Application of oxygen IAD using a new high-power gridless plasma source

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ABSTRACT

An improved plasma source for use with oxygen and other gasses has shown great stability at ion power levels almost an order of magnitude above those of the other commercially available gridless sources. The original motivation for this work was to obtain as powerful a source of oxygen ions with neutralizing electrons (plasma source) for the reactive deposition of SiO_2 from SiO. The results are also applicable to other gasses such as nitrogen, argon, etc., and other deposition materials. The characterization of the source in detail by the use of the Design of Experiments methodology is discussed.

Key Words: Gridless ion sources, high power, high deposition rates, Design of Experiments

1. INTRODUCTION

Ion Assisted Deposition (IAD) has become well established as a means of improving optical coating performance and reducing cost. Some performance improvements include durability, stability with humidity and temperature, and better stoichiometry. Cost reductions result from low temperature deposition and increased rates for reactive processes. Most of the early process development was performed using gridded Kaufman-type sources. These are characterized as commonly being used with a relatively collimated beam of ions with a well defined and narrow distribution of ion energies or electron volts (eV). Cuomo et al.[1] give an extensive description of the various gridded sources and others. The grids are commonly made of graphite to minimize sputtering of the grids and do not stand up well to the use of oxygen in the source. The internal filaments are subject to relatively high gas pressures and are also vulnerable to oxygen. For these reasons, we have worked more extensively with the broad beam sources which work better with oxygen under high power usage.

Since the rate at which a film deposition can occur is limited by the ion beam power, we want to operate the ion sources at the highest beam power practical. We speak here of beam power as the eV of the ions multiplied by the current of the beam. For most materials such as TiO_2, there is an upper limit on the eV beyond which the coating properties are degraded due to ion damage to the deposited materials and therefore to the optical properties, particularly absorption. The power density of the ions cannot practically be increased by added voltage beyond some point such as about 300 eV for TiO_2, although SiO_2 might tolerate 600 eV. Investigations of commercially available End-Hall and Cold Cathode sources have shown that the former tends to have a lower than desired eV capability and the latter tends to be too high. The eV characteristics of both are affected by gas flow and chamber pressure. The excess pressures needed for voltage control and high power operation can degrade the properties such as density and mechanical strength of the deposited films.

Our original motivation for this work was to obtain as powerful a source of oxygen ions with neutralizing electrons (plasma source) as possible and as economically as practical for the reactive deposition of SiO_2 from SiO as mentioned above. However, the results are applicable to other ions such as nitrogen, argon, etc., and other deposition materials. We reported[2] on the development of processes which convert the SiO to SiO_2 during deposition by the use of IAD. The additional oxygen must be supplied in a sufficiently energetic process to provide the material conversion during the SiO deposition on the surface to be coated. The deposition rate (1-2 nm per second), the uniformity, and the repeatability of the processes must also be adequate for the production of the coating at an economical rate. These experiments have been done with commercially available Commonwealth Scientific Mark II End Hall source, the Denton Cold Cathode CC-102R ion source, and two high power plasma sources developed jointly by the author with DynaVac[3]. Our experience to date has included these four types sources and the Ion Tech gridded Kaufman source. Our principal requirements for the SiO to SiO_2 conversion were processes wherein the sources had to operate for many continuous hours. Because the filaments and grids of the Kaufman type source could not be expected to survive the full power oxygen operation required, we made no attempt to use these sources in this case. The Cold Cathode source was said to "prefer" operation with oxygen over argon because the argon would sputter the interior of the source. Therefore, our first efforts were with the Cold Cathode source. Dobrowolski et al.[4] used this source for the IAD of ITO. The End Hall source has some similar characteristics to the Cold Cathode and we also developed it into a somewhat satisfactory solution to our requirements. In both cases, we operated at the maximum power capability of the sources consistent with stable and long term operation.

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2. "COLD CATHODE" SOURCE

The cross section of the Cold Cathode Source on which we have previously reported[2] is seen in Fig. 1. There is a tungsten neutralizer over the aperture which we typically operated at its maximum current of 20 amps. The neutralizer voltage ranged from 12 volts upward with age. The filament sometimes lasted more than 10 hours and was easy and inexpensive to replace, so that it was not as big a problem as in a Kaufman gridded type source. The power supply had three controls: neutralizer amps, bias volts, and drive amps. There were displays of drive volts and beam amps. We set the neutralizer to maximum current, the bias to zero (but not off), and controlled only the drive volts through the drive current and the gas flow.

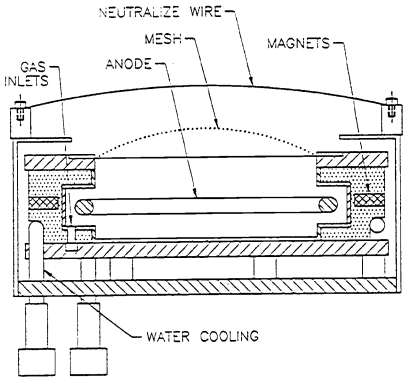

Figure 1 Cold Cathode Source tested.

The behavior of the Cold Cathode Source is a strong function of the gas pressure, flow conditions through the cavity, the neutralizer emission, and the "cleanliness" or surface conditions inside the source cavity. Our experience leads us to think that the drive voltage is somewhat linearly related to the actual output beam voltage and similarly that the drive amps is related to the beam amps. The drive voltage is primarily a function of the drive amps applied and the gas flow through the source. There is also a significant effect of source cleanliness by which we mean the state of deposits which build up in the cavity with use. We found it necessary to clean the source after every usage (of about eight hours).

If any of these five types of sources is operated without enough neutralization, we observe sparks on the substrates and fixturing, and arcing indications on the source power supply. These sparks usually cause damage to coating and substrate. On the other hand, we have seen no ill effects from excess neutralization. We observe that, if the pressure in the cavity of the Cold Cathode source drops too low, the drive voltage increases and at some point the source will arc. This seems to disrupt the steady operation of the ion beam conditions, and therefore we avoid this condition if at all possible. Because neutralization is essential, all of these sources should be considered plasma sources, and the Denton source is *not* a cold cathode source in practice!
Our early experiments with the largest standard aperture supplied with the "Cold Cathode" source pointed to the desirability of keeping the drive volts below 400 for minimum absorption in the films and above 300 to obtain the maximum beam power. We prefer to operate at 300 V or less. We could seldom approach the lower limit of 300 with the large aperture because the gas flow required for that with the typical source conditions and the resulting chamber pressures would be too high to allow the production of the desired robust films.

The use of this source with a reduced aperture increases the pressure inside the cavity while decreasing the chamber pressure for a given gas flow. In this configuration in a 1100 mm chamber, the operating conditions are typically: 20-40 SCCM oxygen flow, 1 amp drive current, 250-300 drive volts (250-300 drive watts), and resulting chamber pressure of $0.7\text{-}2.2\times10^{-4}$ torr. This has been reported to produce results which are equal to or better than the larger aperture results.

When operating at the high powers which we used, the standard power supplies provided to us by the manufacturer did not stand up to continuous operation at full power. There was an internal melt-down of one of the PC boards after extended use on at least six occasions with three separate power supplies.

We have used this deposition arrangement and technique extensively for the development of stacks ranging from 40 to 90 layers of SiO_2 and TiO_2. Insignificant spectral shift with changing humidity can be achieved using this IAD system. Without IAD, we typically may see a 15 to 20 nm spectral shift. The deposition conditions in a 760 mm chamber of such a run using the large source aperture might be: 225°C, 1 nm per second for both materials, 48 SCCM of oxygen through the ion source, 450-500 drive volts, 1.0 drive amps, 20 amps for the neutralizer, and the chamber pressure would be mostly in the range of 1.0 to 1.5×10^{-4} torr. The SiO layers getter more than the TiO_2 and therefore the higher chamber pressures are associated with the TiO_2. These films also pass the adhesion and severe abrasion tests of MIL-C-675. The resulting index of the SiO_2 is about 1.50. We have found that the conditions which give little or no humidity shift with this type of coating are not necessarily compatible with some laser damage requirements. Additional oxygen is required to reduce the laser damage and give an index of about 1.46, but the humidity shift will partially return, perhaps 6-8 nm. There may also be some correlation between the excessively high (450-500) drive volts and the laser damage threshold.

The ion source parameters must be reasonably stable or the film thickness uniformity over a calotte has been seen to have some

changes. The ion beam has a distribution which is clearly more concentrated on the axis of the beam. It appears that if an adequate amount of ions reach the less bombarded areas, the excess ions in the more bombarded areas are not detrimental. We have had some indication that this is less true when the drive volts are in the high (500 V) region. The hypothesis is that some ion etching may be occurring at the higher drive volts and thereby the thicknesses of the layers are slightly reduced at the center of the beam impingement area.

3. END-HALL SOURCE

The End-Hall source has many similarities to the Cold Cathode source described above and some differences. Figure 2 illustrates the general configuration. Kaufman and Robinson[5] and Cuomo, Rossnagel, and Kaufman[1] describe these sources in some detail. The gas to be ionized is admitted to the throat of the anode at a controlled flow rate. Electrons from the AC current heated cathode bombard the gas. A high voltage is applied to the anode and ionization of the gas occurs. The magnetic field in the anode region is primarily axial which enhances the affectivity of the electrons. The ions are accelerated upward from the anode. Electrons from the cathode also serve as the neutralization for the ion beam.

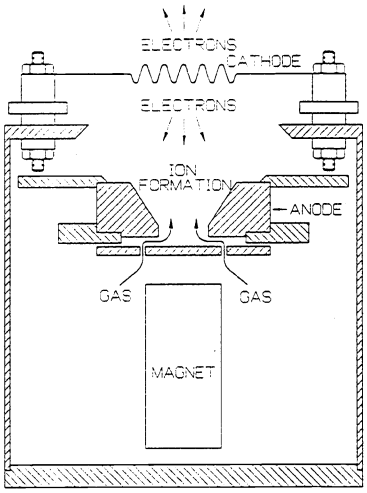

Figure 2 End-Hall Source tested.

It can be seen that the cathode is similar to the neutralizer of the Cold Cathode source. The magnetic fields and gas feeds are similar also. The anode configurations are different in detail, but similar in function. The major difference seems to be that the gas is confined to a smaller space where ionization occurs in the End-Hall source described here. This allows lower ion voltages at lower gas flow rates and therefore lower total chamber pressures.

The source which we have used has limits of: 5.0 amps of drive current, 175 anode or drive volts, 50 SCCM gas flow, 25 amps of cathode or neutralizer current. We have chosen: 4.0 amps drive current, 120 anode volts, and 19.0 amps of starting cathode current because the controller was unstable at the high limits of voltage, current, and gas flow. The controller/power supply is automated to start the discharge and then control the beam to preset values. A starting anode voltage and gas flow are preset, we used 130 volts and 20 SCCM. Upon starting, the controller heats the cathode, stabilizes the gas flow to the preset value, and brings up the anode voltage until the discharge starts. After a number of seconds, the controller adjusts the system to the chosen running values set on the knobs of the controller. In principle, the controller then maintains the ion beam at constant voltage and current. The voltage is controlled by the gas flow in a servo loop, the drive current is maintained by a current control loop, and the neutralizer has a third loop which attempts to maintain neutralizer current.

We initially had great difficulty in achieving stable operation of this system. At first, we were told to be concerned about cleanliness of the source-head components, gas leaks in the interface of the head to its mounting plate, and coating on the cables in the chamber. We did find it necessary to shield the ion source from the electron gun cabling near the baseplate of the chamber to overcome arcing, noise, and interactions. However, our other concerns above turned out to be inconsequential. As long as all of the electrical connections were good and no major coating buildups occurred on insulators leading to the head, we had no difficulties with the head.

The controller was another story. Since our need was to get the maximum ion current density practical at an acceptable voltage from the source, we operated at the limits of the system capability. The three control loops seemed to interfere with each other. We were only able the achieve stable operation after making two changes to the control system. First we removed the neutralizer/cathode power control from the controller and replaced it by a manual variable voltage control. We set the cathode current to about 20 amps before starting the source and left the voltage control set for the rest of the day. This provided satisfactory results and the longest cathode life (about 10 hours). The current through the cathode did drop to the 15 amp range toward the end of its life, but the source operation was stable until the cathode burned out. The second thing we found necessary was to properly compensate the current control loop for stability. As chamber conditions changed such as pressure during evaporation of a gettering material, the current and gas flow controls experienced transients. If the compensations were not correct, this lead to oscillations and/or the gas flow going to its fully open limit with no control. With the changes mentioned, we found stable operation at 4.0 amps and 120 volts (480 drive watts). When transients occurred, the current might approach 5.0 amps. If it exceeded 5.0 amps, it tended to lose control and stay at the upper limit. We therefore operated at 4.0 amps to leave it just enough margin to accommodate normal process

transients.

The anode parts and gas distributor plate used were made of non-magnetic stainless steel. When operated with oxygen, these surfaces developed a brown or orange color and we seem to have observed decreasing system stability. We experimented with 50/50% and 25/75% mixture of Ar/O_2 and found the 25/75% most stable. We were very pleased to find that the cleaning needed for this source when we used the 25/75% mix was very easy. When setting up for a run and before installing a new cathode, we scrubbed the cone of the anode and the exposed spot on the gas distributor plate with ScotchBright$_{TM}$ and removed the dust produced with a vacuum cleaner. The cathodes are a consumable item which we replaced before every long run. It is important to be sure that good electrical contact is made, particularly with the spring fingers of the push-on connectors. This seems to be hypersensitive if the controller has not been modified as we had done to remove the neutralizer control loop.

We found the End-Hall source with the control system as we had modified it to be stable, reproducible, and easy to maintain. The beam gave good results and uniformity over a 1150 mm diameter calotte when aimed at the 70% radius. The densification and oxidation of the SiO/SiO_2 seemed better than the Cold Cathode source under the same conditions. The effects of gettering were not as apparent here since the End-Hall source seemed to achieve higher beam current with less gas flow. The make-up oxygen supplied to keep constant chamber pressure was probably greater with the End-Hall source.

4. COMPARISON OF THE "COLD CATHODE" AND END-HALL SOURCES

Our previous work with gridded Kaufman sources showed that TiO_2 tended to be damaged to the point of some absorption by ions in excess of 200 eV while SiO_2 was not adversely affected by 600 eV. The mean ion eV of the End-Hall source has been estimated by Kaufman and Robinson[5] to be 60% of the anode voltage and by similarity the Cold Cathode source may be about 60% also. This would lead to the estimation that the End-Hall source was providing a mean of about 72 eV ions and the Cold Cathode about 200+ eV. If the drive currents for the two sources can be compared at 4.0 amps and 1.0 amps respectively, this implies a relative maximum ion power of 72x4 to 200x1, or a 288:200 ratio between the End-Hall and Cold Cathode sources. This is consistent with our observations in that the End-Hall seems somewhat stronger, but not overwhelmingly so. It appears that the End-Hall source is challenged to operate at a higher anode voltage for more beam power up to the point of film damage (200ev/.60) while the Cold Cathode source is challenged to operate at a lower anode voltage (333 V) to avoid damage. Both sources have proved usable but have significant room for improvement as provided by the manufacturers.

5. DEVELOPMENT OF A NEW SOURCE

Our needs and desires for the application mentioned would be best met by a system which operated stably at 300 drive volts (V_D) or less and at least 3.0 amps of drive current (A_D). The experience with the above sources and their limitations provided the basis for further developments toward higher power. We measured the performance of a special prototype unit developed by the author with DynaVac which was operated continuously at 3000 drive watts (W_D), as compared with the 300 W_D of the Cold Cathode or 480 W_D of the End-Hall. These tests were conducted with a gas mixture of 75/25% O_2/Ar. The neutralizer current (A_N) was set just above that needed to avoid arcing and sparking, and this seemed to provide optimal performance.

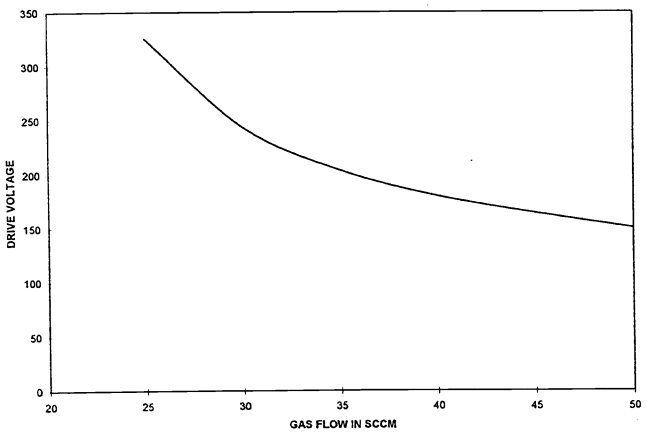

Figure 3 Drive volts versus gas flow at 10 amps drive current, A_D. In order to have not sparking, A_N had to be 15.5 at 25 SCCM and 16.1 at 50 SCCM.

Figure 3 shows that the V_D can be controlled by the gas flow between 175 and 333 volts which was the desirable but missing region between the two other gridless sources. At lower than about 25 SCCM, this particular design becomes too "lean" and unstable, but above this it is very stable and the chamber pressure as tested was always less than 1×10^{-4} torr. We think that it may be possible to adjust the details of this source design to produce ions anywhere in the range from 100 to 600 eV. The A_N required for a 440 mm length of 0.5 mm diameter tungsten wire coiled to fit the connections above the source starts at about 12 amps for low source drive current. At low A_D, it appears that most of the neutralizer power is used to raise its temperature to where thermal electrons are emitted. Only small increases of A_N to 16

amps are needed to neutralize an order of magnitude more ions at 10 A_D. There is a generally flat shape of the V_D with A_D, changing from about 180 volts at 1 amp to 240 volts at 10 amps. The change in the biased ion probe reading with drive current supported our assumption that ion current is nearly proportional to drive current. Figure 4 shows the probe current profile on a flat plane perpendicular to the axis of the source and 575 mm from the source. The beam was developed to be quite broad for coverage of more surface area. There is one caution, however. Because of the much higher level of plasma in a given chamber, the shielding of the high voltage leads of electron beam guns must be very carefully done. An exposed high voltage lead or terminal at many kilovolts will attract positive ions which will cause arcing.

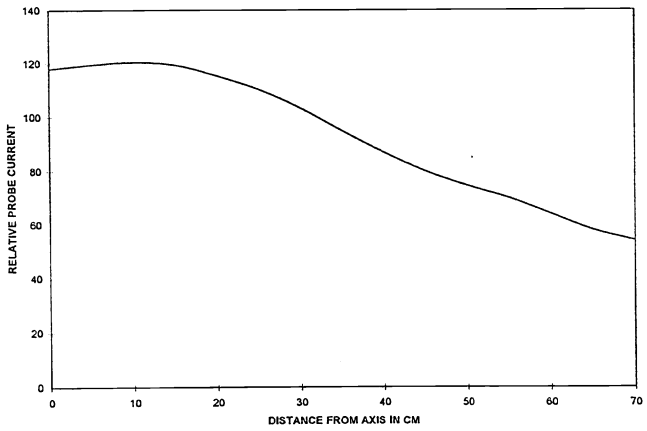

Figure 4 Ion probe readings versus position off-axis in a flat plane perpendicular to the source axis at 60 cm from the source for 26 SCCM, 10 A_D, 310 V_D, and 16.0 A_N.

6. CHARACTERISTICS OF A NEW PRODUCTION SOURCE

The fifth source which we tested was a somewhat lower power commercial version of the prototype source which is now produced by DynaVac as the Model IS1000 ion source. Dozens of these units have had extensive use in production with very satisfactory results. Figure 5 is a result from the use of Design of Experiments (DOE) methodology[6] to efficiently characterize the new ion source. The figure shows the biased ion probe current versus gas flow and drive current. It can be seen that the probe reading is primarily proportional to drive current and not a strong function of gas flow. However, as we discussed above, the drive voltage can be controlled by gas flow and therefore the beam power is a function of gas flow. One problem should be pointed out with the simple ion probe measurements which we have performed. The probe responds only to charged particles and would not register atoms that became neutralized before impinging on the probe. It is possible that the departure from a rectilinear relationship of the probe current to the drive current is due to this effect.

DOE has proved to be a very valuable tool for us because it can maximize the information gained from a minimum of experiments or tests. In the field of optical coatings where there are many variables which can affect the results, any methodology to reduce the number of tests needed in process development and optimization is valuable. DOE can also help in finding how to stabilize a process, which is particularly valuable in many cases. It is this author's opinion that earlier texts on the subject were difficult to study and not very appealing to the practical process engineer. However, Schmidt and Launsby[6] have made the background and application much more palatable and easy to grasp for the statistically unsophisticated. We have used these tools to study the characteristics of the DynaVac IS1000 with great success and a minimum of effort.

The variables available on the IS1000 are: gas type (or mixture), gas flow in SCCM, neutralizer current, and drive current or power. As the source for the anode power of our IS1000, we used an MDX II power supply from Advanced Energy[7]. This unit has the capability to supply 15KW from a selection of taps; we used tap #4 at 800 volts and 18.75 amps. It can be operated in power, current, or voltage regulation modes. The current regulation mode is preferred, but the power mode can sometimes be more stable in certain regions of operation. The results of interest are: drive voltage (ion eV), ion current, ion distribution in space, and stability.

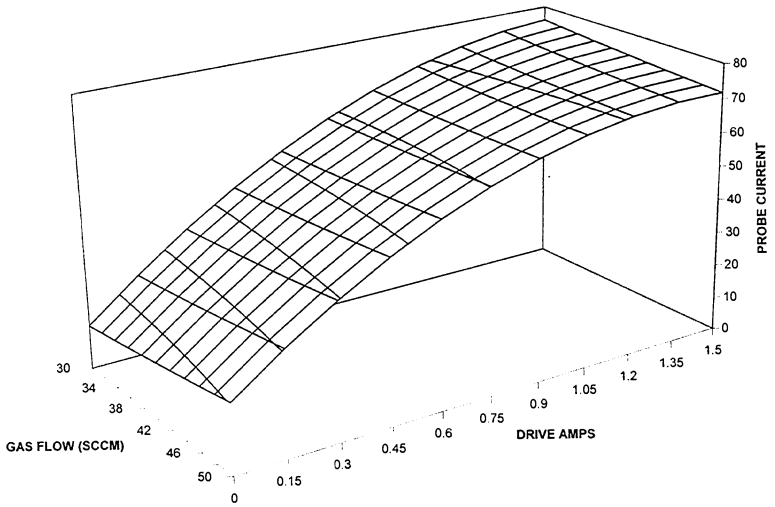

Figure 5 Probe current versus drive current and gas flow of IS1000.

For the purposes of this investigation, we

focussed on the drive voltage result and we assumed that the ion current was approximately proportional to the drive current as in Fig. 5 and that the spacial distributions are essentially the same as Fig. 4. The detailed quantitative study of ion current and stability have been left for a future time where we will record the probe current and its fluctuations. In the present series of tests, we recorded the drive voltage as a function of the variables where the drive power was kept as constant as possible at 1.0 kilowatts by supplying whatever current was needed to reach 1KW. In some extreme regions of operation, it was only possible to get stable readings up to about 0.75KW and extrapolate this data to 1KW. We varied the gas type from pure oxygen (0% argon), to 25% argon, and to 50% argon mixed with 50% oxygen by weight. The remaining variables were then gas flow in SCCM and the neutralizer current setting.

There were two results of major interest which were not apparent from our earlier investigations. Figure 6 shows the variation of drive volts with gas mix or % argon and with the gas flow rate. It shows that a mix with about 35% argon is predicted to give the lowest drive volts with this source for a give gas flow. On the other hand, it would still be possible to reach higher drive voltages when desired by a lesser flow of this mix. Figure 7 shows the results at the mix (25% argon) closest to this predicted optimum as a function of gas flow and neutralizer current. The second result of interest is that the drive volts is only a weak function of the neutralizer current. This implies the A_N can be chosen with impunity to just neutralize ion charging and not otherwise have a significant impact on the performance of the source. Figures 8 and 9 further confirm this for 0% and 50% gas mixes. All of the mixes tested show the increase in voltage with decreased gas flow, but the 0% mix is more rectilinear and goes to higher voltages while the 50% mix has intermediate rectilinearity to 0 and 25% but only goes to lower voltages. Our choice for future operations will probably be a 35% argon mixture.

It should also be pointed out that the gas flow controller used for these recent tests was calibrated for pure argon and therefore the readings for these gas mixes are only relative readings. The gas flow required to achieve a given result also seems to depend on the pumping speed of the chamber in which the ion source is operated. Therefore, these SCCM numbers should only be taken as relative. At one point, we thought that the chamber pressure might be more of a factor than the flow through the ion source. However, on two separate occasions, we supplied the gas to the chamber but not through the ion source and the source would not function at all.

Figure 10 illustrates the test matrix of the Box-Benken[6] type of designed experiment and the measured values of drive

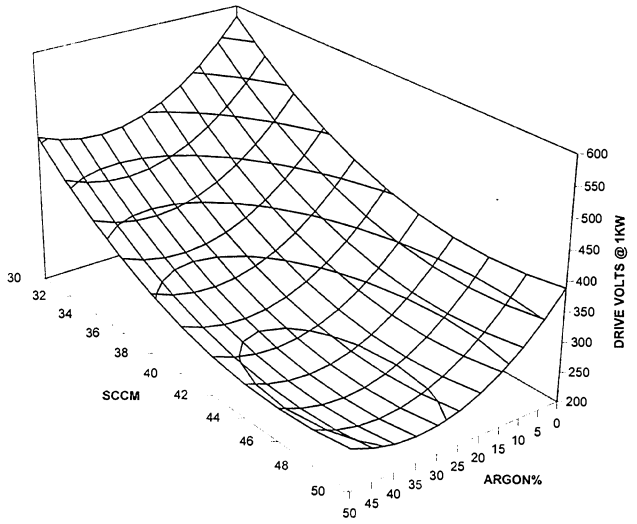

Figure 6 Drive volts as a function of % argon mixed with oxygen and gas flow in SCCM at 1 kilowatt input power.

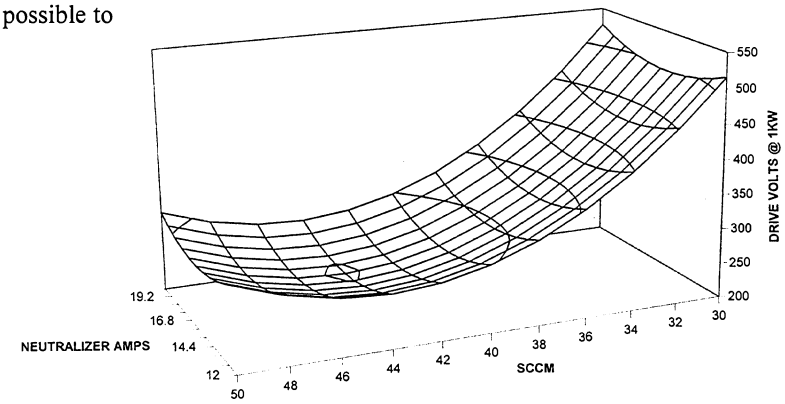

Figure 7 Drive volts as a function of gas flow in SCCM and A_N for a 25% argon in oxygen gas mix.

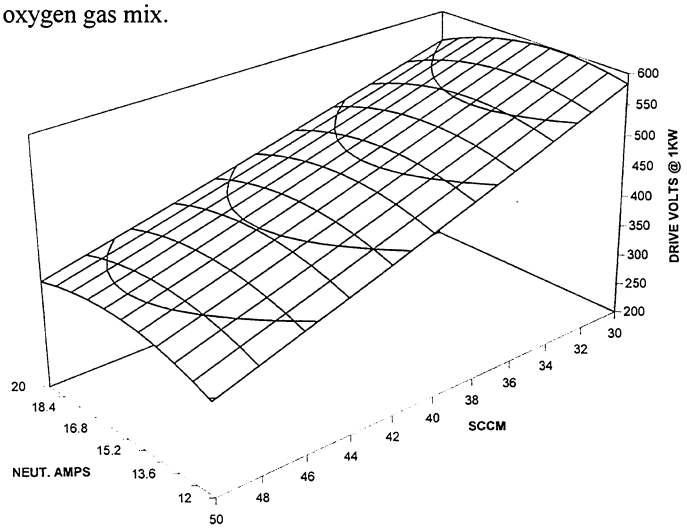

Figure 8 Drive volts as a function of gas flow in SCCM and A_N with pure oxygen (0% argon) at 1 kilowatt of drive power.

volts, Y1. When this data is processes by the DOEKISS software available from the Air Academy Press[6], it generates the results in Fig. 11 and various graphics such as Fig. 6 in the case of this data. From Fig. 11, we can determine the significant factors from the P(2TAIL) column. The smaller values indicate the most significance. Thus we see that ARGON% (B) and SCCM (C) with their squares, BB and CC, are the significant parameters, and ANODE (A) and AB are of some minor influence. ANODE was a variable parameter under investigation which we are not a liberty to discuss at this time, but it was surprising to discover that it was not a major factor by way of these experiments. From the information in Fig. 11, we are able to generate an equation to predict the drive voltage (at 1 kilowatt) as a function of gas mixture and gas flow over the range of those variables which has been investigated. The equation below is such a result from this data.

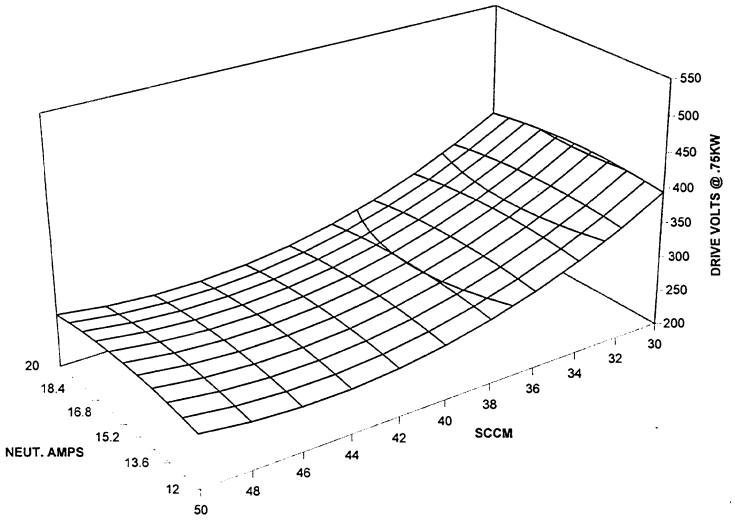

Figure 9 Drive volts as a function of gas flow in SCCM and A_N with 50% argon and 50% oxygen by weight at .75 kilowatts of drive power.

$$V_D = 269.7 - 2.45\ B - 9.50\ C + .1169\ BB + .8104\ CC$$

The values to use for B and C in this equation are the difference in ARGON% from the midpoint, 25%, and the difference in SCCM from the midpoint, 40. Therefore, to find the drive volts at 0% argon and 30 SCCM, we use B=-25 and C=-10 which gives 580 volts as seen in Fig. 6. By taking the derivatives of the equation to find the minimum, we find B=10.48 and C=5.86. These give 229 volts as the minimum at 35.48% argon and 45.86 SCCM. Figure 11 also shows the Standard Error of fit (13.27 volts) between the experimental data and the function generated by the coefficients. The DOE tools can be seen to easily provide useful information and analysis while minimizing the number of experiments needed to characterize and optimize a process.

Column #	1	2	3	
Row #	ANODE	ARGON%	SCCM	Y1
1	-1	0	40	434
2	-1	50	40	257
3	1	0	40	404
4	1	50	40	298
5	-1	25	30	441
6	-1	25	50	254
7	1	25	30	455
8	1	25	50	275
9	0	0	30	575
10	0	0	50	376
11	0	50	30	469
12	0	50	50	275
13	0	25	40	271
14	0	25	40	269
15	0	25	40	269

Figure 10 DOE design for three variables with drive volts measurement input, Y1.

7. SUMMARY

The new plasma source satisfies the needs which were not entirely met by previously available sources. After extensive development and laboratory testing, the resulting improved plasma source with oxygen and argon mixtures has shown great stability at ion power levels many times greater than those of the other commercially available gridless sources. This source has been extensively characterized using the Design of Experiments methodology. It was found that a minimum voltage is predicted when 35% of argon by weight is mixed with oxygen and our actual tests with a 25% mix have shown great stability at over one (1) kilowatt of drive power. It has been shown that the neutralizer current can be selected with impunity to balance the ion charge without significantly affecting the ion source performance.

FACTOR	COEF	P(2 TAIL)	TOL	LOW	HIGH	EXPER	ACTIVE
Constant	269.6667	*0.0000*					
ANODE	5.7500	0.2751		-1	1	0	X
ARGON%	-61.2500	*0.0000*		0	50	25	X
SCCM	-95.0000	*0.0000*		30	50	40	X
AB	17.7500	*0.0441*					X
AC	1.7500	0.8026					X
BC	1.2500	0.8580					X
AA	5.5417	0.4589					X
BB	73.0417	*0.0001*					X
CC	81.0417	*0.0001*					X
R Sq	0.9939						
Adj R Sq	0.9831						
Std Error	13.2753						
F	91.2271		PRED Y			269.67	
Sig F	0.0001						

Figure 11 Results generated by DOEKISS from data in Fig. 10 and used to form the prediction equation, etc.

8. REFERENCES

1. J. J. Cuomo, S. M. Rossnagel, and H. R. Kaufman, *Handbook of Ion Beam Processing Technology,* (Noyes Publications, Park Ridge, NJ , 1989.)

2. R. R. Willey, "Achieving Improved Optical Thin Film Control and Uniformity of Silicon Dioxide by Using Ion Assisted Deposition," *Proc. Soc. Vac. Coaters* **36**, 75-81 (1993).
3. DynaTenn, Inc., dba DynaVac, 30 Woodrock Road, Weymouth, MA 02189-0004.
4. J. A. Dobrowolski, F. C. Ho, D. Menagh, R. Simpson, and A. Waldorf: "Transparent, conducting indium tin oxide films formed on low or medium temperature substrates by ion-assisted deposition," *Appl. Opt.* **26**, 5204-5210 (1987).
5. H. R. Kaufman and R. S. Robinson, *Operation of Broad-Beam Sources,* Sec. VI, (Commonwealth Scientific Corp., Alexandria, VA, 1984.)
6. S. R. Schmidt and R. G. Launsby, *Understanding Industrial Designed Experiments,* Air Academy Press, Colorado Springs, 4th edn.,1994
7. Advanced Energy Industries, Inc., 1625 Sharp Point Drive, Fort Collins, CO 80525.