Surface Wettability Studies of PDMS using Flame Plasma Treatment

by

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Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of

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Abstract

The flame plasma treatment studied in this thesis was able to oxidize the surface of Polydimethylsiloxane (PDMS) in a fraction of a second. It was found to be a much faster way to modify PDMS surface wettability than the current technologies. The surface wettability of Polydimethylsiloxane (PDMS) treated with flame plasma was studied. The surface wettability was characterized by contact angle measurements using water and a surface tension liquid as the probe liquids. Two experimental parameters were varied in this investigation: a) distance from the PDMS surface to the inner flame cone; b) the dwell time of the PDMS under the flame. The study concluded that the same surface wettability can be achieved through different combinations of distance and dwell time. The shortest dwell time needed to induce a contact angle of 10^0 or less on the treated PDMS surface in this experimental setup was approximately 0.18 second. This study also found that over treatment of the PDMS surface in the flame plasma yielded a reversal treatment effect and decreased the surface wettability. The flame plasma yielded uniform contact angle measurements within 15% across the PDMS surface. The recovery mechanism in the treated PDMS surfaces was dominated by the diffusion of untreated polymers from the bulk PDMS to the treated surface. The results from this investigation demonstrated the potential for the flame plasma treatment to be used in rapid manufacturing of PDMS microfludic devices.

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Chapter I: Introduction

PDMS based microfluidic devices have become popular in the recent decade in biological applications. An essential step in fabricating PDMS microfluidic devices is to oxidize the surface in order to assemble the microfluidic device. This thesis will investigate using flame plasma as a faster and cheaper way to oxidize the PDMS surface.

PDMS consists of inorganic siloxane backbone and organic methyl groups attached to the silicon as shown in Fig 1. PDMS has unique combination of properties beneficial to microfluidic fabrication [1]: a) it has a low glass transition temperature which allows it to be in the liquid state at room temperature. The liquid polymer can be transformed into solid elastomer by using a curing agent which activates cross-linking within the polymer; b) the cured PDMS has high elasticity which makes demolding of the microfluidic device an easy job; c) PDMS membranes are permeable to gasses, which facilitates the removal of air bubbles inside the PDMS in liquid state; d) PDMS is transparent down to 300nm which makes it feasible to perform visual inspection of the microchannels under a microscope; e) After curing, PDMS has low interfacial free energy, also known as surface tension($\approx$21.6 dyne/cm), and the surface tension can be increased by exposure to plasma, which is an ionized gas, and assembled into microfluidic devices. .

The plasma modified PDMS surface offers two major advantages: first, the PDMS microchannels become hydrophilic, which allow polar fluids to fill the channel much faster [2]; second, the plasma modified surface allows the PDMS to bond irreversibly to a range of materials including glass, silicon, silicon oxide, quartz, silicon nitride, polyethylene, polystyrene, glassy carbon. The plasma modified PDMS is also capable of bonding to another piece of plasma modified PDMS.

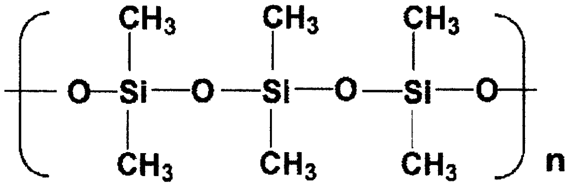


Fig 1: Chemical composition of PDMS

Plasma can be generated from several different sources. The two plasmas commonly used in literature are Oxygen Plasma and Corona Plasma. Oxygen Plasma is a radio-frequency (RF) excited gas. The gas contains O^+,O_2^+, O^-, O_2^- $O(^3P)$,$O_2(^1\Delta_g)$ and free electrons. The concentration of ions will vary depending on the strength of the applied electric field, pressure, impurities or contaminants. The actual plasma medium is very complex because depending on the plasma chemistry. However, it is known that the primary reactions will involve $O(^3P)$,$O_2(^1\Delta_g)$ [3]. Studies by Morra *et al* have shown that the oxygen plasma mainly affect the Si atoms on the surface. They used Static secondary ion mass spectrometry (SSIMS) to confirm that the PDMS surface is oxidized by the oxygen plasma through converting $-OSi(CH_3)_2O-$ groups to $-O_nSi(OH)_{4-n}$[4]. The typical oxidization time is around 1 minute. The complexity of the oxygen plasma thus requires special operating conditions such as low vacuum environment in the presence of oxygen gas and clean room facilities. Thus the operating cost of oxygen plasma treatment is high. Furthermore, the oxidized surface reverts back to hydrophobic properties if exposed in atmosphere for a few hours. [5]

The corona plasma is created by a hand held corona device that generates a high voltage potential across a thin wire electrode. The electrode then ionizes the air to create the localized corona plasma. The thin wire electrode is passed back and forth approximately 1/4 inch above the sample for ten to twenty seconds. The duration in which the surface remains oxidized varies from a few minutes to a few days depending on experimental conditions. The level of corona treatment depends on non-numerical power setting, distance from the electrode to the sample, treatment time and size of the sample. The actual mechanism of the corona discharge is not yet known. There are two major draw back to the portable corona system: a) the corona produces a significant amount of ozone; therefore the corona device should be used in well ventilated areas; b) the corona device produces RF noise, which can reset nearby electrical equipment [6].

The major draw backs in oxygen plasma and corona plasma treatments on PDMS surfaces inspired the focus of this thesis: the study of plasma generation through oxygen-rich flame in applications of PDMS surface treatment. In industry, the flame plasma is used to modify the surface of polyolefins to ensure wetting of water-based coatings, inks, and adhesives, however, very little work in literature had been done on flame treatment of PDMS [7]. Direct flame treatment consists of passing the PDMS sample under an oxygen-rich flame for a couple seconds for surface oxidation. In direct flame treatment, the resulting combustion products include oxygen molecules, oxygen atoms and ions, free electrons, carbon, nitrogen atoms as well as carbon-oxygen and oxygen-hydrogen groups. Studies by Mark Strobel from 3M demonstrated that in polyolefins, flame treatment induced formations of hydroxyl (OH), carbonyl (COOH) and carboxyl (O=CO), functionalities [8]. In PDMS, this study expects to find that the effect of the flame induced plasma will convert $-OSi(CH_3)_2O-$ groups to $-O_nSi(OH)_{4-n}$ through reactions with the oxygen ions in the combustion byproducts. In polyolefins, the effect of the oxidized surface lasted longer than both oxygen plasma and corona plasma treatments and with much shorter treatment duration: 1-2 seconds [9]. Compared to Oxygen plasma and Corona plasma, Flame-induced plasma is capable of oxidizing surfaces of large numbers PDMS samples through a conveyor belt system to allow rapid production of micro fluidic channels. Table I. summarizes the strength and weakness of flame plasma treatment in comparison with oxygen plasma and corona treatments concluded from the polyolefins surface treatment industry [9]. This thesis aims to characterize and understand the treatment of flame plasma on PDMS surfaces.

TABLE I. COMPARISON OF TREATMENT USING DIFFERENT PLASMAS

Plasma Technology	Advantage	Disadvantage
Oxygen Plasma	1. well controlled treatment	1. Requires clean facilities and vacuum 2. High capital cost 3. Long reaction time: >1 minute 4. Oxidized surface reverts back to original surface tension in atmosphere
Corona Plasma	1. Lower initial cost 2. Portable equipment 3. Conductible in room temperature	1. Ozone generation 2. RF generation 3. Less controlled over large areas
Flame-induced Plasma	1. Capable of rapid treatment 2. Oxidized surface lasts longer 3. Conductible at room temperature	1. higher cost than corona plasma but cheaper than oxygen plasma

Chapter II: Flame Treatment System

In order to study the effect of flame plasma treatment, a flame treatment system needed to be designed and built. The flame treatment system needed to be able to control the dwell time of the PDMS sample under the flame and the distance of the sample from the flame. The following sections explain the flame treatment system design process.

i. System Piping Layout:

The flame treatment system uses Propane (C_3H_8) as the fuel and compressed air as the source of oxygen for combustion. The pipe fitting used to connect the different components are made of 316/316L stainless steel for its high strength at high temperatures. The piping system is shown in Fig. 2.

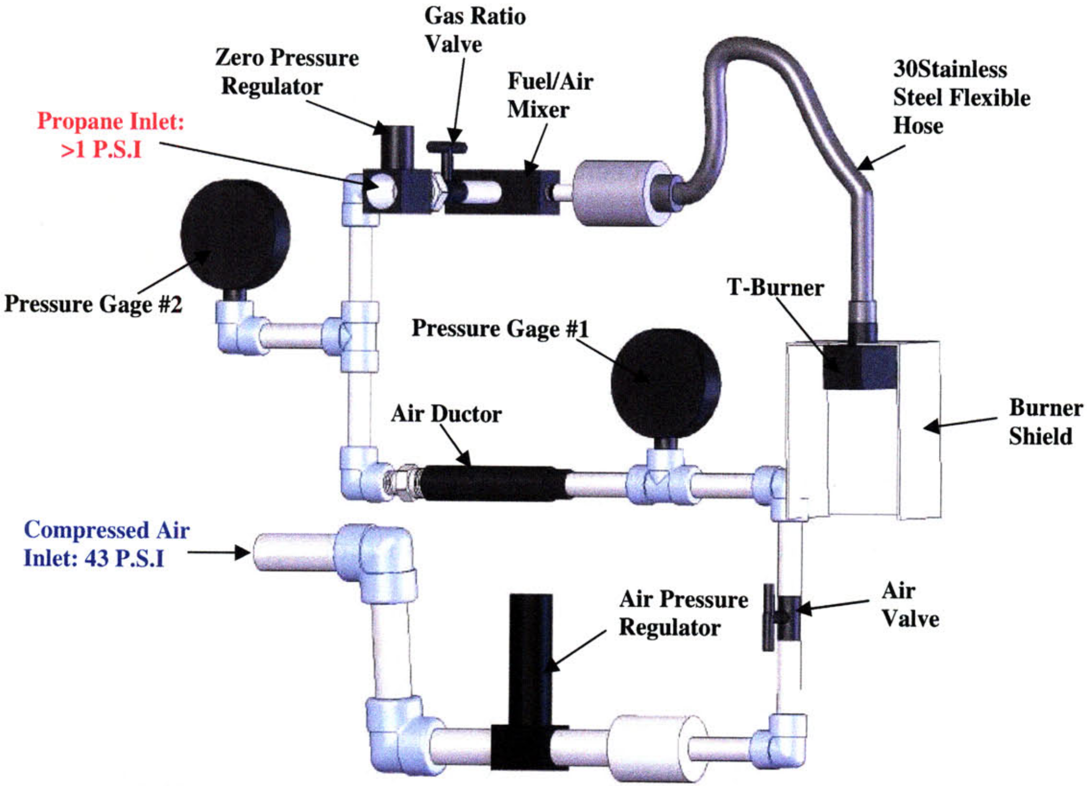


Fig 2. A complete model of the piping for the flame treatment system.

The specifications and functions of each component are described below, starting from the compressed air inlet and following along the piping of the system.

- Air Pressure Regulator—reduces the pressure of the compressed air. Typical pressures of compressed air ranges from 40 P.S.I to 80 P.S.I. Without the air pressure regulator, the air pressure entering the subsequent components would be too high and cause the burner to choke. Furthermore, the pressure of the compressed air tends to fluctuate depending on compress air usage by others in the laboratory, and the air pressure regulator will eliminate the fluctuations, and create a smooth and constant pressure in the pipe line.
- Air Needle Valve—adjusts the amount of air flowing through the pipes, and therefore controls the output of the burner.
- 100 P.S.I. Air Pressure Gauge—provides air pressure reading before the flow enters the air ductor.
- Air ductor—uses 6 orifices as nozzles to suck in room air to mix with the compressed air in order to decrease the overall air pressure. After the air ductor, the air flowing through the pipes will comprise of 65% room air and 35% compressed air. The air ductor will prevent problems such as burner stall.
- 35 in. Air Pressure Gauge—provides a finer measurement of the air pressure after it has passed through the air ductor.
- Unimixer—mixes the air and fuel using venturi mixing principle to create a suction of the fuel using the incoming air.
- Air/fuel ratio valve—sets the air/fuel ratio that the Unimixer is drawing to the burner.
- Gas Zero Pressure Regulator—sets the incoming propane gas to zero gauge pressure so that the gas after the zero pressure regulator can be draw in easily by the air

running in the mixer. The zero pressure regulator also prevents any back flow of the gas if the air pressure is too high.

- T Ribbon Burner—A T-shaped burner with stainless steel ribbon ports which allow an evenly distributed and stable flame over the width of the burner.

ii. PDMS Feeding System Design

The main objective in designing the PDMS feeding system is to utilize a simple mechanism that allows control of the speed in which the PDMS sample passes under the flame, and the distance between the PDMS sample and the flame. The PDMS feeding system is shown in Fig. 3. The complete system fits into a 30 in.x12 in x 16 in volume to allow experiments have to be carried out in a fume hood for flame safety.

The PDMS sample rests on a cantilever fixture which allows it to move under the flame. The 24V DC Gear motor was selected based on the speed and torque requirement of the system. The speed requirement of the motor was based on the conventional dwell time of the flame treatment used for polyolefins in industry [9]. The speed and torque requirement are listed in Table II. Because of the low angular velocities required, a gear motor was chosen. The large torque levels that a gear motor supplies renders the torque requirement inconsequential.

TABLE II: MOTOR SPECIFICATIONS

	Angular Velocity, ω (RPM)	Torque, τ (lbf · in.)
Motor Requirement	7.0	0.1
Motor Specification	7.4	10.94

The rotating feeding design was selected because it provides a simple mechanism to transport the PDMS sample under the flame provided that the arm of the cantilever is sufficiently long. In the designed feeding system, the linear speed variation over the width of the PDMS situated at the end of the cantilever remains within 10%. Due to the long cantilever length required for an acceptable linear speed variation, a counter weight was placed on the right hand side to balance the bending moment on the motor shaft. The speed control of the motor was achieved through a DC power supply due to the low voltage requirement of the motor.

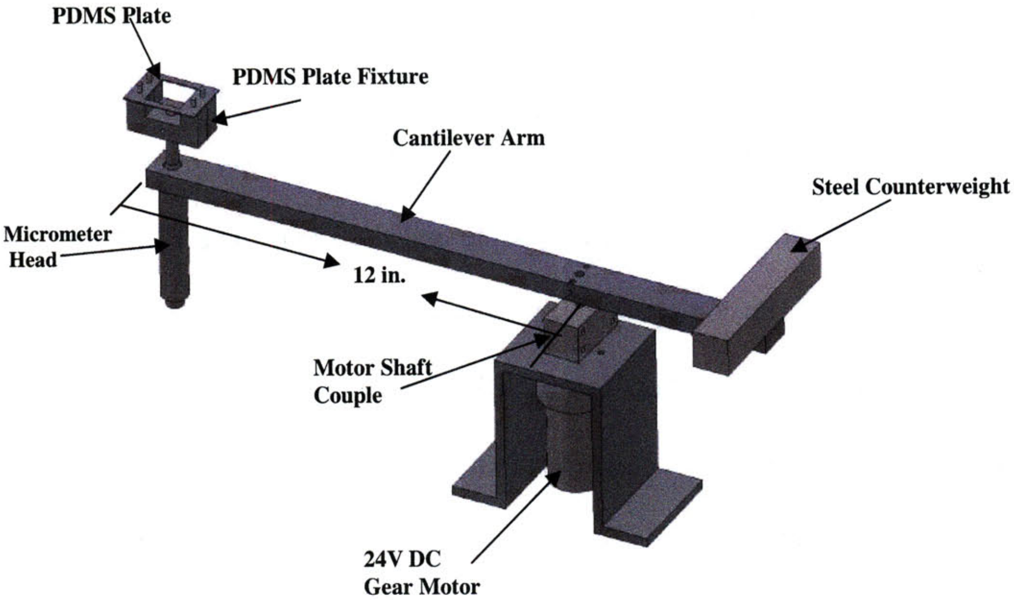


Fig 3. A solid model of the PDMS feeding system

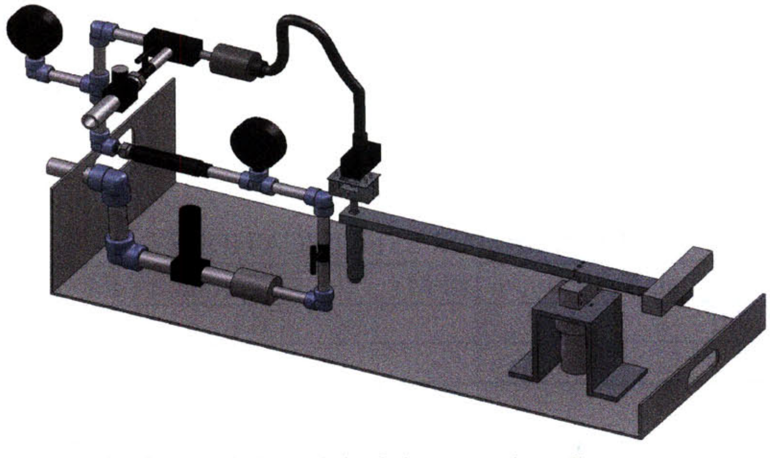


Fig 4. A solid model of the complete flame treatment system.

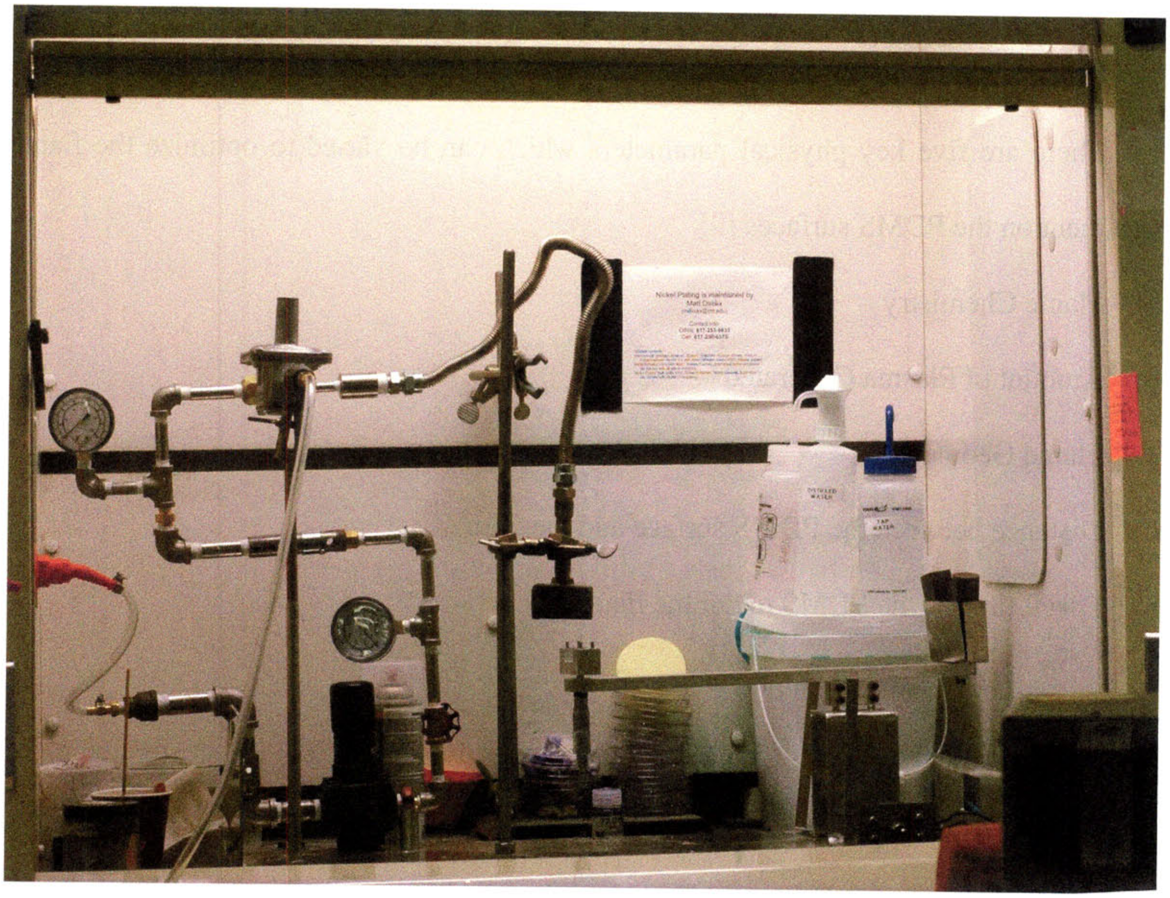


Fig. 5 The completed flame plasma treatment system in a fume hood.

Chapter III: Experimental Design

i. Experimental Parameters

There are five key physical parameters which can be varied to optimize the flame treatment on the PDMS surfaces [9].

a) Flame Chemistry

b) Amount of Plasma Generated

c) Flame Geometry

d) Distance between the PDMS surface and the flame

e) Dwell time of the PDMS under the flame

a) Flame Chemistry

The flame chemistry is determined by the air/fuel ratio. For flame treatment of polyolefins in industry, natural gas, LPG, butane, and propane are commonly used. In this experimental design, propane will be used as the fuel. The following equation describes the combustion reaction of propane:

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O + heat$$

For propane, a stoichiometric ratio is approximately 15:1. In order to optimize the flame treatment on the PDMS surface, an air/fuel ratio higher than the stoichiometric ratio is required to generate excess oxygen molecules and ions. For propane, the air/fuel ratio which provides the optimal flame geometry is around 20:1 [9]. It is important to control the air/fuel ratio based on the mass flow of the air and the fuel rather than the volumetric flow because the volumetric air/fuel ratio does not take into account the O_2 concentration in the room air. Since the air used for combustion consists of 35% compressed air and 65% room air supplied by the air ductor, the humidity and the temperature of room air will have a large effect flame plasma generation. As a result, the optimal air/fuel ratio may vary from day to day depending on the air humidity and temperature. In this flame treatment system, the air/fuel ratio is controlled by the air/fuel ratio valve. Ideally, a precise control of air/fuel ratio of the flame treatment requires a feedback system which measures the O_2 concentration in the air at a given humidity level and temperature. For the purpose of this investigation, a feedback system is too complex to implement. As a result, the flame treatment system does not provide offer a way to quantify the air/fuel ratio.

b) Amount of Plasma Generated

The amount of plasma generated from the flame is controlled in this flame treatment through the Air Needle Valve. The Air Needle valve adjusts the amount of air flow through the air ductor, air/fuel mixer, and the burner. The high volume of air leads to more fuel drawn into air/fuel mixer and burner, and consequently a higher flame plasma output.

c) Flame Geometry

In order to ensure a uniform treatment of the surface, the plasma must be generated from the burner without discontinuity. The T-burner has stainless steel "ribbons" as shown in Fig 6 which allows uniform flame geometry.

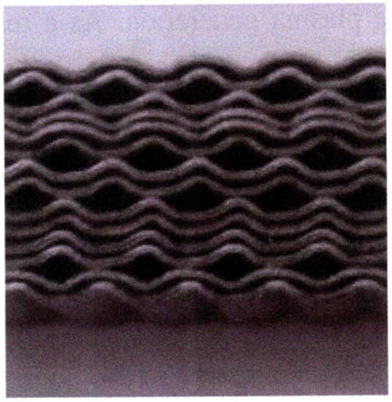


Fig. 6. The stainless steel "ribbons" in the T-burner.

d) Distance between the Flame and the PDMS Surface

This is one of the two main parameters that are optimized in this investigation. A typical flame consists of two main sections: the inner flame cone and the outer flame tail. The flame from the T-burner in this flame treatment system is shown in Fig 7. The inner flame cone in this flame treatment system is around 1/10''-1/4''and the outer flame tail is around 3'', both depend on the firing rate of the burner; Studies done by the flame treatment of polyolefins in industry reported an optimum distance from the flame inner cone to the substrate surface to be between 3/8'' -1/2'' [9]. This means that the PDMS surfaces are treated within the tail of the flame. The flame treatment section of the flame will extend until approximate 1.5 inches away from the inner cone. The PDMS surface should never come within the inner flame cone because it is a sub-stoichiometric zone of the flame at temperatures around 2000 K and cause damage the PDMS surface. In this experiment, the distance between the flame and the PDMS surface is control through the micrometer head.

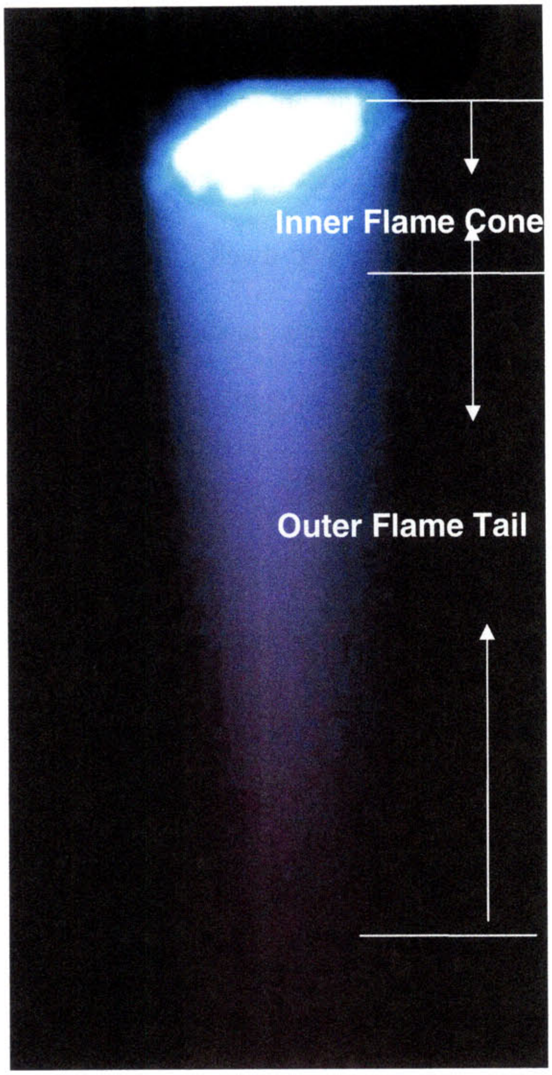


Fig 7. A picture of the flame taken with Nikon 50mm lens in front of the burner. The geometries of the flame are labeled.

e) Dwell time of the PDMS under the flame

This is the other parameter optimized in this investigation. The PDMS surface must be exposed to the flame plasma long enough to allow oxidation of the surface. Meanwhile, over exposure inside the flame plasma will reverse the oxidation effect potentially through reactions between the polar hydroxyl groups on the PDMS surface and the other ions in the plasma. The dwell time of the PDMS surface in the flame plasma is controlled through the speed which the PDMS sample travels under the burner.

ii. Surface Tension Measurement

Contact angle measurement is an ideal method for characterizing the surface energy and wettability of the PDMS surface. The treatment levels of the PDMS surface with varying distance from the flame and dwell time were measured using a probe fluid with a surface tension of 72 dyne (close to the surface tension of water). The probe liquid contains around 3.6% Formamide and 96.4% distilled, deionized water by volume. The probe liquid was chosen because of its dark violet color which allows better images of the droplet to be captured for contact angle measurement. A controlled amount of the probe liquid using a pipettor was placed onto the treated PDMS surface within 5 minutes of the flame treatment. A camera equipped with a micro-lens was placed at the same level as the PDMS to capture the contact angle between the probe liquid and the PDMS surface. The static contact angle is governed by its free surface energy. The fundamental equations relating contact angle to the surface energy is described by the Yong's equation [4]. An example of a contact angle measurement is illustrated in Fig 8.

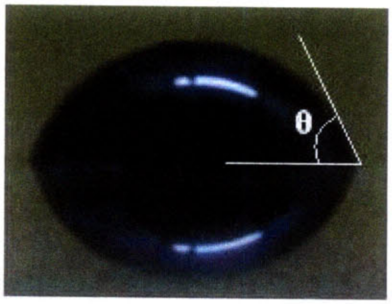


Fig 8. An example of a contact angle measurement on a drop of liquid.

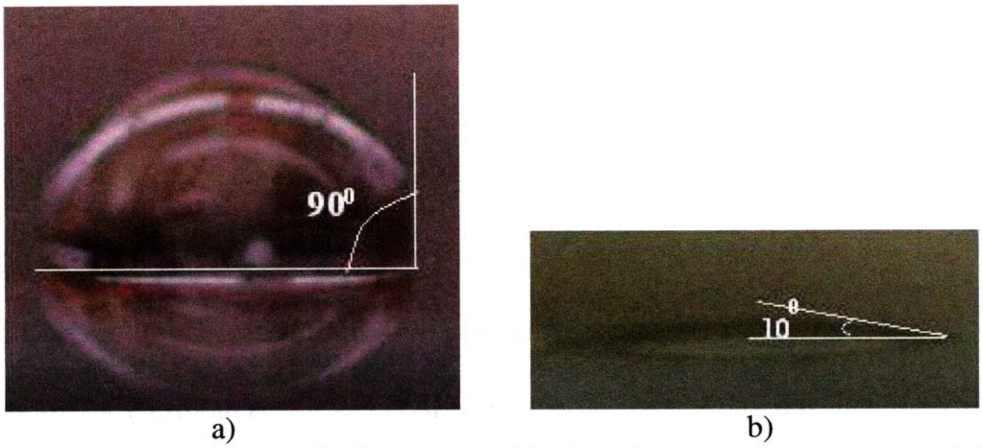
Chapter IV: Results & Discussion

This section will present results and discuss the following investigations using the flame plasma treatment:

i. Surface wetting tests with water
ii. Effect of the distance between the flame and PDMS, and dwell time
iii. Flame plasma treatment spatial uniformity
iv. Contact angle recovery over time

i. Initial Surface Wettability Tests with Water

Initial contact angle measurements were performed with distilled water as the probe liquid to assess the wettability of the flame plasma treated surface. Fig. 9 shows two images of a water drop on an untreated and treated PDMS surface. The contact angled measured before the treatment was around 90^0, and after the flame treatment at 0.4 in away from the flame inner cone with a dwell time of 0.18 seconds, the contact angle between the water and the PDMS surface decreased to approximately 10^0.



a) b)

Fig 9. Images of tests with distilled water. a) Before flame plasma treatment b) After flame plasma treatment

ii. Effect of distance between flame and the PDMS and dwell time

After the initial contact angle observations using water as the probe liquid, experiments using different combinations of distances from the flame and dwell times were performed on PDMS surfaces. A dark purple 72 dyne surface tension liquid was used as the probe liquid instead of water because it was easier to capture the profile of the liquid drop using the dark purple liquid. Intuitively, there would be a number of combinations of distance and dwell time which give optimum results because the concentration of flame plasma decreases as the surface moves further away from the flame inner cone (see the experimental chapter). An experimental setup that was farther away from the flame and exposed in the plasma for a longer dwell time could provide the same level of treatment as a setup that was closer to the flame and exposed in the plasma for a shorter dwell time. The relationship between contact angle and the dwell time at a given distance is illustrated in Fig. 10. The results in Fig. 10 demonstrate the optimal contact angle was achieved in different combinations of dwell time and distance from the flame. The increase in distance effectively shifted the contact angle vs. Dwell time curve to the right. The shift implied that at a distance further away from the flame, a longer dwell time was needed to achieve the same minimum contact angle.

In Fig. 10, the contact angle vs. dwell time relation demonstrated a slanted v-shape where there was steep decrease to the left of the minimum contact angle. This behavior resembled the existence of a flame plasma exposure threshold where once the threshold exposure was achieved, the surface properties of the PDMS was modified instantaneously; hence the measurement contact angle decreased sharply. At long dwell times, (after the dwell time corresponding to the minimum contact angle), over-exposure in the flame plasma increased the measured contact angle. The effect of over-exposure was also found in oxygen plasma treatments [10]. The similar behavior observed between the flame plasma and the oxygen plasma was reasonable because both plasmas used excess oxygen ions to modify the PDMS surface. Studies on PDMS wettability using Scanning Electron Microscopy (SEM) conducted by Owen and Smith suggested that the oxygen plasma created a brittle silica layer on the PDMS surface which could develop micro-cracks on the surface under over-exposure in the plasma [11]. Potentially the increase in contact angle due to over-exposure in the flame plasma was caused by similar observations suggested by Owens and Smith. This hypothesis can be verified with detailed studies of the PDMS surface treated with flame plasma using SEM. This could be a potential future study on flame plasma treatment in order to gain better understanding of the process.

Fig. 10 also showed more fluctuations in the measured contact angles for a distance that was further away from the flame (distance from flame is 1.24 in, black curve with diamond markers) than the contact angles measured from a surface treated at a closer distance (the distance was 0.41 in. blue curve with dot marker). The fluctuations were mainly caused by the flickering of the flame tail due to the turbulent ventilation in the fume hood. The magnitude of the flame movement was highest at the end of the flame tail. The contact angle measured would contain less fluctuation if the experiments were carried out in a static environment.

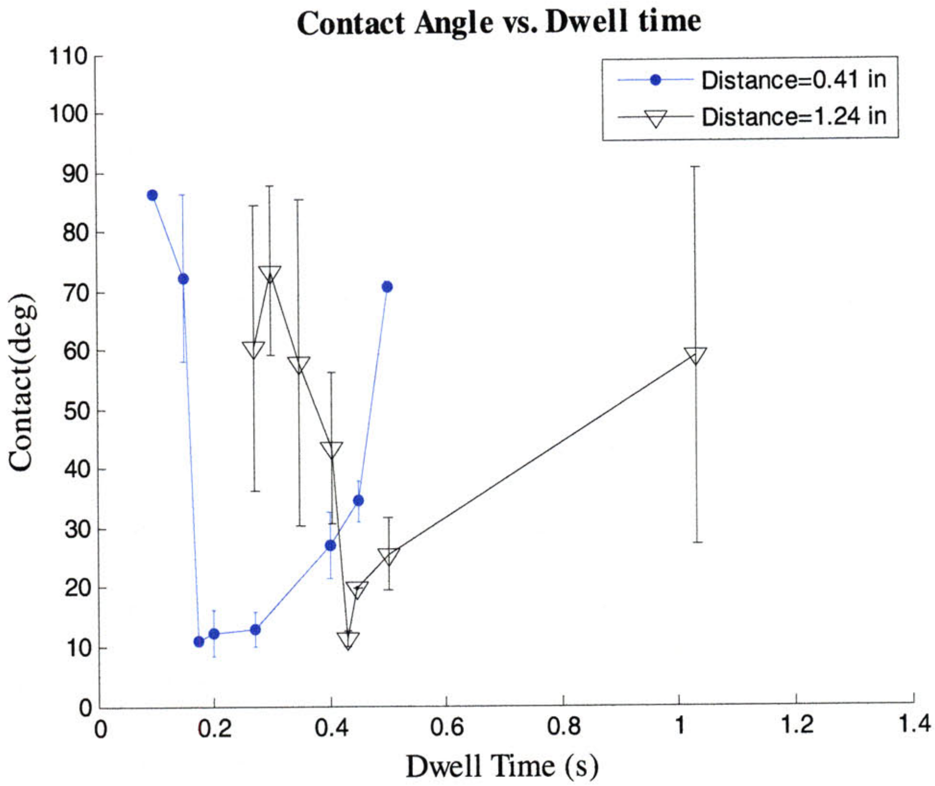


Fig 10. Contact angle vs. the dwell time of the PDMS surface under the flame.

Fig. 10 suggests that there are numerous combinations of dwell time and distance from the flame which gives a wettable PDMS surface. The contact angle measurement is a characterization of the effect of the flame plasma treatment. The total effect of the flame plasma treatment can be expressed in the following integral,

$$Treatment = \int I \cdot dt \quad (1)$$

where *I* is the intensity of the flame plasma treatment, which is a function of the distance from the flame, and *t* is time.

Assuming an inverse relationship between intensity, *I,* and the distance from the flame, *D*, approximating *dt* with the dwell time under the flame, $t_{d.}$ The minimum contact angles achieved using both distances 0.41 in. and 1.24 in. should experienced approximately equal treatment under the flame plasma. Eq. (1) in discrete time form becomes,

$$Treatment = \frac{t_d}{D} \qquad (2)$$

Using Eq. (2) and equate the treatment at the minimum contact angle at the two distances, the two curves can be normalized by,

$$\frac{t_{d0.41}}{t_{d1.24}} = \frac{D_{0.41}}{D_{1.24}} = C \qquad (3)$$

where *C* is a characteristic constant of the flame plasma.

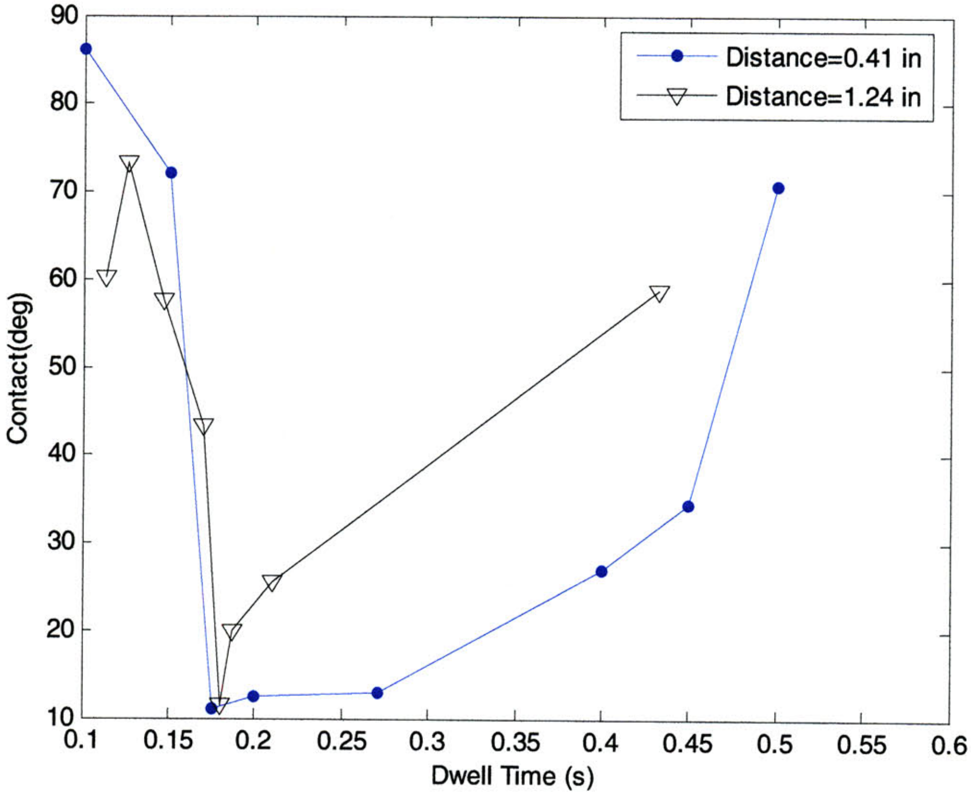


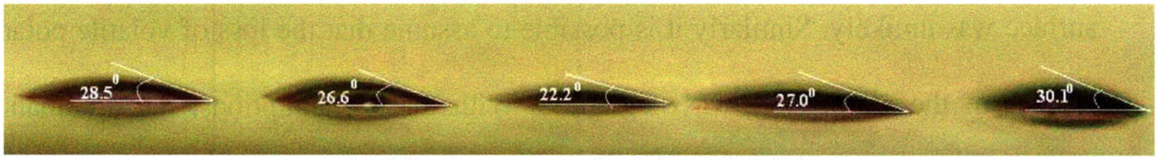
Fig. 11: Normalized the curve of 1.24 in. and the two curves nearly coincide into one curve.

Normalizing the curve at 1.24in with *C*, and leaving the curve at 0.41 in unchanged, the two curves collapsed almost into one curve shown in Fig. 11. This suggests that the intensity of the flame plasma is closely related to the inverse of the distance from the flame and the modeled above can be used to characterize the effect of the flame plasma treatment.

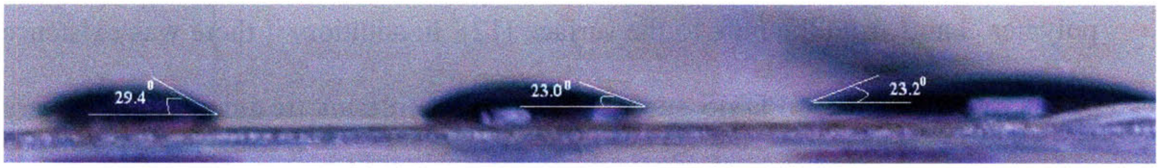
In summary, the flame plasma treatment had demonstrated modification of the PDMS surface in a fraction of second. The flame plasma embodied under-exposure and over-exposure characteristics similar to oxygen plasma: underexposure and overexposure in the flame plasma led to high contact angles. The flame plasma treatment can be well characterized by the inverse of the distance from the flame and the dwell time.

iii. Flame Plasma Treatment Spatial Uniformity

The uniformity of the flame plasma treatments over a 1.5in x 1in PDMS surface was investigated. The PDMS surface was treated at a distance of 1.24 in away from the flame inner cone for 0.42 seconds. The droplet shape and contact angle measurements across the length and width of the PDMS sample are shown in Fig. 12 and Table III. The variations between different locations on the surface were within maximum of 7^0 from each other. This indicated that the entire surface was treated thoroughly. It is important to ensure that the burner is wider than the width of the PDMS.



a) Measurements along length 1.5 in



b) Measurements along width: 1 in

Fig. 12: Contact angle images and measurements along the length and width of a PDMS surface treated at d=1.24 in, t_D=0.43s. a) Length; b) Width

TABLE III: SURFACE TREATMENT UNIFORMITY MEASUREMENT

Mean Contact Angle Measurements Along Length	$26.1^0 \pm 2.7^0$
Mean Contact Angle Measurements Along Width	$25.2^0 \pm 3.6^0$

iv. Contact Angle Recovery Over Time

The recovery of PDMS surface wettability treated with flame plasma was investigated in this section. A series of contact angle measurements were performed at different times on a surface treated at a distance of 1.24 in from the flame for 0.43 second. At each measurement, the probe liquid was placed on a different location on the surface to obtain contact angle measurement. The uniformity study above showed consistency of contact angle measurements within 7^0 provided a basis for this measurement. The variation of contact angle over time is illustrated in Fig 13. There are three major mechanisms where contact angle recovery occurs in an oxidized PDMS surface [11]: a) the diffusion of untreated polymer chains from the bulk to surface; b) the loss of volatile oxygen-rich or other polar entities to the atmosphere; c) external contamination of the surface. Since the flame plasma treated PDMS was kept in a Petri dish through out the experiment, so the contamination of the polymer surface was unlikely. Similarly it is possible to assume that the loss of volatile polar entities to the atmosphere was negligible. With these assumptions, the dominant contact angle recovery mechanism in this investigation was the diffusion of untreated polymer chains from the bulk to the surface [12]. In addition, if there was existence of micro-cracks on the PDMS surface due to flame plasma treatment, the recovery process would be sped up.

This hypothesis was supported by the results shown in Fig 13. There was an exponential relationship between contact angle recovery and time elapsed after treatment, which correlated to the exponential relation in diffusion between two species. Since diffusion is driven by concentration gradient, therefore initially the diffusion of the untreated polymers was much higher than later times; hence the increase in measured contact at longer time after treatment was small. In addition, the flame plasma increased the temperature of the PDMS sample, which increased the diffusion coefficient of the untreated polymer chains. As a result the flame treatment of PDMS recovered at a faster rate than oxygen plasma [12]. This conclusion contradicted what was concluded from industrial studies of flame plasma treatment on polyolefins in Table I. The contradiction could be explained through the higher mobility of untreated and uncured PDMS polymers than the polyolefins used in the industrial study. A further study of recovery time of other polyolefins is necessary to gain better understand of the mechanisms that are dominate in the flame plasma treatment of polyolefins.

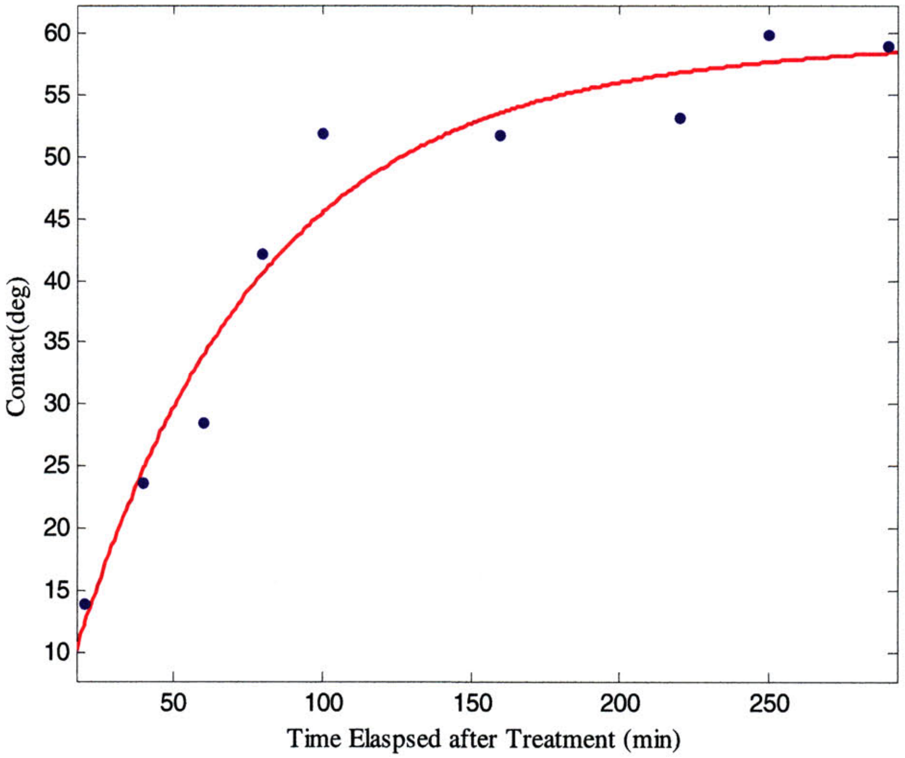


Fig 13. The recovery of contact angle over time elapsed after the treatment. An exponential curve was fitted to the data with a R^2 value of 0.95.

Chapter V: Conclusion

The flame plasma was capable of oxidizing a PDMS surface in 0.18 s to achieve a contact angle of approximately 10^0 with water. In addition, the entire surface of the PDMS was treated thoroughly provided the burner is larger than the treating surface. The flame treatment yielded an exponential relationship of the contact angle recovery over time. This study demonstrated the potential applications of flame plasma treatment for fast prototyping of PDMS microfluidic devices through a conveyor belt system. Potential future studies such as SEM characterization of the flame plasma treated surface, and an understanding of the combined effect of dwell time and distance from the flame would be beneficial to better optimize the process. The flame plasma treatment can oxidize the PDMS surface at a faster rate than the current leading PDMS surface oxidation technology. It has huge potentials to enable a fast and reliable assembly of microfluidic devices.

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References:

[1] Y. Xia, Whiteside, G. "Soft Lithography" *Annu. Rev. Material Science*, vol 28, pp. 153-184, 1998.

[2] Duff D C. Olivier J C M, Schueller J A and Whitesides GM, "Rapid prototyping of microfluidic systems in poly (dimethylsiloxane)," *Anal, Chem.* vol.70, pp. 4974-4984, 1998.

[3] J. R. Hollahan, G. L. Carlson, "Hydroxylation of polymethylsiolxane surfaces by oxidizing plasmas," *Journal of Applied Polymer Sci.* Vol 14, pp. 2499-2508, 1970.

[4] Morra, M.; Occhiello, E.; Marola, R.; Garbassi, F.; Humphrey, P.; Johnson, D., "On the aging of oxygen plasma-treated polydimethylsiloxane surfaces," *J. Colloid Interface Sci.* vol 137, no.1, 1990.

[5] M. A. Eddings, M. A. Johnson, B. K. Gale, "Determining the optimal PDMS-PDMS bonding technique for microfluidic devices," *J. Micromech. Microeng.* vol 18, 067001 (4pp), 2008.

[6] K. Haubert, T. Drier, D. Beebe, "PDMS bonding by means of a portable, low-cost corona system," *lab on a chip* DOI: 10.1039/b610567j, 2006.

[7] F. Katzenberg, "Plasma-bonding of Poly (dimethylsiloxane) to glass," *E-polymers*, no. 060, 2005.

[8] Strobel, M., Walzak, M.J., Hill, J.M., Lin, A., Karbshenski, E., Lyons, C. S., "A Comparison of Gas Phase Methods of Modifying Polymer Surfaces," *J. Adhesion Sci. Tech.* vol. 9(3):365, 1994.

[9] J. DiGiacomo, "Adhesion promotion using flame plasma surface treatment," *Flynn Burners Corporation* 2007.

[10] Bhattacharya, S., Datta, A., Berg, J., and Gangopadhyay, S. "Studies on surface wettability of poly (Dimethyl) Siloxane (PDMS) and Glass under oxygen-plasma treatment and correlation with bond strength." *J. Microelectromechanical Systems*, vol. 14, no. 3, pp. 590-597, 2005.

[11] Owen, M. and Smith, P, "Plasma treatment of polydimethylsiloxane", *J. Adhesion Sci. Tech.* vol 8. no 10. pp1063-1075, 1994.

[12] Kim, J, Chaudhury, M. , Owen, M., Orbeck, T. "The mechanisms of hydrophobic recovery of polydimethylsiloxane elastomers exposed to partial electrical discharges," *Journal of Colloid and Interface Sci.* 244, pp. 200-207, 2001.