STUDY OF A NOVEL IONIZER CONFIGURATION FOR THE ION THRUSTER

by

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December 2006

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Micro-satellites often require the adaptation of existing propulsion systems. Electric propulsion thrusters are perhaps the best candidates to meet these needs and ion engines are among the most scalable. Miniaturizing the ion engine will require novel concepts for the ionizer with perhaps novel propellants. MEMS, nanotechnology and other technological advances are expected to impact on new designs.

Our work shows that the ionization of Argon, which is an alternate fuel to Xenon, can be achieved at low voltages by utilizing Micro-Structured Electrode (MSE) Arrays. Copper-clad sheets separated by a dielectric material (fiberglass laminate epoxy resin system combined with a glass fabric substrate) of varying thickness (0.1 mm to 0.4 mm) form the discharge electrodes in the MSE arrays. The wafers are drilled with an array of holes and this geometry serves to concentrate the electric field between electrodes enhancing electron emission at the cathode. Minimum breakdown voltages between 240 and 280 Volts at pressures of around 100 mTorr (0.133N/m²) were consistently obtained with arrays of hole diameter ranging from 300 to 500µm. These results are consistent with conventional Paschen-curves with two empirical constants that arise from our unconventional geometrical arrangements and from the different material properties.
STUDY OF A NOVEL IONIZER CONFIGURATION FOR ION THRUSTERS

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Lieutenant, United States Navy
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Chairman, Department of Mechanical and Astronautical Engineering
ABSTRACT

Micro-satellites often require the adaptation of existing propulsion systems. Electric propulsion thrusters are perhaps the best candidates to meet these needs and ion engines are among the most scalable. Miniaturizing the ion engine will require novel concepts for the ionizer with perhaps novel propellants. MEMS, nanotechnology and other technological advances are expected to impact on new designs.

Our work shows that the ionization of Argon, which is an alternate fuel to Xenon, can be achieved at low voltages by utilizing Micro-Structured Electrode (MSE) Arrays. Copper-clad sheets separated by a dielectric material (fiberglass laminate epoxy resin system combined with a glass fabric substrate) of varying thickness (0.1 mm to 0.4 mm) form the discharge electrodes in the MSE arrays. The wafers are drilled with an array of holes and this geometry serves to concentrate the electric field between electrodes enhancing electron emission at the cathode. Minimum breakdown voltages between 240 and 280 Volts at pressures of around 100 mTorr (0.133N/m²) were consistently obtained with arrays of hole diameter ranging from 300 to 500µm. These results are consistent with conventional Paschen-curves with two empirical constants that arise from our unconventional geometrical arrangements and from the different material properties.
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I. INTRODUCTION

A. ION ENGINE HISTORY

The theories behind ion engines have been attributed to the German scientist Dr. Wernher von Braun during the 1930s. At this time, the German military was more interested in weapons of war than interplanetary rockets, so his theories remained untested until the end of World War II, when he and hundreds of fellow scientists were brought to the United States. Once in the US, they were able to develop their theories enough that in 1958, the Army Ballistic Missile Agency initiated a contract with Electro-Optical Systems to study ion propulsion. The result of this was a 0.1 pound-thrust engine developed by Hughes Research Laboratory before it stopped due to the Apollo program [8, 9].

In the early 1990s, the NASA Solar Electric Power Technology Applications Readiness project revived the Hughes ion thruster. This project began to study the idea of using a Xenon propellant within an ion engine. In 1996 one such engine was built and fired for over 8000 hours, making the test a success. Deep Space I was a small space craft that was launched onboard a small Delta II rocket from Cape Canaveral Air Station, Florida on October 24, 1998. The propulsion system managed to propel the craft at a rate where it could sometimes travel at 750,000 miles per day. After the scheduled end of the test, the mission was extended for the opportunity to fly close to the comet Borrelly, and take some of the best pictures to date [8].

B. ION ENGINE THEORY

Modern ion thrusters use inert gases for the propellant. The majority of these thrusters use Xenon, which is chemically inert, colorless, odorless, and tasteless. The propellant is injected upstream of the thruster and flows to the downstream end. This injection method is preferred because it increases the time that the propellant remains in the chamber thereby ensuring higher ionization efficiencies [9].

In a basic ion thruster, electrons are created at a hollow cathode, called the discharge cathode, located at the center of the engine on the upstream end. The electrons
flow out of the discharge cathode and are attracted to the discharge chamber walls, which are charged to a high positive potential by the thruster’s power supply.

The electrons from the discharge cathode ionize the propellant by means of electron bombardment. High-strength magnets are placed along the discharge chamber walls so that as electrons approach the walls, they are redirected into the discharge chamber by the magnetic fields. By maximizing the length of time that electrons and propellant atoms remain in the discharge chamber, the chance of ionization is maximized, which makes the ionization process as efficient as possible at these low pressures.

In an ion thruster, ions are accelerated by electrostatic forces. The electric fields used for acceleration are generated by electrodes positioned at the downstream end of the thruster. Each set of electrodes, called ion optics or grids, contains thousands of coaxial apertures. Each set of apertures acts as a lens that electrically focuses ions through the optics.

Most ion thrusters use a two-electrode system, where the upstream electrode is charged highly positive, and the downstream electrode is charged highly negative. Since the ions are generated in a region of high positive charge and the accelerator grid’s potential is negative, the ions are attracted toward the accelerator grid and are focused out of the discharge chamber through the apertures, creating thousands of ion jets. The stream of all the ion jets together is called the ion beam. The thrust force is the change of momentum to the ions produced by the accelerator grid. The exhaust velocity of the ions in the beam is proportional to the voltage applied to the optics.

Because the ion thruster produces a large amount of positive ions, an equal amount of negative charge must be expelled to keep the total charge of the exhaust beam neutral. A second hollow cathode called the neutralizer is located on the downstream perimeter of the thruster and expels the needed electrons as depicted in Figure 1.
The ion propulsion system consists of five main parts: the power source, power processing unit, propellant management system, the control computer, and the ion thruster. The ion propulsion system power source can be any source of electrical power, but solar and nuclear are the primary options. A solar electric propulsion system uses sunlight and solar cells for power generation. A nuclear electric propulsion system uses a nuclear heat source coupled to an electric generator. The power processing unit converts the electrical power generated by the power source into the power required for each component of the ion thruster. It generates the voltages required by the ion optics and discharge chamber and the high currents required for the hollow cathodes. The propellant management system controls the propellant flow from the propellant tank to the thruster and hollow cathodes [9].

The control computer controls and monitors system performance. The ion thruster then processes the propellant and power to perform work. Modern ion thrusters are capable of propelling a spacecraft up to 90,000 meters per second (about 200,000 miles per hour). The tradeoff for this high top speed is low thrust (or low acceleration) [9].
Modern ion thruster units can deliver up to 0.5 N of thrust. To compensate for low thrust, the ion thruster must be operated for a long time for the spacecraft to reach its desired speed. Because ion thrusters use inert gas for propellant, they eliminate the risk of explosions associated with chemical propulsion. The usual propellant is Xenon, but other gases such as Krypton and Argon may be used [9].

C. FIELDS COVERED

Ion propulsion is one of several propulsion methods utilized for orbital maintenance of spacecraft as well as interplanetary applications. With the advent of the Hall thruster, ion propulsion technology is beginning to take a back seat in research as Hall Effect technology is more readily adaptable to different applications, however, ion propulsion technologies should not be ignored. Current ion technology utilizes Xenon as the propellant of choice due to its high atomic mass, which as the mass is increased so is the momentum change and thus the net thrust. Unfortunately, Xenon is quite expensive. If more common elements such as Argon could be used the price of the propellant would become much cheaper [4].

Another problem with current ion engine technologies is that they have reached size limitations with current technologies. To make ion engines a viable alternative to other propulsion methods they must be scalable beyond where they are now. A possible approach to this would be the use of Micro Structured Electrode (MSE) Arrays [6]. This would reduce or even eliminate the ionization chamber of current engines allowing huge mass and size savings. It would also allow the engines to be scaled to much smaller sizes for applications such as micro satellite propulsion. Another benefit of utilizing MSE Arrays is the reduction in power requirements. Typical ion engines operate in the kilowatt range but by redesigning the technology to use MSE arrays the power requirements would drop to the range of hundreds of watts and at only a few hundred volts, thus requiring less power generation and a smaller spacecraft power bus.

This thesis is concerned with utilizing MSE arrays to modify the design of the ionizer section. Different configurations of MSE arrays are studied in a wide pressure range from 10 milli-Torr to 1 Torr (or 0.122289 N/m² to 133.289 N/m²). The configurations studied involved materials and design, the type of insulator and the structure diameters.
The MSE arrays were studied with respect to the electrical characteristics of the materials and the gas.

The second chapter covers the test equipment setup used for the experiments and offers a description of the MSE wafers. The third chapter covers ion engine theory, both current ion engine configurations and MSE array theory. The MSE array theory will cover the breakdown process at various pressures and the mechanisms for generating sustained discharges. The fourth chapter will cover the data and results of the simulations and testing of the MSE arrays. The fifth and sixth chapters will draw conclusions based on those results and recommendations for future studies. The thesis of LT Frank Perry compliments this effort [7].

The ultimate purpose of this research is to explore the use of MSE arrays as a viable alternative to the present ionizing chambers in the ion propulsion system.
II. EXPERIMENTAL APPARATUS

A. VACUUM CHAMBER AND ASSOCIATED EQUIPMENT

The primary test apparatus used in this work consists of a stainless steel/glass/plexiglass vacuum chamber, two roughing pumps, a turbomolecular vacuum pump, an Argon supply system, high voltage DC power supply, and various metering equipment such as a volt meter, ammeter and oscilloscope. The vacuum chamber is a cylindrically shaped glass chamber with a removable plexiglass top cover, and a bottom stainless steel interface where a high-vacuum gate valve connects to the turbomolecular vacuum pump. The stainless steel interface also has various ports to connect the two roughing pumps, the Argon supply system and the various electrical leads from/to the power supply and metering equipment. One of the roughing pumps is mounted to the side of the turbo pump and is used to draw the pressure of the chamber down to the tens of milli-Torr range before the turbo pump is started. The thesis written by Frank Perry covers the vacuum chamber set up in more detail [7]. For start up sequence and operation procedures refer to Appendix A.

Once the Turbo molecular pump is engaged and draws the vacuum down to the range of $10^{-6}$ Torr the turbo pump and roughing pump are isolated and Argon is back filled into the chamber to the desired pressure for testing by the use of a metering valve. The pressure in the chamber is monitored by thermocouple sensors and a filament sensor.

A DC power supply is used to feed voltage to the sample wafer in the chamber while the breakdown voltage is monitored by and oscilloscope and a voltmeter with an ammeter to measure the current drawn.

Once the breakdown voltage has been achieved the system is reset for the next experiment by evacuating the chamber to $10^{-6}$ torr.

B. MICRO-STRUCTURED ELECTRODE ARRAY WAFERS

The MSE structures used in these experiments are made from two copper layers sandwiching a fiberglass laminate epoxy resin system combined with a glass fabric substrate insulator. These Cu-dielectric-Cu structures are cut from larger sheets into approximately two inch by two inch pieces. These are then marked appropriately for
insulator thickness and nine micro-holes are drilled, using a precision drill press, in the center in a three by three grid pattern. The holes are spaced so that they are 2 mm apart. Each wafer is then etched using Ferric Chloride so as to strip the copper away from the edges – thus leaving 10 mm of dielectric exposed to prevent current flow across the edges [7].

Once etched, they are cleaned of oils and other contaminants by immersion into an alcohol bath and rubbed down. Excess alcohol is allowed to evaporate. Each wafer is then inspected for contaminants and then placed into the vacuum chamber for experimentation as needed [7].
III. THEORY OF IONIZATION ENGINE MODIFICATIONS

A. TOWNSEND THEORY OF BREAKDOWN

The concept behind the use of MSE arrays is to enhance the local electric field when a potential difference is applied to the electrodes. Within a gaseous medium such as Argon, the high field regions free electrons that can be amplified in an avalanche process. When the electric field exceeds a threshold level the number of charged particles multiplies exponentially and a discharge is started [6].

When a sufficiently strong electric field is applied, breakdown occurs. Breakdown is the process where a gas is converted from a non conducting material to a conducting one.

From the Townsend theory of breakdown, we know that the charge carriers are produced by volume processes. This is depicted by the ionization coefficient $\alpha$, and by secondary emission coefficient $\gamma$. To start a self sustaining discharge, for every electron lost at the anode one has to be replaced by a secondary electron that was created in the gas or at the cathode. The ionization coefficient depicts how the electrons multiply in the gas medium in the direction of the electric field. The second ionization coefficient depicts the electron production at the cathode-gas interface. The secondary coefficient explains the effect of ions, photons, and neutrals [1].

At low pressures the production of electrons is primarily caused by ion impact on the cathode surface. The breakdown voltage can be shown in Equation (1) to be:

$$V_b = \frac{Bpd}{\ln(pd) + \ln\left(\frac{A}{\ln(1+\gamma^{-1})}\right)}$$

(1)

where $p$ is the pressure of the gas medium in Torr (760 Torr = 1 atmosphere at sea level, 1 Torr = 133.289 N/m²), $d$ is the distance between parallel-plate anode and cathode in cm, $A$ and $B$ are constants that vary for each gas medium [1]. The breakdown voltage can be graphically represented by the use of a Paschen curve, which depicts the breakdown voltage versus pressure-times-distance as shown by plotting Equation 1 in
nondimensional form in Figure 2. This curve was generated using the general equation (Equation 2) for a Paschen curve.

\[ Y = \frac{X}{\ln(X)} \]  \hspace{1cm} (2)

Where \( Y \) represents the Breakdown voltage and \( X \) represents the pressure times distance. Figure 3 shows the general Paschen curve for an Argon medium.

On the left hand side of a Paschen curve the breakdown voltage rises rapidly as pressure times distance (\( pd \)) decreases due to the low possibility of ionizing collisions requiring a strong electric field. On the right hand side of the curve the breakdown voltage rises gradually as \( pd \) increases due to the probability that an electron will produce ionization even at lower electric fields than the left hand side. The minimum of the curve is where the ionization process occurs at the minimum breakdown voltage. This
The limitation of the Townsend theory is its assumption of homogeneous electric fields and \( pd \) values. When using non-homogeneous fields and variable geometry the Townsend theory breaks down and it is necessary to determine the field structure that is being produced. Experiments with the MSE geometries differ greatly from those with planar geometries discussed previously.

**B. MSE ARRAY GEOMETRY**

With three-dimensional MSE array geometries it can be expected that high electric fields can be achieved locally within the structure. The electric field structure in the MSE array can be expected to be non uniform with respect to planar geometries and

![Paschen Spark Curve for Argon](image_url)
localized within the structure. Due to the imperfect manufacturing techniques used for these experiments the precise geometry of the individual holes differs slightly from each other. The high electric field thus generated in the structure is desirable for the ionization of Argon producing plasma and aids in electron emission from the cathode [6].

Figure 4. Cross-sectional view of Cu-dielectric-Cu layers without microhole structures.

Figure 5. MSE array Cross-sectional view of Cu-dielectric-Cu layers with microhole structures (Hole diameters from 300 µm to 500 µm).

The three-dimensional MSE array geometry used is a three-by-three grid of holes in a two-inch by two-inch structure of two copper layers sandwiching a silicate insulator. The copper layers represent the electrodes. Figure 4 is a cross sectional representation of
this composite structure. Figure 5 is a cross sectional representation of the wafer with a hole drilled through it from top to bottom. Each of the nine holes can be a source of a micro-discharge that takes place between the two copper layers as they are in parallel. The insulation layers used for this experiment range in thickness from 100µm to 400µm and the holes range in diameter from 300µm to 500µm. For further information on the wafer construction please refer to Perry [7].

C. FIELD EMISSION

Field emission of electrons from the cathode could be a primary agent causing ionization in these experiments. Field emission is the process by which electrons are liberated from a surface that is under the effect of an electric field. These electrons are then accelerated in the applied electric field until they collide with neutral species, in the case of Argon gas these are atomic species. During the collision, additional electrons are liberated, which in turn are accelerated by the electric field and collide with other atoms ionizing them and producing even more electrons and so on causing an avalanche effect. This is an avalanche situation due to the exponential nature of the electron liberation.

Our experiments will benefit by utilizing the field emission effect to cause ionization in an Argon medium. The unique geometry of the three dimensional MSE arrays creates a concentrating effect of an applied electric field allowing the liberation of some electrons through the field emission effect at lower energy levels than would be required with parallel electrodes. There may be ways to further enhance their effects through manufacturing improvements and through the introduction of carbon nanotubes at the cathode [4].
IV. EXPERIMENTAL RESULTS

A. INTRODUCTION

The objectives of our experiments were to measure the breakdown voltages at various pressures for the composite-structures of three different thicknesses and with three different diameter holes. (See Table 1.) The thickness refers to the thickness of the insulation between the copper layers for each composite structure on Figure 3. There were a total of twelve structures utilized in the experiments not including a few that were used to determine appropriate equipment set up. The twelve structures were organized into three groups of four. Each group consisted of a baseline structure without holes that was used to determine a baseline breakdown voltage for the operating pressures used. The other three consisted of one wafer each with 300, 400, 500µm diameter holes respectively.

<table>
<thead>
<tr>
<th>Group one</th>
<th>Group two</th>
<th>Group three</th>
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<tbody>
<tr>
<td>127 µm structure</td>
<td>254 µm structure</td>
<td>381 µm structure</td>
</tr>
<tr>
<td>Baseline</td>
<td>Baseline</td>
<td>Baseline</td>
</tr>
<tr>
<td>300µm holes</td>
<td>300µm holes</td>
<td>300µm holes</td>
</tr>
<tr>
<td>400µm holes</td>
<td>400µm holes</td>
<td>400µm holes</td>
</tr>
<tr>
<td>500µm holes</td>
<td>500µm holes</td>
<td>500µm holes</td>
</tr>
</tbody>
</table>

Table 1. Composite Structure’s Experimental Matrix.

Each MSE was attached to leads from the high voltage DC power supply and placed inside the vacuum chamber which was subsequently evacuated to a minimum of 10⁻⁶ Torr and then back filled with ultra pure research grade Argon (with a purity of 99.995%) to the needed experimental pressures. After each measurement the vacuum chamber was once again evacuated to remove ionized Argon and any contaminants and then backfilled with Argon to the next pressure. The breakdown voltage was determined by increasing the applied voltage and monitoring the voltage with a Tektronix oscilloscope. Once breakdown voltage was achieved the voltage level was recorded. (See Appendix A for diagrams of equipment and operational procedures.)
Once the breakdown voltages were obtained for all microstructures the data was put into MATLAB and graphed. (See appendix B for data tables of breakdown voltages and Paschen curves.) A typical Paschen curve for Argon is given in Figure 3. The data was then analyzed to determine where the minimum breakdown voltage occurred for each test case.

**B. CALCULATING EXPECTED RESULTS**

Once the experimental data was obtained, it was compared with the expected results. To determine the expected results a Paschen curve was generated for each structure. The expected Paschen curves were found by determining the experimental constants using Equation (3):

\[
V_b = \frac{C_1 \cdot pd}{\ln(pd) + \ln(C_2)}
\]

where \( C_1 \) and \( C_2 \) are the experimental constants and \( V_b \) the breakdown voltage. Solving for the minimums using Equations (4) and (5) gives:

\[
pd_{\text{min}} = \frac{2.718}{C_2}
\]

\[
V_{b\text{min}} = \frac{2.718 \cdot C_1}{C_2}
\]

where \( pd_{\text{min}} \) and \( V_{b\text{min}} \) are the minimum values from the experimental data. The following three tables (Tables 2, 3, 4) show the MATLAB calculated \( C_1 \) and \( C_2 \) values for each micro structure:

| Group 1 \( C_1 \) & \( C_2 \) MATLAB calculated values |
|-----------------------------|-----------------------------|
| Hole Diameter | \( C_1 \) (Volts\(^{-1}\)) | \( C_2 \) (Torr\(^{-1}\)-cm\(^{-1}\)) |
|-----------------------------|-----------------------------|
| Baseline | 181820.00 | 1764.90 |
| 300µm | 172910.00 | 1926.20 |
| 400µm | 107800.00 | 1153.60 |
| 500µm | 164040.00 | 1741.60 |

Table 2. Group 1 \( C_1 \) & \( C_2 \) MATLAB calculated values.
Table 3. Group 2 $C_1$ & $C_2$ MATLAB calculated values.

<table>
<thead>
<tr>
<th>Hole Diameter</th>
<th>$C_1$ (Volts$^{-1}$)</th>
<th>$C_2$ (Torr$^{-1}$-cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>71994.00</td>
<td>627.1777</td>
</tr>
<tr>
<td>300µm</td>
<td>101420.00</td>
<td>1111.6000</td>
</tr>
<tr>
<td>400µm</td>
<td>92142.00</td>
<td>894.4320</td>
</tr>
<tr>
<td>500µm</td>
<td>95202.00</td>
<td>1035.0000</td>
</tr>
</tbody>
</table>

Table 4. Group 3 $C_1$ & $C_2$ MATLAB calculated values.

<table>
<thead>
<tr>
<th>Diameter</th>
<th>$C_1$ (Volts$^{-1}$)</th>
<th>$C_2$ (Torr$^{-1}$-cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>50690.00</td>
<td>488.5677</td>
</tr>
<tr>
<td>300µm</td>
<td>60938.00</td>
<td>707.8125</td>
</tr>
<tr>
<td>400µm</td>
<td>92879.00</td>
<td>934.9845</td>
</tr>
<tr>
<td>500µm</td>
<td>38286.00</td>
<td>369.0127</td>
</tr>
</tbody>
</table>

Interested to note is the $C_1$ and $C_2$ values decrease as the thickness of the wafers increases. The values also decrease as the hole diameter decreases.

The next step was to graph the expected Paschen curve and compare it to the curve generated by the experimental data.
Figure 6. Graphical Representation of group one (thin) wafer actual breakdown voltages and expected breakdown voltage curve.
Figure 7. Graphical Representation of group two (middle) wafer actual breakdown voltages and expected breakdown voltage curve.
As can be seen in Figures 6, 7 and 8, the lowermost data points are close to the expected curves. Some variation can be seen but the minima are very close.

### C. REPEATABILITY

The next question to be answered was whether the experiments can be duplicated with some degree of consistency. Two wafers were randomly chosen to be retested with the following results (Tables 5 and 6, Figures 9 and 10):
Table 5. Data table contrasting the first and second run with the same wafer.

<table>
<thead>
<tr>
<th>Pressure (p) (milli-Torr)</th>
<th>Breakdown Voltage (Volts)</th>
<th>Pressure (p) (milli-Torr)</th>
<th>Breakdown Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Run</td>
<td>Second Run</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.2</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>30.3</td>
<td>326</td>
<td>30</td>
<td>318</td>
</tr>
<tr>
<td>51.3</td>
<td>310</td>
<td>50.7</td>
<td>292</td>
</tr>
<tr>
<td>83.7</td>
<td>290</td>
<td>80.9</td>
<td>268</td>
</tr>
<tr>
<td>102</td>
<td>270</td>
<td>101</td>
<td>248</td>
</tr>
<tr>
<td>150</td>
<td>282</td>
<td>150</td>
<td>292</td>
</tr>
<tr>
<td>203</td>
<td>334</td>
<td>200</td>
<td>316</td>
</tr>
<tr>
<td>498</td>
<td>354</td>
<td>499</td>
<td>288</td>
</tr>
</tbody>
</table>

Figure 9. Comparison of Paschen curves for two runs of the middle wafer with 400µm diameter holes.

The comparison between the first and second runs (as shown in figure 9) of the middle wafer with 400µm diameter holes shows a high degree of similarity. The minimum voltages are within 22 volts of each other at the same pressure.
500µm – Group 3 structure with d=0.372mm/0.01465in

<table>
<thead>
<tr>
<th>Pressure (p) (milli-Torr)</th>
<th>Breakdown Voltage (Volts)</th>
<th>Pressure (p) (milli-Torr)</th>
<th>Breakdown Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.6</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>30.7</td>
<td>346</td>
<td>34</td>
<td>316</td>
</tr>
<tr>
<td>50.6</td>
<td>346</td>
<td>50</td>
<td>306</td>
</tr>
<tr>
<td>83.1</td>
<td>308</td>
<td>81.6</td>
<td>292</td>
</tr>
<tr>
<td>98.2</td>
<td>298</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>149</td>
<td>298</td>
<td>150</td>
<td>296</td>
</tr>
<tr>
<td>198</td>
<td>282</td>
<td>201</td>
<td>306</td>
</tr>
<tr>
<td>498</td>
<td>352</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 6. Data table contrasting the first and second run with the same wafer

Figure 10. Comparison of Paschen curves for two runs of the thick wafer with 500µm diameter holes

The comparison of the first and second runs (as shown in Figure 10) of the thick wafer with 500µm diameter holes shows that there is less consistency between these runs.
The minimum voltage for breakdown varies by 10 volts but the pressure regions vary by 116 Torr with the first run minima occurring at 198 Torr and the second run minima occurring at 81.6 Torr.

The difference between the two runs can be in part contributed to the wear on the electrodes of the microstructures, which modifies the three dimensional geometry slightly.

**D. DETERIORATION**

One of the main unknowns of this experiment is the amount of deterioration of the electrodes during the ionization process. The purpose of this experiment is not to quantify the amount of deterioration of the electrodes but it must be realized that the deterioration will change the three dimensionality of the geometry over time. The deterioration is a function of the time that the electrodes are under discharge conditions; the robustness of the material used for the electrodes; and the voltage-current conditions. In our case copper was used to demonstrate that deterioration did in fact take place on the MSE arrays that were examined both before and after the ionization process. Microscope images are presented below –please see Perry [7] for further details.
Figure 11. Photo of 300µm diameter hole at 290 magnification before testing.
Figure 12. Photo of 400µm diameter hole at 48 magnification before testing.
In Figures 11, 12 and 13 some roughness around the edges of the hole can be seen but these are due to the inaccuracies of the manufacturing methods used.
Figure 14. Photo of 300µm diameter hole at 290 magnification after testing.
Figure 15. Photo of 400µm diameter hole at 48 magnification after testing.
As can be seen in Figures 14, 15 and 16, there is significant deterioration of the electrodes after the ionization process in Argon has occurred. The amount of deterioration varies depending on the hole size and the time that the hole was subjected to the discharge. In this respect, copper was not a robust electrode material – ion engines require long life times, therefore future research must include the study of suitable electrode materials.
V. CONCLUSIONS

This thesis shows that the ionization of Argon, which is an alternate fuel to Xenon, can be achieved at low voltages by utilizing Micro-Structured Electrode (MSE) arrays. The MSE arrays serve to concentrate the electric fields between electrodes allowing the production of electrons enhancing the field emission effect. Minimum breakdown voltages between 240 and 280 volts at pressures of around 100 milli-Torr (0.133N/m²) were consistently obtained with arrays of hole diameter ranging from 300 to 500µm. The MSE arrays were fabricated from composite Cu-SiO2-Cu structures with varying thicknesses from 100 µm to 400 µm. The micro structures (holes) were fabricated using precision conventional machining and hole diameters between 300 and 500 um were achieved.

Using the experimental data and MATLAB we were able to obtain the experimental constants (C₁ and C₂) for the Paschen curves. With these values in hand the minimum breakdown voltages were calculated for each of the MSE arrays. The values of the experimental constants decreased as the thickness of the layered structures increased and as the hole diameter decreased.

Another achievement has been the utilization of commonly available materials and manufacturing methods for the construction of the MSE arrays. Thus yielding a low–cost method for conducting experiments in this field.
VI. RECOMMENDATIONS

Several recommendations resulted from this study

A. REPEATABILITY STUDIES

Additional repeatability studies should be performed to verify that ionization can be achieved for the same MSE array many times at the same voltage. This will also serve to establish accurate empirical data required for any future optimization studies.

B. DETERIORATION STUDIES

Further work should include the study of the rate and amount of deterioration that is incurred by repeating the ionization process many times with the same MSE array. With each repetition the three dimensionality of the structures changed and the modeling and understanding of this change will be vital to predicting future performance.

C. FLOW STUDIES

This experiment was conducted in a static atmosphere. Future ion engine applications will not be utilizing such an atmosphere but will instead be utilizing the flow of Argon through the MSE array. Additional studies should be performed to determine the effects of a flow (both constant and variable) through the array on the breakdown voltages and on ionization efficiency.

D. MATERIAL STUDIES

Another point of interest is the materials that make up the MSE array. For these experiments copper electrodes were used. Ion propulsion applications will require long life times, therefore suitable materials need to be identified

E. STRUCTURES STUDIES

The current experiment used a circular hole through the electrodes and insulator material. Other three dimensional structures should be investigated for optimal ionization performance and efficiency.
APPENDIX A

A. PROCEDURE FOR VACUUM CHAMBER OPERATION.

Steps:

1. Vent vacuum chamber to normal atmospheric pressure by opening venting valve.

2. Open vacuum chamber and connect wafer to copper leads utilizing plastic clips. Ensure that the two copper leads are attached on opposite sides of the wafer from each other.

3. Close vacuum chamber and inspect seals. Ensure venting valve and roughing pump number 2 valve are closed. Open isolation valve and start roughing pump number 1.

4. Turn on instrument panel and thermocouple (TC) gages 1 and 2 and 3. Once TC2 and TC3 indicate chamber pressure around 100 milli-Torr turn power on to the Turbo Molecular Pump (TMP) and monitor as power up sequence commences. Turn on Filament gage and monitor pressure.

5. Once vacuum chamber pressure is at its minimum pressure (approximately $1.5 \times 10^{-6}$ Torr) fasten Argon line to vent valve on chamber and ensure metering valve is closed. Open pressure valve on Argon tank and open cut off valve to metering valve on Argon line to vacuum chamber.

6. Close Isolation Valve and begin backfilling vacuum chamber with Argon by opening vent valve and open metering valve. Adjust and control flow of Argon into Vacuum chamber by adjusting metering valve and monitoring TC3 meter.

7. Once pressure in vacuum chamber has reached required pressure shut off metering valve and close vent valve.
B. PROCEDURE FOR INSTRUMENT PANEL OPERATION

Steps:

1. Once the procedures in part A are complete and the experiment is ready to be run, turn on power to the equipment cabinet ensuring that the voltmeter, amp meter and oscilloscope power up.

2. Switch amp meter from AC to DC setting. Volt meter should default to DC setting. Set oscilloscope to 5 volts per division and 5 seconds per division.

3. For Safety Ensure No One is touching any wires or the vacuum chamber.

4. Ensure power supply is set to zero volts and turn on power supply.

5. Begin by incrementing voltage levels and monitor oscilloscope and voltmeter for breakdown voltage.

6. Once breakdown voltage has been achieved record voltage and turn off power supply and set dials on power supply back to zero volts.

7. Set up for next experiment.
C. DIAGRAMS

Figure 17. Diagram of vacuum chamber assembly.
Figure 18.  Diagram of control panel for pressure sensors and pump controls.
Figure 19. Layout of equipment rack.
Figure 20. Argon supply system layout.
APPENDIX B

A. DATA TABLES

1. Group 1

<table>
<thead>
<tr>
<th>Pressure (p) (milli-Torr)</th>
<th>Breakdown Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.5</td>
<td>N/A</td>
</tr>
<tr>
<td>32.4</td>
<td>366</td>
</tr>
<tr>
<td>51.4</td>
<td>310</td>
</tr>
<tr>
<td>82.3</td>
<td>286</td>
</tr>
<tr>
<td>100</td>
<td>280</td>
</tr>
<tr>
<td>153</td>
<td>282</td>
</tr>
<tr>
<td>200</td>
<td>320</td>
</tr>
<tr>
<td>495</td>
<td>346</td>
</tr>
</tbody>
</table>

Table 7. Group 1 baseline.

<table>
<thead>
<tr>
<th>Pressure (p) (milli-Torr)</th>
<th>Breakdown Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.8</td>
<td>N/A</td>
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<tr>
<td>35.2</td>
<td>326</td>
</tr>
<tr>
<td>51.3</td>
<td>292</td>
</tr>
<tr>
<td>82.2</td>
<td>262</td>
</tr>
<tr>
<td>103</td>
<td>244</td>
</tr>
<tr>
<td>151</td>
<td>252</td>
</tr>
<tr>
<td>202</td>
<td>260</td>
</tr>
<tr>
<td>509</td>
<td>302</td>
</tr>
</tbody>
</table>

Table 8. Group 1 with 300µm holes.

<table>
<thead>
<tr>
<th>Pressure (p) (milli-Torr)</th>
<th>Breakdown Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.4</td>
<td>N/A</td>
</tr>
<tr>
<td>32.1</td>
<td>364</td>
</tr>
<tr>
<td>52.9</td>
<td>310</td>
</tr>
<tr>
<td>82.9</td>
<td>276</td>
</tr>
<tr>
<td>98.3</td>
<td>264</td>
</tr>
<tr>
<td>154</td>
<td>254</td>
</tr>
<tr>
<td>204</td>
<td>276</td>
</tr>
<tr>
<td>517</td>
<td>348</td>
</tr>
</tbody>
</table>

Table 9. Group 1 with 400µm holes.
500µm - Thin Wafer with d=0.136mm/0.00535in

<table>
<thead>
<tr>
<th>Pressure (p) (milli-Torr)</th>
<th>Breakdown Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>N/A</td>
</tr>
<tr>
<td>35.1</td>
<td>316</td>
</tr>
<tr>
<td>50</td>
<td>284</td>
</tr>
<tr>
<td>83.8</td>
<td>266</td>
</tr>
<tr>
<td>102</td>
<td>256</td>
</tr>
<tr>
<td>148</td>
<td>264</td>
</tr>
<tr>
<td>199</td>
<td>326</td>
</tr>
<tr>
<td>500</td>
<td>364</td>
</tr>
</tbody>
</table>

Table 10. Group 1 with 500µm holes.

2. **Group 2**

Baseline - Middle Wafer with d=0.287mm/0.0113in

<table>
<thead>
<tr>
<th>Pressure (p) (milli-Torr)</th>
<th>Breakdown Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.9</td>
<td>N/A</td>
</tr>
<tr>
<td>31.5</td>
<td>386</td>
</tr>
<tr>
<td>50.4</td>
<td>374</td>
</tr>
<tr>
<td>85.9</td>
<td>340</td>
</tr>
<tr>
<td>100</td>
<td>328</td>
</tr>
<tr>
<td>151</td>
<td>312</td>
</tr>
<tr>
<td>198</td>
<td>312</td>
</tr>
<tr>
<td>496</td>
<td>386</td>
</tr>
</tbody>
</table>

Table 11. Group 2 baseline.

300µm - Middle Wafer with d=0.303mm/0.0119in

<table>
<thead>
<tr>
<th>Pressure (p) (milli-Torr)</th>
<th>Breakdown Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.9</td>
<td>N/A</td>
</tr>
<tr>
<td>33.9</td>
<td>296</td>
</tr>
<tr>
<td>50.9</td>
<td>276</td>
</tr>
<tr>
<td>80.7</td>
<td>248</td>
</tr>
<tr>
<td>106</td>
<td>258</td>
</tr>
<tr>
<td>159</td>
<td>258</td>
</tr>
<tr>
<td>208</td>
<td>274</td>
</tr>
<tr>
<td>503</td>
<td>324</td>
</tr>
</tbody>
</table>

Table 12. Group 2 with 300µm holes.
Table 13. Group 2 with 400µm holes.

<table>
<thead>
<tr>
<th>Pressure (p) (milli-Torr)</th>
<th>Breakdown Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.4</td>
<td>N/A</td>
</tr>
<tr>
<td>31.8</td>
<td>332</td>
</tr>
<tr>
<td>48</td>
<td>318</td>
</tr>
<tr>
<td>84.3</td>
<td>284</td>
</tr>
<tr>
<td>107</td>
<td>280</td>
</tr>
<tr>
<td>152</td>
<td>284</td>
</tr>
<tr>
<td>200</td>
<td>298</td>
</tr>
<tr>
<td>500</td>
<td>360</td>
</tr>
</tbody>
</table>

Table 14. Group 2 with 500µm holes.

<table>
<thead>
<tr>
<th>Pressure (p) (milli-Torr)</th>
<th>Breakdown Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.9</td>
<td>N/A</td>
</tr>
<tr>
<td>31.7</td>
<td>322</td>
</tr>
<tr>
<td>56.6</td>
<td>290</td>
</tr>
<tr>
<td>81.4</td>
<td>260</td>
</tr>
<tr>
<td>101</td>
<td>250</td>
</tr>
<tr>
<td>150</td>
<td>272</td>
</tr>
<tr>
<td>200</td>
<td>318</td>
</tr>
<tr>
<td>499</td>
<td>300</td>
</tr>
<tr>
<td>800</td>
<td>340</td>
</tr>
</tbody>
</table>

3. Group 3

Table 15. Group 3 baseline.

<table>
<thead>
<tr>
<th>Pressure (p) (milli-Torr)</th>
<th>Breakdown Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>N/A</td>
</tr>
<tr>
<td>32.4</td>
<td>N/A</td>
</tr>
<tr>
<td>53.4</td>
<td>338</td>
</tr>
<tr>
<td>83.8</td>
<td>314</td>
</tr>
<tr>
<td>101</td>
<td>304</td>
</tr>
<tr>
<td>152</td>
<td>282</td>
</tr>
<tr>
<td>205</td>
<td>324</td>
</tr>
<tr>
<td>497</td>
<td>N/A</td>
</tr>
</tbody>
</table>
### Table 16. Group 3 with 300µm holes.

<table>
<thead>
<tr>
<th>Pressure (p) (milli-Torr)</th>
<th>Breakdown Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.1</td>
<td>N/A</td>
</tr>
<tr>
<td>32.2</td>
<td>382</td>
</tr>
<tr>
<td>50.7</td>
<td>320</td>
</tr>
<tr>
<td>84.1</td>
<td>284</td>
</tr>
<tr>
<td>100</td>
<td>234</td>
</tr>
<tr>
<td>149</td>
<td>262</td>
</tr>
<tr>
<td>200</td>
<td>276</td>
</tr>
<tr>
<td>518</td>
<td>348</td>
</tr>
</tbody>
</table>

### Table 17. Group 3 with 400µm holes.

<table>
<thead>
<tr>
<th>Pressure (p) (milli-Torr)</th>
<th>Breakdown Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.2</td>
<td>N/A</td>
</tr>
<tr>
<td>30.3</td>
<td>326</td>
</tr>
<tr>
<td>51.3</td>
<td>310</td>
</tr>
<tr>
<td>83.7</td>
<td>290</td>
</tr>
<tr>
<td>102</td>
<td>270</td>
</tr>
<tr>
<td>150</td>
<td>282</td>
</tr>
<tr>
<td>203</td>
<td>334</td>
</tr>
<tr>
<td>498</td>
<td>354</td>
</tr>
</tbody>
</table>

### Table 18. Group 3 with 500µm holes.

<table>
<thead>
<tr>
<th>Pressure (p) (milli-Torr)</th>
<th>Breakdown Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.6</td>
<td>N/A</td>
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<tr>
<td>30.7</td>
<td>346</td>
</tr>
<tr>
<td>50.6</td>
<td>346</td>
</tr>
<tr>
<td>83.1</td>
<td>308</td>
</tr>
<tr>
<td>98.2</td>
<td>298</td>
</tr>
<tr>
<td>149</td>
<td>298</td>
</tr>
<tr>
<td>198</td>
<td>282</td>
</tr>
<tr>
<td>498</td>
<td>352</td>
</tr>
</tbody>
</table>
B. PASCHEN CURVE RESULTS

1. Paschen Curve Comparison of Data

Figure 21. Comparison of thin (Group 1) breakdown voltages.
Figure 22. Comparison of middle (Group 2) breakdown voltages.
Figure 23. Comparison of thick (Group 3) breakdown voltages.
APPENDIX C

A. MATLAB CODE USED TO GRAPH FIGURES 6-8

%%% Thesis Data

clear all
close all
clc

%%% Thinnest Wafers
%%% Thinnest wafer Baseline
pdmin = 100*.0154  %milli-Torr
pdmin = pdmin/1000  %Torr
Vbmin = 280

c2 = 2.718/pdmin
c1 = Vbmin*c2/2.718
x = .00066:.0001:.01;
vb = (c1.*x)./(log(x)+log(c2));
figure(1)
subplot(2,2,1)
plot(x,vb,'r.-','linewidth',3)
hold on
d = .0154; %cm or 0.00605in
P = [32.4 51.4 82.3 100 153 200 495]; % pressure in milliTorr
P = P/1000; % pressure in Torr
Vb = [366 310 286 280 282 320 346]; % voltage in volts
pd = d*P;
plot(pd,Vb,'linewidth',3)
title('Paschen curve of thinnest wafer Baseline.')
xlabel('pd (Torr-cm)')
ylabel('Vb')
legend('Expected','Data','Location','SouthEast')
grid on
hold on
scatter(pd,Vb)
%% 300um thinnest wafer

\[ \text{pdmin} = 103 \times 0.137 \text{ Torr} \]
\[ \text{pdmin} = \text{pdmin}/1000 \text{ Torr} \]
\[ \text{Vbmin} = 244 \]
\[ c2 = 2.718/\text{pdmin} \]
\[ c1 = \text{Vbmin} \times c2/2.718 \]
\[ x = 0.00066:0.001:0.01; \]
\[ v_b = (c1 \times x)/(\log(x) + \log(c2)); \]

\begin{verbatim}
subplot(2,2,2)
plot(x,vb,'r.-','linewidth',3)
hold on
d = 0.137; %cm or 0.00535in
P = [35.2 51.3 82.2 103 151 202 509]; % pressure in milliTorr
P = P/1000; % pressure in Torr
Vb = [326 292 262 244 252 260 302]; % voltage in volts
pd = d*P;
plot(pd,Vb,'linewidth',3)
end

%axis tight
hold on
scatter(pd,Vb)
\end{verbatim}

%% 400um thinnest wafer

\[ \text{pdmin} = 154 \times 0.153 \text{ Torr} \]
\[ \text{pdmin} = \text{pdmin}/1000 \text{ Torr} \]
\[ \text{Vbmin} = 254 \]
\[ c2 = 2.718/\text{pdmin} \]
\[ c1 = \text{Vbmin} \times c2/2.718 \]
\[ x = 0.001:0.001:0.01; \]
\[ v_b = (c1 \times x)/(\log(x) + \log(c2)); \]

\begin{verbatim}
subplot(2,2,3)
plot(x,vb,'r.-','linewidth',3)
hold on
scatter(pd,Vb)
\end{verbatim}
d=.0153; %cm or 0.00605in
P=[32.1 52.9 82.9 98.3 154 204 517]; %% pressure in milliTorr
P=P/1000; %% pressure in torr
Vb=[364 310 276 254 276 348]; %% voltage in volts
pd=d*P;
plot(pd,Vb,'linewidth',3)
title('Paschen curve of thinnest wafer with 400um holes')
xlabel('pd (torr-cm)')
ylabel('Vb')
legend('Expected','Data','Location','SouthEast')
grid on
hold on
scatter(pd,Vb)

%%% 500um thinnest wafer
pdm5= 102*.0153  %millitorr
pdm5=pdm5/1000  %torr
Vb5min=256
c5=2.718/pdm5
cl5=Vb5min*c5/2.718
x=.00066:.0001:.01;
v=5(c1.*x)./(log(x)+log(c2));
subplot(2,2,4)
plot(x,v,'r.-','linewidth',3)
hold on
d=.0153; %cm or 0.00605in
P=[35.1 50 83.8 102 148 199 500]; %% pressure in milliTorr
P=P/1000; %% pressure in torr
Vb=[316 284 266 256 326 364]; %% voltage in volts
pd=d*P;
plot(pd,Vb,'linewidth',3)
title('Paschen curve of thinnest wafer with 500um holes')
xlabel('pd (torr-cm)')
ylabel('Vb')
legend('Expected','Data','Location','SouthEast')
grid on
hold on
scatter(pd,Vb)

%%% Middle Wafers
%%% Middle wafer Baseline
pdmin = 151*0.0287 %millitorr
pdmin = pdmin/1000 %torr
Vbmin = 312
c2 = 2.718/pdmin
c1 = Vbmin*c2/2.718
x = .002:.0001:.015;
vb = (c1.*x)./(log(x)+log(c2));
figure(2)
subplot(2,2,1)
plot(x,vb,'r.-','linewidth',3)
hold on
d = 0.287; %cm or 0.0113in
P = [31.5 50.4 85.9 100 151 198 496]; %% pressure in millitorr
P = P/1000; %% pressure in torr
Vb = [386 374 340 328 312 312 386]; %% voltage in volts
pd = d*P;
plot(pd,Vb,'linewidth',3)
title('Paschen curve of middle wafer Baseline.')
xlabel('pd (torr-cm)')
ylabel('Vb')
legend('Expected','Data','Location','NorthEast')
grid on
hold on
scatter(pd,Vb)

%%% 300um middle wafer
pdmin = 80.7*0.0303 %millitorr
pdmin = pdmin/1000 %torr
Vbmin = 248
c2 = 2.718/pdmin
c1 = Vbmin*c2/2.718
x = .001:.0001:.016;
vb = (c1.*x)./(log(x)+log(c2));
subplot(2,2,2)
plot(x,vb,'r.-','linewidth',3)
hold on
d=.0303; %cm or 0.0119in
P=[33.9 50.9 80.7 106 159 208 503]; %% pressure in millitorr
P=P/1000; %% pressure in torr
Vb=[296 276 248 258 258 274 324]; %% voltage in volts
pd=d*P;
plot(pd,Vb,'linewidth',3)
title('Paschen curve of middle wafer with 300um holes')
xlabel('pd (torr-cm)')
ylabel('Vb')
legend('Expected','Data','Location','NorthEast')
grid on
hold on
scatter(pd,Vb)

%% 400um middle wafer
pdmin= 107*.0284  %millitorr
pdmin=pdmin/1000  %torr
Vbmin=280
c2=2.718/pdmin
c1=Vbmin*c2/2.718
x=.003:.0001:.016;
vb=(c1.*x)./(log(x)+log(c2));
subplot(2,2,3)
plot(x,vb,'r.-','linewidth',3)
hold on
d=.0284; %cm or 0.01115in
P=[31.8 48 84.3 107 152 200 500]; %% pressure in millitorr
P=P/1000; %% pressure in torr
Vb=[332 318 284 280 284 298 360]; %% voltage in volts
pd=d*P;
plot(pd,Vb,'linewidth',3)
title('Paschen curve of middle wafer with 400um holes')
xlabel('pd (torr-cm)')
ylabel('Vb')
legend('Expected','Data','Location','SouthEast')
grid on
hold on
scatter(pd,Vb)

%%% 500um middle wafer
padmin= 101*.026  %millitorr
padmin=padmin/1000  %torr
Vbmin=250
c2=2.718/padmin
c1=Vbmin*c2/2.718
x=.0015:.0001:.02;
vb=(c1.*x)./(log(x)+log(c2));
subplot(2,2,4)
plot(x,vb,'r.-','linewidth',3)
hold on
d=.026; %cm or 0.01025in
P=[31.7 56.6 81.4 101 150 200 499 800]; %% pressure in millitorr
P=P/1000; %% pressure in torr
Vb=[322 290 260 250 272 318 300 340]; %% voltage in volts
pd=d*P;
plot(pd,Vb,'linewidth',3)
title('Paschen curve of middle wafer with 500um holes')
xlabel('pd (torr-cm)')
ylabel('Vb')
legend('Expected','Data','Location','SouthEast')
grid on
hold on
scatter(pd,Vb)

%%% Thick Wafers
%%% Thick wafer Baseline
padmin= 152*.0366  %millitorr
padmin=padmin/1000  %torr
Vbmin=282
c2=2.718/padmin
c1=Vbmin*c2/2.718
x=.0025:.0001:.008;
vb=(c1.*x)./(log(x)+log(c2));
figure(3)
subplot(2,2,1)
plot(x,vb,'r.-','linewidth',3)
hold on
d=.0366; %cm or 0.0144in
P=[53.4 83.8 101 152 205]; % pressure in millitorr
P=P/1000; % pressure in torr
Vb=[338 314 304 282 324]; % voltage in volts
pd=d.*P;
plot(pd,Vb,'linewidth',3)
title('Paschen curve of thick wafer Baseline.')
xlabel('pd (torr-cm)')
ylabel('Vb')
legend('Expected','Data','Location','NorthEast')
grid on
hold on
scatter(pd,Vb)

% 300µm thick wafer
pdmin= 100*.0384 % millitorr
pdmin=pdmin/1000 % torr
Vbmin=234
c2=2.718/pdmin
c1=Vbmin*c2/2.718
x=.0016:.0001:.025;
vb=(c1.*x)./(log(x)+log(c2));
subplot(2,2,2)
plot(x,vb,'r.-','linewidth',3)
hold on
d=.0384; % cm or 0.0151 in
P=[32.2 50.7 84.1 100 149 200 318]; % pressure in millitorr
P=P/1000; % pressure in torr
Vb=[382 320 284 262 276 348]; % voltage in volts
pd=d.*P;
plot(pd,Vb,'linewidth',3)
title('Paschen curve of thick wafer with 300um holes')
xlabel('pd (torr-cm)')
ylabel('Vb')
legend('Expected','Data','Location','SouthEast')
grid on
hold on
scatter(pd,Vb)

%% 400um thick wafer
pdmin= 102*.0285  %millitorr
pdmin=pdmin/1000  %torr
Vbmin=270
c2=2.718/pdmin
c1=Vbmin*c2/2.718
x=.0015:.0001:.016;
vb=(c1.*x)./(log(x)+log(c2));
subplot(2,2,3)
plot(x,vb,'r.-','linewidth',3)
hold on
d=.0285; %cm or 0.0112in
P=[30.3 51.3 83.7 102 150 203 498]; %% pressure in millitorr
P=P/1000; %% pressure in torr
Vb=[326 310 290 270 282 334 354]; %% voltage in volts
pd=d*P;
plot(pd,Vb,'linewidth',3)
title('Paschen curve of thick wafer with 400um holes')
xlabel('pd (torr-cm)')
ylabel('Vb')
legend('Expected','Data','Location','SouthEast')
grid on
hold on
scatter(pd,Vb)

%% 500um thick wafer
pdmin= 198*.0372  %millitorr
pdmin=pdmin/1000  %torr
Vbmin=282
c2=2.718/pdmin
\[c1=Vbmin*c2/2.718\]
x=.004:.0001:.02;
vb=(c1.*x)./(\log(x)+\log(c2));
subplot(2,2,4)
plot(x,vb,'r.-','linewidth',3)
hold on
d=.0372; \%cm or 0.01465in
P=[30.7 50.6 83.1 98.2 149 198 498]; \% pressure in millitorr
P=P/1000; \% pressure in torr
Vb=[346 346 308 298 298 282 352]; \% voltage in volts
pd=d*P;
plot(pd,Vb,'linewidth',3)
title('Paschen curve of thick wafer with 500um holes')
xlabel('pd (torr-cm)')
ylabel('Vb')
legend('Expected','Data','Location','SouthEast')
grid on
hold on
scatter(pd,Vb)

B. MATLAB CODE USED TO GRAPH FIGURES 21-23 IN APPENDIX B
\%
\% Thesis Data Comparison

clear all
close all
clc

\%
\%\%\%Thinnest Wafers
\%
\% Thinnest wafer Baseline
db=.0154; \%cm or 0.00605in
Pb=[32.4 51.4 82.3 100 153 200 495]; \% pressure in millitorr
Pb=Pb/1000; \% pressure in torr
Vbb=[366 310 286 280 282 320 346]; \% voltage in volts
pdb=db*Pb;
%% 300um thinnest wafer
\[ d_3 = 0.0137; \text{ cm or 0.00535 in} \]
\[ P_3 = [35.2, 51.3, 82.2, 103, 151, 202, 302]; \text{ pressure in millitorr} \]
\[ V_{b3} = [326, 292, 262, 244, 252, 260, 302]; \text{ voltage in volts} \]
\[ p_{d3} = d_3 \times P_3; \]

%% 400um thinnest wafer
\[ d_4 = 0.0153; \text{ cm or 0.00605 in} \]
\[ P_4 = [32.1, 52.9, 82.9, 98.3, 154, 204, 517]; \text{ pressure in millitorr} \]
\[ V_{b4} = [364, 310, 276, 264, 254, 276, 348]; \text{ voltage in volts} \]
\[ p_{d4} = d_4 \times P_4; \]

%% 500um thinnest wafer
\[ d_5 = 0.0153; \text{ cm or 0.00605 in} \]
\[ P_5 = [35.1, 50, 83.8, 102, 148, 199, 500]; \text{ pressure in millitorr} \]
\[ V_{b5} = [316, 284, 266, 256, 264, 326, 364]; \text{ voltage in volts} \]
\[ p_{d5} = d_5 \times P_5; \]

%% Comparison plot for thinnest wafers
figure(1)
plot(p_{d3}, V_{b3}, 'go:', 'linewidth', 2)
hold on
plot(p_{d4}, V_{b4}, 'rx-.', 'linewidth', 2)
hold on
plot(p_{d5}, V_{b5}, 'k+--', 'linewidth', 2)
hold on
grid on
title('Paschen curves of thinnest wafers.')
xlabel('pd (torr-cm)')
ylabel('Vb')
legend('Baseline', '300um', '400um', '500um', 'Location', 'SouthEast')

%%% Middle Wafers
%%% Middle wafer Baseline
\[ d_{b} = 0.0287; \text{ cm or 0.0113 in} \]
Pb=[31.5 50.4 85.9 100 151 198 496]; \%\% pressure in millitorr
Pb=Pb/1000; \%\% pressure in torr
Vbb=[386 374 340 328 312 312 386]; \%\% voltage in volts
pdb=db*Pb;
\%\% 300um Middle wafer
d3=.0303; \% cm or 0.0119in
P3=[33.9 50.9 80.7 106 159 208 503]; \%\% pressure in millitorr
P3=P3/1000; \%\% pressute in torr
Vb3=[296 276 248 258 258 274 324]; \%\% voltage in volts
pd3=d3*P3;
\%\% 400um Middle wafer
d4=.0284; \% cm or 0.01115in
P4=[31.8 48 84.3 107 152 200 500]; \%\% pressure in millitorr
P4=P4/1000; \%\% pressute in torr
Vb4=[332 318 284 280 284 298 360]; \%\% voltage in volts
pd4=d4*P4;
\%\% 500um Middle wafer
d5=.026; \% cm or 0.01025in
P5=[31.7 56.6 81.4 101 150 200 499 800]; \%\% pressure in millitorr
P5=P5/1000; \%\% pressute in torr
Vb5=[322 290 260 250 272 318 300 340]; \%\% voltage in volts
pd5=d5*P5;
\%\% Comparison plot for Middle wafers
figure(2)
plot(pdb,Vbb,'b.-','linewidth',3)
hold on
plot(pd3,Vb3,'go:','linewidth',2)
hold on
plot(pd4,Vb4,'rx-.','linewidth',2)
hold on
plot(pd5,Vb5,'k+--','linewidth',2)
hold on
grid on
title('Paschen curves of middle wafers.')
xlabel('pd (torr-cm)')
ylabel('Vb')
legend('Baseline','300um','400um','500um','Location','SouthEast')
%%% Thick Wafers

%% Thick wafer Baseline

\[ \text{d}_b = 0.0366 \text{ cm or 0.0144in} \]

\[ \text{P}_b = \begin{bmatrix} 53.4 & 83.8 & 101 & 152 & 205 \end{bmatrix} \text{ pressure in millitorr} \]

\[ \text{P}_b = \frac{\text{P}_b}{1000}; \text{ pressure in torr} \]

\[ \text{V}_{bb} = \begin{bmatrix} 338 & 314 & 304 & 282 & 324 \end{bmatrix} \text{ voltage in volts} \]

\[ \text{p}_{db} = \text{d}_b \times \text{P}_b; \]

%% 300um Thick wafer

\[ \text{d}_3 = 0.0384 \text{ cm or 0.0151in} \]

\[ \text{P}_3 = \begin{bmatrix} 32.2 & 50.7 & 84.1 & 100 & 149 & 200 & 518 \end{bmatrix} \text{ pressure in millitorr} \]

\[ \text{P}_3 = \frac{\text{P}_3}{1000}; \text{ pressure in torr} \]

\[ \text{V}_{b3} = \begin{bmatrix} 382 & 320 & 284 & 262 & 276 & 348 \end{bmatrix} \text{ voltage in volts} \]

\[ \text{p}_{d3} = \text{d}_3 \times \text{P}_3; \]

%% 400um Thick wafer

\[ \text{d}_4 = 0.0285 \text{ cm or 0.0112in} \]

\[ \text{P}_4 = \begin{bmatrix} 30.3 & 51.3 & 83.7 & 102 & 150 & 203 & 498 \end{bmatrix} \text{ pressure in millitorr} \]

\[ \text{P}_4 = \frac{\text{P}_4}{1000}; \text{ pressure in torr} \]

\[ \text{V}_{b4} = \begin{bmatrix} 326 & 310 & 290 & 270 & 282 & 334 & 354 \end{bmatrix} \text{ voltage in volts} \]

\[ \text{p}_{d4} = \text{d}_4 \times \text{P}_4; \]

%% 500um Thick wafer

\[ \text{d}_5 = 0.0372 \text{ cm or 0.01465in} \]

\[ \text{P}_5 = \begin{bmatrix} 30.7 & 50.6 & 83.1 & 98.2 & 149 & 198 & 498 \end{bmatrix} \text{ pressure in millitorr} \]

\[ \text{P}_5 = \frac{\text{P}_5}{1000}; \text{ pressure in torr} \]

\[ \text{V}_{b5} = \begin{bmatrix} 346 & 346 & 308 & 298 & 298 & 282 & 352 \end{bmatrix} \text{ voltage in volts} \]

\[ \text{p}_{d5} = \text{d}_5 \times \text{P}_5; \]

%% Comparison plot for Thick wafers

figure(3)

plot(pdb, Vbb, 'b.-', 'linewidth', 3)
hold on
plot(pd3, Vb3, 'go:','linewidth', 2)
hold on
plot(pd4, Vb4, 'rx-.' , 'linewidth', 2)
hold on
plot(pd5, Vb5, 'k+--','linewidth', 2)
hold on
grid on
title('Paschen curves of thick wafers.')
xlabel('pd (torr-cm)')
ylabel('Vb')
legend('Baseline','300um','400um','500um','Location','SouthEast')
LIST OF REFERENCES


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