that is essential in the process for successful results.

Through this study our aim would be to clearly identify the factors that affect the particle manipulation and deposition and in addition to that I would also study that how to manipulate the deposition patterns that are left behind the evaporating droplet with the help of applied electric field. Therefore, the results achieved now surely gave us little better insight of the factors that are affecting the particle manipulation and deposition pattern and bolstered the knowledge about the how particle concentration and different surfaces. We hope that our study would someday favor the quality of the futuristic products (flexible electronics, Lab on a chip device etc.)

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