Using a Microplasma for Propulsion in Microdevices

David Arndt
University of California, Irvine

Faculty Mentors:
Professor John LaRue, Department of Mechanical and Aerospace Engineering, UCI
Professor Richard Nelson, Department of Electrical Engineering and Computer Science, UCI

1. Abstract

It has been shown in various studies that plasma pumps can be used to create unidirectional fluid motion and even delay flow separation in fluid flows over airfoils or helicopter blades. The goal of this project is to utilize the pumping capabilities of plasma pumps at the MEMS level, in order to move air through microchannels. Eventually, photolithographic techniques will be used to create the plasma pump on a chip, but first a macro-scale plasma pump was created in order to characterize the effect on pumping velocities for different variables such as electrode geometry, dielectric thickness, and input voltage and waveform of the plasma generator. Copper tape was used for the electrodes and Kapton tape was used for a separating dielectric. The electrodes were placed in a glass channel which was then filled with smoke in order to visualize the flow produced by the plasma. Video of the smoke flow was taken for multiple electrode geometries and analyzed frame by frame to calculate rough velocities at positions along the length of the channel. The effect of dielectric material and thickness was also studied. It was found that changes in electrode width as well as small changes in dielectric thickness had no noticeable effect upon flow velocity. Control over flow direction and path was demonstrated by utilizing multiple plasma generators connected in parallel. A microplasma pump has not yet been created, but design parameters have been established based upon results obtained. Overlapping electrodes and a glass dielectric will be used due to ease of use.

2. Key Terms

Continuous flow pump, MEMS, plasma pump

3. Introduction

One very important field of current research is that which involves utilizing phenomena that occur at the micro or nano-scale. Much of this research is in the area of Micro-Electro-

Mechanical Systems, a rapidly growing field that promises to transform almost every scientific and technological discipline. Micro-Electro-Mechanical Systems, or MEMS, are interactive systems at the micro scale that implement mechanical, electrical, and possibly fluidic or optical components.

Microfluidic MEMS devices utilize micropumps to propel gases or liquids through microchannels. There are two general types of micropumps; continuous flow and reciprocating. Reciprocating micropumps contain moving mechanical parts that rotate or oscillate in order to pump a fluid, while continuous flow micropumps take advantage of chemical, thermal, or electrostatic phenomenon in order to continuously provide a force to the fluid (Woias 2005). The advantage of continuous flow micropumps is first the lack of moving parts and secondly the ability to continually displace a fluid which prevents backflow and the need for valves. A plasma pump is a continuous flow pump.

4. Background and Motivation

It has been shown by Martiqua Post et al. (Post et al. 2004a, Post 2004b, Enloe et al. 2004) that plasma created using two electrodes with a separating dielectric can be used to impart a unidirectional force onto the surrounding air. A voltage differential is created between two electrodes separated by a dielectric. The air in the vicinity of the electrodes is weakly ionized which results in a plasma discharge. The air ions move in response to the generated electric field and transfer momentum to surrounding air molecules, resulting in a body force on the ambient air. According to Post, the body force per unit volume of a plasma is the vector given by

$F_B = (\frac{-\varepsilon_0}{\lambda_D{}^2 \phi})E$ (1) where ε_0 is the permittivity of free space, λ_D is the Debye length, ϕ is the electric potential, and E is the electric field vector. $E = -\nabla \phi$ (2) which for a one dimensional force, results in $F_B = (\frac{\varepsilon_0}{2})(\nabla E^2)$ (3) (Post 2004a). Post utilized this fact to delay boundary layer separation in flows over airfoils in order to increase the angle of attack possible before stalling occurs.

This same concept has potential to be used as a micropump in a MEMS device. Potential applications for a microplasma pump include the manipulation of gas carried particles, gas sensing, and possibly MEMS cooling. Before a MEMS device is created however, it is necessary to construct a macro-scale plasma pump in order to characterize various device parameters and assess the capability of a plasma pump to control both flow direction and path. The macro-scale plasma pump will then be used as a basis for the microplasma pump although additional micro-scale phenomenon may need to be taken into consideration.

5. Experimental Setup

5.1 Power Source and Plasma Generator

The basic experimental setup used was based on the research of Martiqua L. Post and also on that of Mingye Liu in his honors undergraduate research thesis for the University of California, Irvine. The basic setup shown in Figure 1 includes a DC power source which is connected to a high voltage plasma generator. The specific plasma generator used in our experiments was the PG13 Plasma Generator made by Ramsey Electronics. According to the Ramsey Electronics website, the PG13 Plasma Generator is capable of generating up to 25 kV at 20 kHz (Ramsey Electronics). The plasma generator was connected to the covered electrode via a 100 $k\Omega$ resistor.

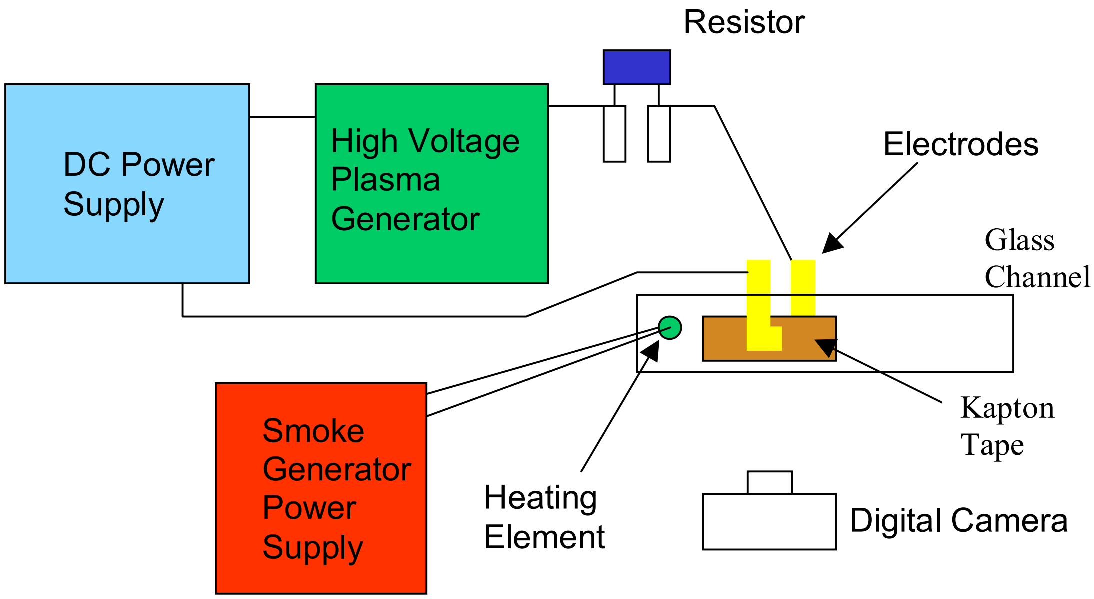

Figure 1: Basic Experimental Setup

5.2 Electrodes

The electrodes were made with copper tape. Scissors were used to round the corners of the electrodes to prevent point discharges. The covered electrode was placed on a glass microscope slide spray painted with a flat black paint. Liu used quartz plates as a base, which was tried initially, but for the majority of the research, glass slides were used because they fit easily into our channel and produced no observable negative effect upon the plasma or pumping capabilities. Over the lower electrode was placed three layers of 2 mil Kapton tape. Each layer was measured to be 3.5 mils thick including the adhesive, and had a dielectric strength of 12000 volts (Kaptontape.com). On top of the dielectric layer, the upper electrode was placed. The upper electrode was then connected to the ground terminal of the power source.

5.3 Channels

The electrode assembly was placed inside a glass channel created by super gluing glass microscope slides together. The electrodes inside the glass channel are shown in Figure 2. The channel is approximately .55 inches tall, 3 inches long and 1 inch wide.

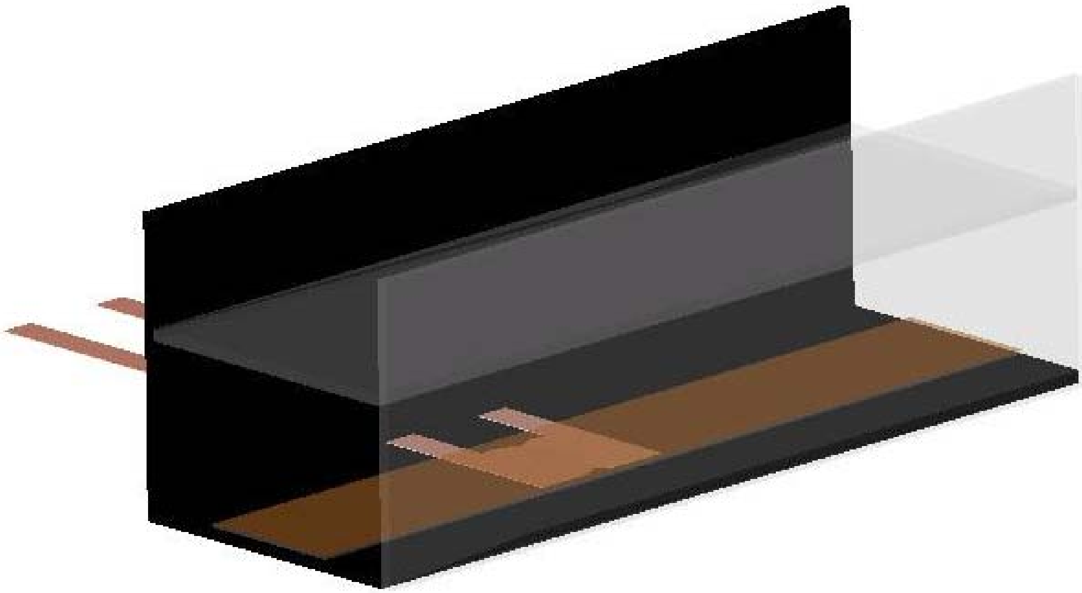

Figure 2: Solidworks model of the electrode-channel assembly.

A smaller channel measuring 2 mm tall, 2 mm wide, and 3 inches long was also created in order to get closer to the micro-scale while still being able to use the same materials and methods that were used for the larger channel. Top view and side view channels were created and it was found that side view channels generally were easier to visualize the smoke flow. The smaller channel is shown in Figure 3 below.

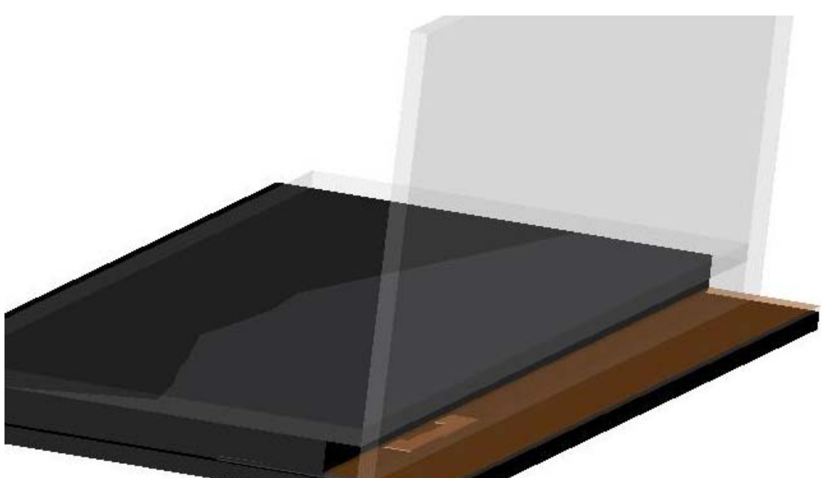

Figure 3: Side-view millimeter scale channel.

For demonstration of flow path control, a bifurcating Y shaped channel was also created using 3 of the larger scale channels. A picture of the channel is shown below in Figure 4. The schematic for the bifurcating channel is shown in Figure 5.

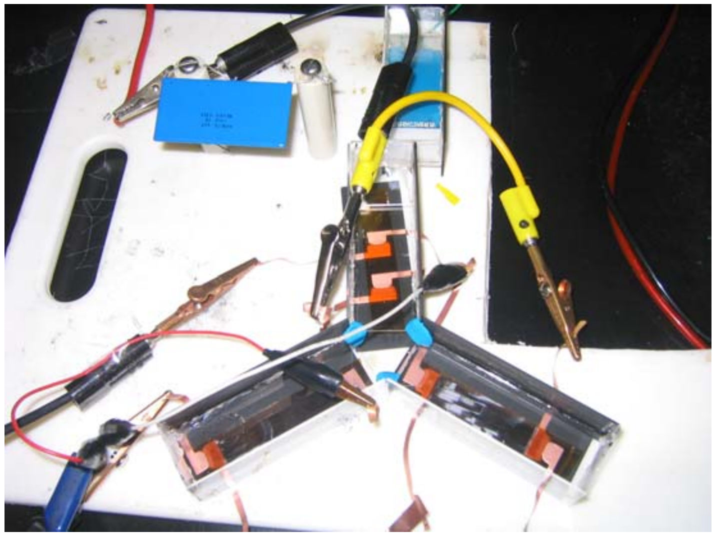

Figure 4: Bifurcating Y channel.

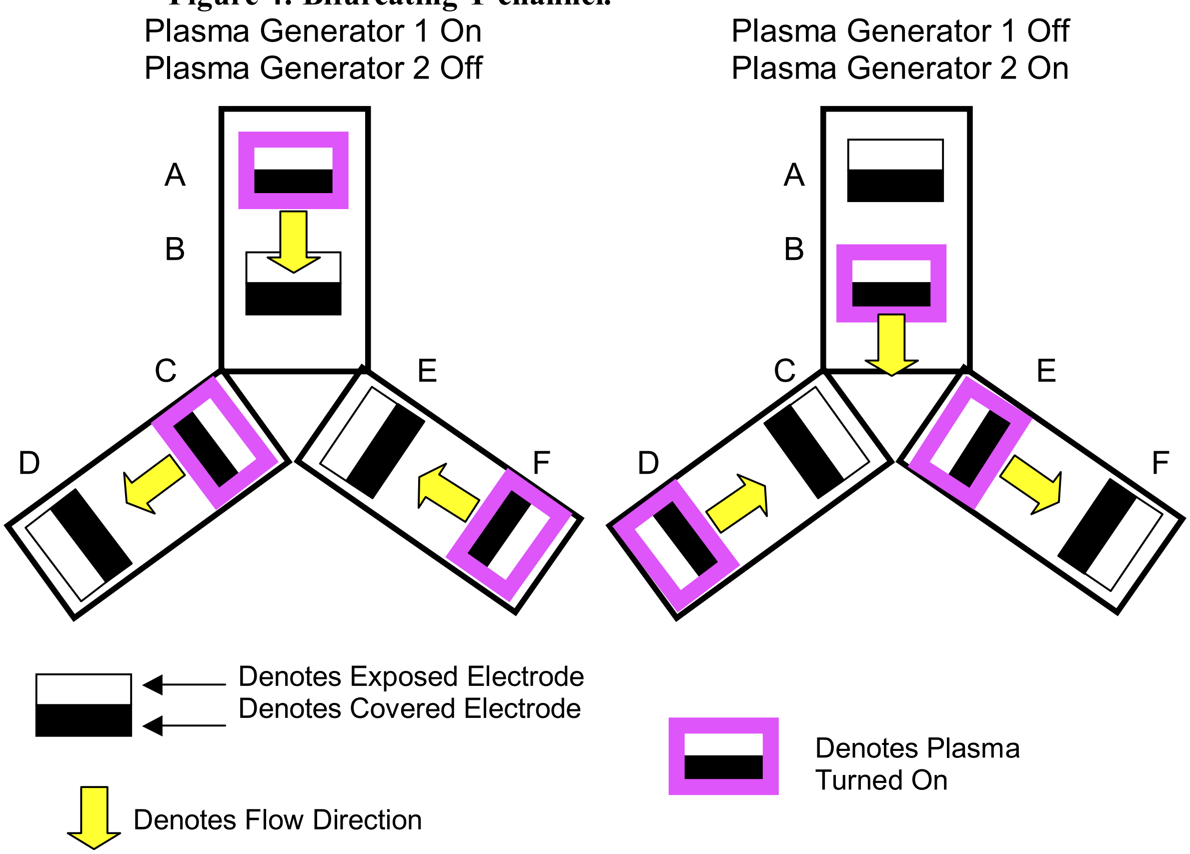

Figure 5: Bifurcating channel schematic

The bifurcating channel setup utilizes 6 pairs of electrodes in order to completely control flow path. Electrodes A, C, and F are connected to one plasma generator, while electrodes B, D, and E are connected to a second plasma generator.

5.4 Flow Visualization

To visualize the flow produced, a smoke source of some kind was needed. Many different options were considered including commercial smoke generators and also burning mineral oil, incense, or cigarettes. A commercial smoke generator was not used both because of the cost and also because of the huge quantities of smoke they are designed to produce. Cigarettes were not used because of legal implications in the lab as well as health risks. Mineral oil and incense both produced smoke, but neither were substantially more advantageous than the method that Liu had stumbled upon; burning Play-Doh. Play-Doh is easy to handle and produced a white wispy smoke.

To burn the Play-Doh, a smoke generator apparatus was constructed. A resistive steel wire was soldered to two wires leads which were then attached to a power source. Turning up the voltage on the power source resistively heated the wire which burnt the Play-Doh, producing smoke which was captured in a separate glass chamber before diffusing into the glass visualization channel. A separate chamber was needed because the process of burning Play-Doh creates condensation which can disrupt plasma generation, possibly due to a short being created. A handheld digital camera was used to record video of the smoke flow.

6. Experimental Procedure

6.1: Smoke and Plasma Generation

Throughout the research, the experimental procedure was kept roughly the same. First the electrode arrangement was attached to the plasma generator and ground as described in the preceding section. Then a small piece of Play-Doh was attached to the heating wire and the smoke generator assembly was placed inside the smoke generation chamber which was then sealed off using Play-Doh in order to prevent interference from outside air currents as well as prevent smoke leakage. The smoke generation chamber was then attached to the visualization channel and any remaining openings were sealed with Play-Doh. A picture of a sealed millimeter size channel is shown below in Figure 6. Also, the smoke generator wire leads were connected to the smoke generator power source.

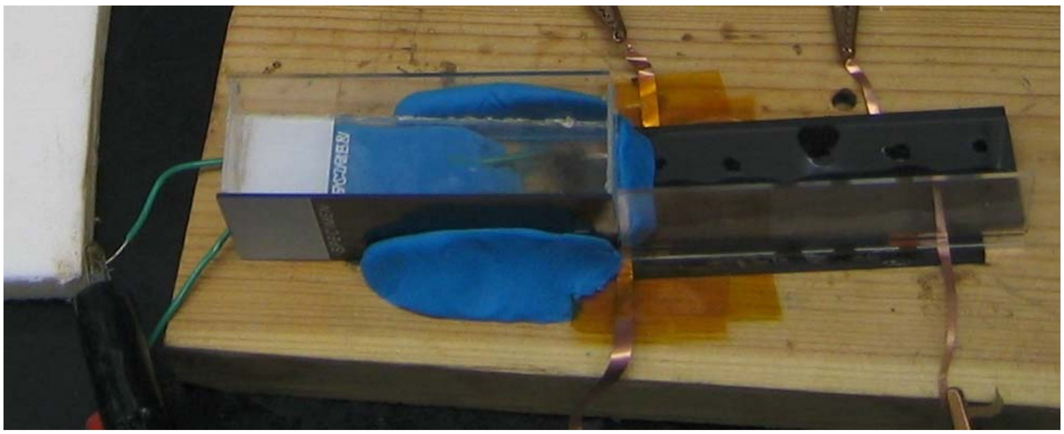

Figure 6: Smoke generation chamber attached to millimeter scale visualization channel and sealed with Play-Doh

After the assembly was set up, the smoke generator power source was turned on and the voltage was turned up until the heating element was sufficiently hot to burn the Play-Doh. This was generally at around 2 V. If the voltage is turned up too high, the heating element may break. Then, the plasma generator kit was switched on and the power supply was switched on. After some smoke collected in the visualization channel, the voltage on the power supply was turned up until the breakdown voltage was reached, at which point, plasma is generated and flow is produced. It is important to note that flow is produced in the direction from the exposed electrode towards the covered electrode. For most of our experiments the breakdown voltage was 6 V, but when multiple plasma generators were hooked up in parallel to the power supply and the current limiting resistor was removed, the breakdown voltage was generally 4 V. After initial plasma generation, it is possible to turn down the voltage while still maintaining the plasma, but for our experiments we kept the power supply at the breakdown voltage throughout the experiments.

6.2: Velocity Measurements

In order to measure flow velocity, a paper ruler was taped to the side of the visualization channel. The digital camera was placed on the lab counter and focused. Video of the flow was recorded and transferred to a computer. Using a program called VirtualDub the video was analyzed frame by frame. The velocity at various horizontal positions was obtained by calculating the distance traveled by a smoke wisp or front between frames and then dividing by the time per frame. In our case, the camera recorded video at 15 frames per second. The velocity data for each configuration was then plotted in Microsoft Excel in order to determine the effect of changing various experiment parameters.

A more precise method of measuring flow velocity would have been to utilize a particle image velocimetry system as is described in the literature (Post 2004b). We lacked such equipment, but the frame by frame method was sufficient to get a general idea of the flow velocities in the produced flow and evaluate the effect of various experimental parameters.

6.3: Problems and Difficulties

One of the most frequent problems that were encountered was one in which no plasma was generated when the voltage on the power supply was increased up to and even beyond the normal breakdown voltage. This problem seemed to occur when a lot of smoke was allowed to collect above the electrodes for a long enough amount of time. It was hypothesized that moisture in the smoke may have created a short so that a sufficient voltage differential was not able to be created. To solve this problem, different smoke sources were considered as is described in the Experimental Setup section, but alternate sources failed to produce satisfactory smoke.

Another way to avoid the problem was to simply not allow too much smoke to collect above the electrodes. To do this, the plasma generator switch was turned on for a short period, turned off for a short period, and then turned on for a short period. This was continued in order to see the effect of the plasma upon the smoke without letting too much smoke collect above the electrodes.

7. Results

7.1 Electrode Geometry

The effect of varying the width of the exposed electrode was studied for upper electrode widths ranging from 3 mm to 12 mm while holding the covered electrode constant at a width of 9 mm. It was found that even the drastic width difference between a 3 mm wide top electrode and a 12 mm wide top electrode resulted in velocity distributions that were not significantly different as shown in Figure 7 below. The horizontal position is the displacement from the center of the electrodes.

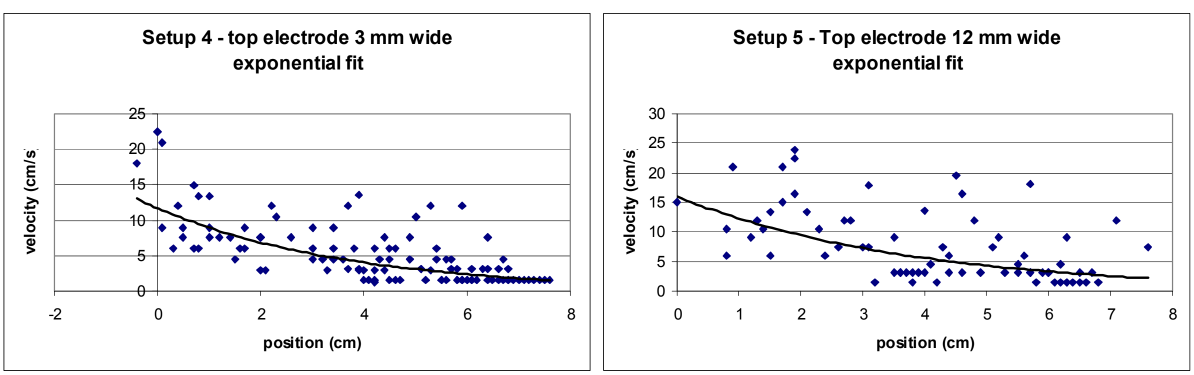

Figure 7: Plots of velocity vs. horizontal position in channel for a top electrode width of 3 mm and 12 mm.

7.2 Electrode Overlap

The effect of having overlapping electrodes rather than a gap was also studied. Electrode widths were held constant at 20 mm for both the top and bottom electrode. Velocity measurements were taken for a 1mm gap, a 1mm overlap, and a 3 mm overlap. Insufficient data was taken for the 1 mm gap and the 1 mm overlap configurations, although the data that was taken was in the bounds of previous velocity measurements. Sufficient data was taken for the 3 mm overlap configurations, and the plot is shown below in Figure 8.

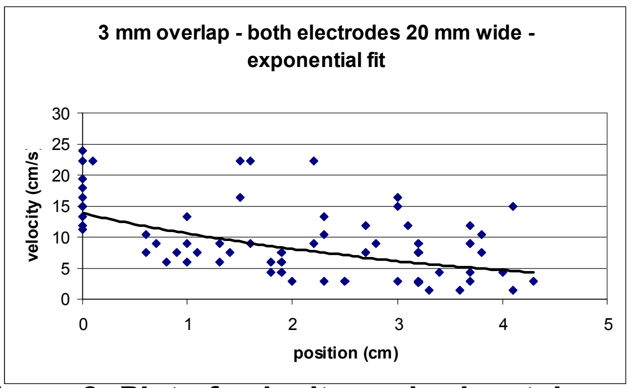

Figure 8: Plot of velocity vs. horizontal position for an electrode overlap of 3 mm.

7.3 Dielectric Experimentation

In addition to electrode width and overlap, the effect of dielectric thickness and material was studied. In all previous experiments, 3 layers of Kapton tape were used, but 1 layer was used to see if the flow was any different. Shown below in Figure 9 is a plot comparing 3 layers of Kapton to tape to just 1 layer of Kapton tape. With only 1 layer of Kapton tape, the plasma started burning through the Kapton tape after only a short period of time.

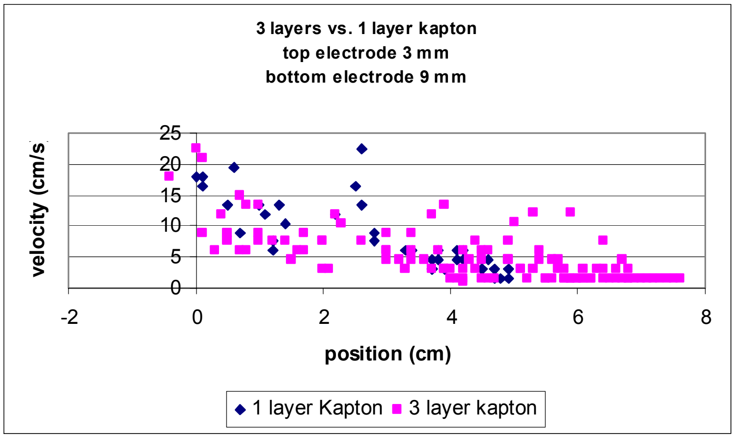

Figure 9: Plot of velocity vs. horizontal position for 3 layers and 1 layer of Kapton tape.

In addition to Kapton tape, plasma generation was tried with 6 mil slide cover glass as the dielectric. The flow that was produced looked identical to that produced with the Kapton tape configuration, but no data was taken. The glass slide cover suffered no noticeable damage.

7.4 Direction and Path Control

After experimentation concerning experimental parameters was completed, it was desired to demonstrate the capability of a plasma pump array at the macro-scale in order to display its potential at the micro-scale in a MEMS device. Two plasma generators were connected in parallel in order to independently control electrode sets. The millimeter scale channel shown in Figure 3 was used for the direction experiment. Two pairs of electrodes were placed inside the channel in such a way that they pumped in opposite directions. First the left most electrode pair was turned on, propelling the smoke towards the right electrode pair. Then, the left electrode pair was turned off at the same instant that the right electrode pair was turned on, which reversed the direction of smoke back towards the left hand electrode pair.

Next, it was demonstrated that in a split channel such as the one shown in Figure 4, a plasma pump array can be used to completely control the path taken by the flow produced. Smoke was introduced in the channel at the top of Figure 4. A total of six pairs of electrodes can be seen in Figure 4. The original plan was to use two plasma generators attached to 3 electrode pairs each to control the flow path. A schematic of the original plan is shown in Figure 5. This plan would definitely work in theory, but problems were encountered wiring all the electrodes. All the electrode sets could not consistently be turned on and this was thought to be because of a short in the circuit somewhere due to the number of exposed alligator clip wires that were used to connect the copper tape electrodes to the plasma generator and ground. The problem was investigated but ultimately the experiment setup was simplified in order to get meaningful results. For the simplified experiment, only electrode pairs A, C, and E were used. Electrode pair A was controlled by one plasma generator while the second plasma generator was connected first to electrode pair C to produce flow in the left branch of the channel and then manually disconnected from electrode pair C and connected to electrode pair E in order to produce flow in the right branch of the channel. It was observed that all smoke flow occurred in the channel branch with the activated electrode pair.

8. Discussion

The results obtained in this experimentation on a macro-scale plasma pump can serve as a basis for further research in plasma pump technology, particularly future work done on microplasma pumps for use in MEMS devices. Varying the electrode width as well as using an overlap versus a gap seemed to have little to no effect upon the flow velocity. This is promising for a microplasma pump because the electrodes would have to have widths on the order of a few microns. It also means that because the amount of overlap or gap does not seem to be critical, the overlap or gap can be tailored to the specific desired geometry or manufacturing procedure if necessary. For a plasma pump, it was found that Kapton tape works well as a dielectric, but it may not be suitable for a MEMS device, in which case it may be better to use glass as a dielectric. Further experimentation can also be done upon other experiment parameters such as the voltage output by the plasma generator as well as the signal’s waveform. This project did not experiment upon these parameters because there was no access to a high voltage probe at the time.

In addition to parameter experimentation, it was also demonstrated that an array of plasma pumps can be independently controlled in order to control both the path and direction of airflow. In a MEMS device with multiple channels and branches, a plasma pump array would be able to effectively pump air to any part of the device.

A plasma pump could be incorporated into a MEMS device by using MEMS fabrication and processing techniques. Metallic electrodes could be deposited using electron beam vacuum deposition and photolithographic patterning. A channel could be formed multiple ways, one of which is casting a silicone material that can be patterned with UV light using a mask. For visualization, smoke could be introduced via a syringe, or possibly created internally. Also, it may be possible to utilize a micro particle image velocimetry system in order to document the flow velocity.

9. Acknowledgements

Project direction:

Professors John LaRue and Richard Nelson

Technical expertise and advice:

Allen Kine and George Horansky

Research Team:

Eric Cheung, Michael Peng, and Patrick Nguyen Huu

10. Works Cited

Enloe, C.L., McLaughlin, Thomas E., VanDyken, Robert D., Kachner, K.D., Jumper, Eric J., Corke, Thomas C., Post, M., and Haddad, O. "Mechanisms and Responses of a Single Dielectric Barrier Plasma Actuator: Geometric Effects." AIAA Journal 42.3 (2004): 595-604

Kaptontape.com. http://www.kaptontape.com/tech_pages/2mil_polyimide_sheets.php

Liu, Mingye. "Plasma Pump for MEMS." Honors Undergraduate Thesis for University of California, Irvine. (2006)

Post, Martiqua L. and Corke, Thomas C. "Separation Control on High Angle of Attack Airfoil Using Plasma Actuators." AIAA Journal 42.11 (2004a): 2177-2184.

Post, Martiqua L. "Plasma Actuators for Separation Control on Stationary and Oscillating Airfoils." PhD Dissertation for the University of Notre Dame. (2004b)

Ramsey Electronics. http://www.ramseyelectronics.com/cgi-bin/commerce.exe?preadd=action&key=PG13

Woias, Peter. "Micropumps—past, progress and future prospects." Sensors and Actuators B.105 (2005): 28-38.