Improvements in Gridless Ion Source Performance

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ABSTRACT

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. The rate at which a deposition can occur with IAD is limited by the ion beam power; twice the power would allow twice the rate. Beam power is the electron volts (eV) of the ions times the current of the beam. For most materials there is an upper limit on the eV beyond which the coating properties are degraded due to ion "damage." Investigations of commercially available End-Hall and Cold Cathode sources have shown that the former has a lower than desired eV capability and the latter tends to be too high. Both sources have exhibited operational stability problems due to source component changes with use and power supply instabilities. 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 performance of the deposited films. The concepts and techniques used to overcome these limitations and increase the power and stability by several times are discussed.

INTRODUCTION

Our original motivation for this work was to obtain as powerful a source of oxygen ions with neutralizing electrons (plasma source) as economically as practical for the reactive deposition of SiO_2 from SiO. However, the results are applicable to other ions such as nitrogen, argon, etc., and other deposition materials. We reported[1] on the development of processes which convert the SiO to SiO_2 during deposition by the use of ion assisted deposition. 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 (10-20Å 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 End-Hall and Cold Cathode ion sources and a developmental model of a new plasma source. A comparison of the results and behavior observed with each type of source are reported. Our experience to date has included four types of ion sources: the Ion Tech gridded Kaufman source, the Denton Cold Cathode CC-102R, the Commonwealth Scientific Mark II End Hall source, and a high power plasma source of our own design. In all cases, our process speed was limited by the rate at which we could deposit the materials and obtain the desired properties. This rate is limited in turn by the ion current density which can be provided. We therefore want to operate the ion sources at the highest beam power practical. We also have learned from the literature and our own observations that there is an upper limit on the eV of the ions. Excess eV will cause 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 300eV for TiO_2, although SiO_2 might tolerate 600eV. Our principal requirements for the SiO to SiO_2 conversion were processes which run for many hours. It is our understanding (and experience) that the filaments and grids of the Kaufman type source could not be expected to survive the full power oxygen operation required, and therefore we made no attempt to use these sources in the present case. The Cold Cathode source was said to "prefer" operation with oxygen over argon because of sputtering effects. Therefore, our first efforts were with the Cold Cathode source. The End Hall source has some similar characteristics to the Cold Cathode and was also developed 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.

COLD CATHODE SOURCE

The cross section of the Cold Cathode Source on which we have previously reported[1] is seen in Fig. 1. A molybdenum anode is surrounded by an aluminum cavity which is in turn surrounded by a ring of permanent magnets which produce a magnetic field. The gas is admitted to the source chamber through six (6) small orifices below the anode ring by a gas flow controller. The source is water cooled. It can be biased to offset the voltage of the whole system with respect to ground, but we have no experience with this; we have only operated at zero bias volts. 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
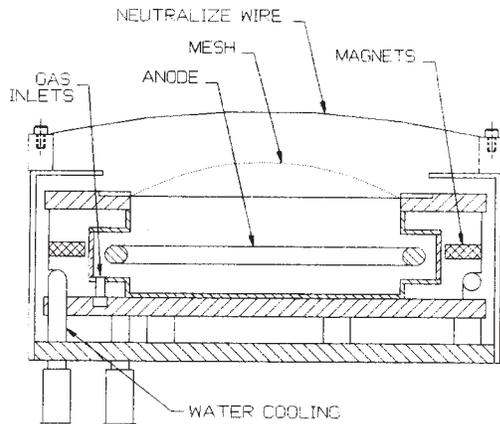
Fig. 1. Cross section of the Cold Cathode source tested.

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.

Cold Cathode Source Characteristics
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. We assume 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 four 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. 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 source pointed to the desirability of keeping the drive volts below 400 for minimum absorption in the films and above 300 for maximum densifying effect (beam power).

We prefer to operate at 300V 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 1100mm 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 0.7-2.2×10^{-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, if the neutralizer were turned off, one could observe the molybdenum anode to be glowing a dull red. We believe that we accidentally operated the source without water cooling at one time and that this partially demagnetized the magnets of the source. The result of the lower magnetic field is to increase the drive voltage under otherwise constant conditions. Since this is very undesirable, operation without water cooling is to be assiduously avoided. The magnets cost $150-$600 to replace. We have also experimented with a higher current power supply and seemed to have overheated and damaged the magnets at about 2.0 amps of drive current even with water cooling. The standard power supplies provided to us by the manufacturer did not stand up to continuous operation at full power. There was an internal meltdown of one of the PC boards after extended use on at least six occasions with three separate power supplies.

Results with the Cold Cathode Source
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 20nm spectral shift. The deposition conditions in a 760mm chamber of such a run using the large source aperture might be: 225 degrees Celsius, 10Å 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 6-8nm. There may also be some correlation between the excessively high (450-500) drive volts and the laser damage threshold.

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The ion source parameters must be reasonably stable or the uniformity 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 (500V) 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.

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[2] and Cuomo, Rossnagel, and Kaufman[3] describe these sources in some detail, but we will also give a brief description here for the convenience of the reader. 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.
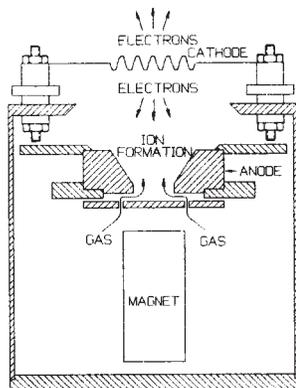

Fig. 2. Cross section of the End-Hall source tested.

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.

End-Hall Source Characteristics

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 volts 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 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 fight 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 Variac control. We set the cathode current to about 20 amps before starting the source and left the Variac 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 amps 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 saw transients. If the compensations were not correct, this lead to oscillations and/or the gas flow going full open with no control. With the changes mentioned, we found very stable operation at 4.0 amps and 120 volts (480 drive watts). When transients occurred, the current might go near 5.0 amps. If it exceeded 5.0 amps, it tended to lose control and get "locked-up." We therefore operated at

4.0 amps to leave it just enough headroom 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 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.

Results with the End-Hall Source
We found the End-Hall source with the control system as we had modified it to be quite stable, reproducible, and easy to maintain. The beam gave good results and uniformity over a 1150mm diameter calotte when aimed at about 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.

AN IMPROVED PLASMA SOURCE

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 200eV while SiO$_2$ was not adversely affected by 600eV. The mean ion eV of the End-Hall source has been estimated[3] 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 about 72eV 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 ion power of 72x4 to 200x1 or 288:200. This is consistent with out 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 (333V) to avoid damage. Both sources have proved usable but have significant room for improvement as provided by the manufacturers.

Our needs and desires 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. The experience with the above sources and their limitations provided the basis for further developments toward higher power. The resulting improved plasma source might be called a "Fafnir" because it is like a *fire-breathing-dragon.* We will describe the measured performance of a prototype unit which was operated continuously at 3000 drive watts (W$_D$), as compared with the 300W$_D$ of the Cold Cathode or 480W$_D$ of the End-Hall. Unless otherwise noted, the test data is all given for operation with a gas mixture of 75/25% O$_2$/Ar at 30 sccm at a drive current (A$_D$) of 10 amps and the neutralizer current (A$_N$) was set just above that needed to avoid arcing and sparking.
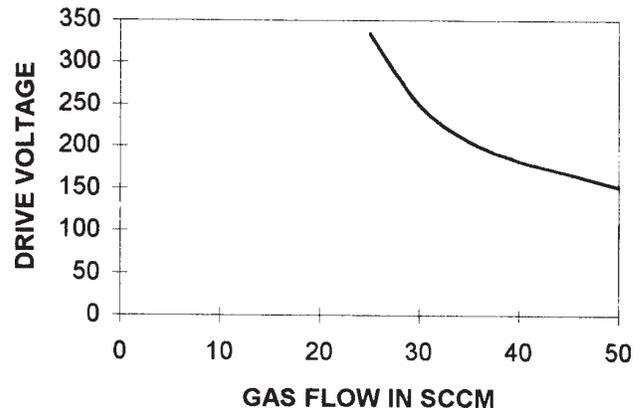

Fig. 3. V$_D$ versus Gas Flow at 10A$_D$. To have no sparking required 15.5A$_N$ at 25 sccm and 16.1A$_N$ at 50sccm.

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", but above this it is very stable and the chamber pressure as tested was always less than 1×10^{-4} torr. The A$_N$ is shown in Fig. 4 for a 17" length of .020" diameter tungsten wire coiled to fit the connections above the source. 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$_N$ are needed to neutralize an order of magnitude more ions at 10 A$_D$. Figure 5 shows the generally flat shape of the V$_D$ with A$_D$, the ripples are probably experimental irregularities. Figure 6 shows the change in the biased ion probe reading with drive current which partially supports our assumption that ion currentis proportional to drive current. Figure 7 shows the probe current profile on a flat plane perpendicular to the axis of the source and 23" 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
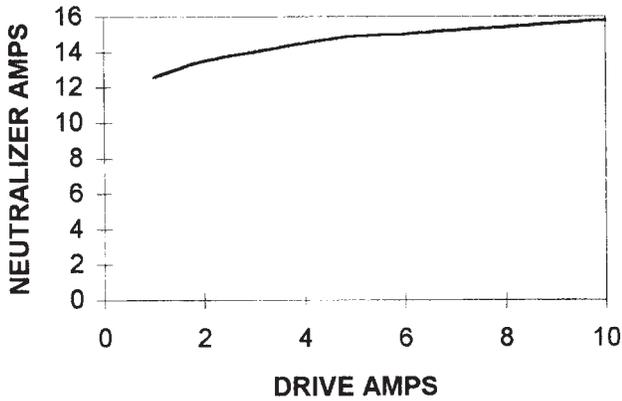
Fig. 4. A_N versus A_D at 30sccm, same test as in Figs. 5 and 6.

guns must be very carefully done. An exposed high voltage lead or terminal at many kilovolts will attract positive ions which will cause arcing. This is probably similar to the needs in a reactive ion plating system.
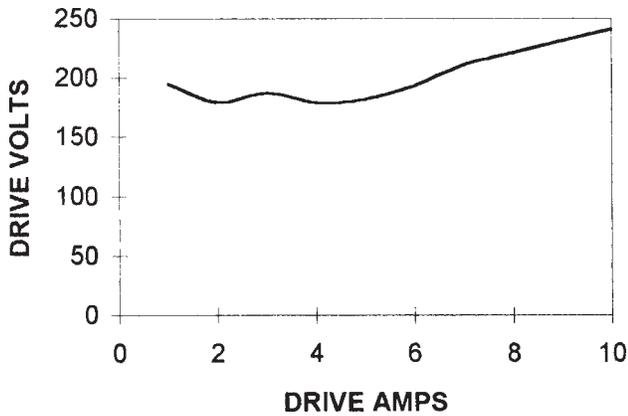

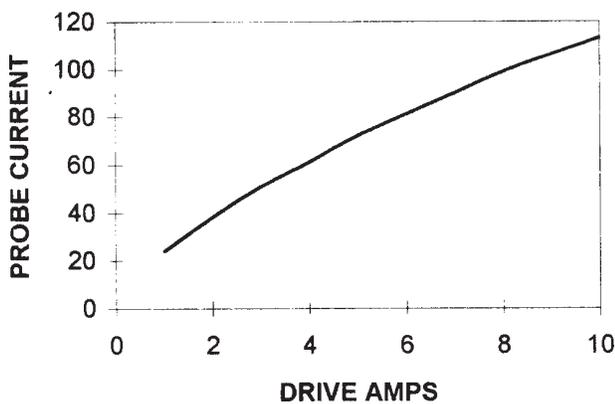Fig. 5. Fafnir V_D versus A_D in same test as Figs. 4 and 6.

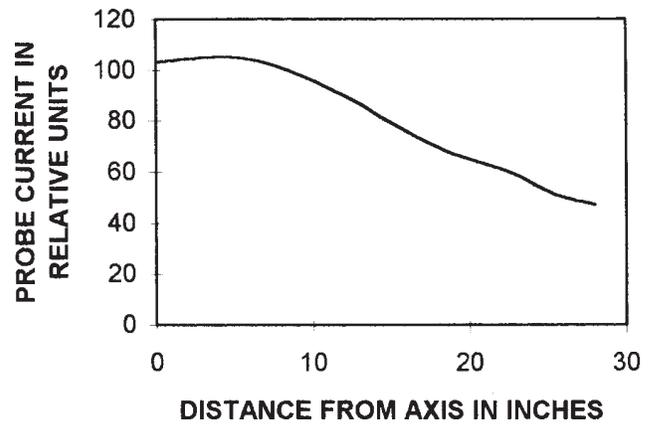Fig. 6. Fafnir A_P versus A_D in same test as Figs. 4 and 5.

Fig. 7. Fafnir beam current versus position off-axis in a flat plane perpendicular to the axis at 26sccm, $10A_D$, $310V_D$, and $16.0A_N$.

CONCLUSIONS

After some modifications, the particular End-Hall source which we used proved to be very stable. The Cold Cathode source changed somewhat with operating time due to erosion of the anode and gas distributor plate and resulting deposits; and it showed less than desirable behavior for long production processes. Both the Cold Cathode and End-Hall sources allowed us to obtain some of the desired results of producing good SiO_2 from SiO at high rates for many layers. We found that low humidity shifts could be obtained along with fully oxidized films. This full densification, however, usually required about half the rates of deposition or twice the ion densities which we have described here. This lead to the need for a more powerful source. After extensive development, laboratory testing of the resulting improved plasma source (Fafnir) with oxygen has shown great stability at ion power levels almost an order of magnitude above those of the other commercially available gridless sources.

REFERENCES

1. R. R. Willey, "Achieving Improved Optical Thin Film Control and Uniformity of Silicon Dioxide by Using Ion Assisted Deposition," Soc. Vac. Coaters 36th Tech. Con. Proc., 75-81 (1993).
2. H. R. Kaufman and R. S. Robinson, *Operation of Broad-Beam Sources,* Sec. VI, Commonwealth Scientific Corp., Alexandria, VA, 1984.
3. J. J. Cuomo, S. M. Rossnagel, and H. R. Kaufman, *Handbook of Ion Beam Processing Technology,* Chap. 4, Noyes Publications, Park Ridge, NJ , 1989.