Linear Anode-Layer Ion Sources with 340- and 1500-mm Beams

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ABSTRACT

Anode layer ion sources (ALS) with 340-mm and 1500-mm beam lengths have been developed and tested. These sources deliver intense, collimated ion beams for treatment of large-area substrates, such as glass and flexible webs. Substrates are typically translated perpendicular to the major axis of the ion source in an in-line coating system. Typical applications include cleaning of substrates prior to deposition and inter-layer treatment between deposition layers. Data are presented showing energy and current density of ion beams at the substrate. Longitudinal beam current uniformity of ±5% has been obtained over the active area of the beam. Etch rates of substrates translating in front of the source are presented. Treatment of glass samples with the ion source decreased water contact angles substantially. Substrate contamination was measured and found to be minimal.

INTRODUCTION

Anode layer ion sources are a variant of the Hall current or closed drift ion source. Anode layer sources were first developed in the Soviet Union in the 1960s as spacecraft propulsion devices [1,2], similar to the gridded thrusters developed by NASA in the United States. Like gridded thrusters, ALS are also used for thin film processing and surface modification applications [3,4].

Anode layer sources used for space propulsion or for treatment of small substrates are typically round. However, for industrial applications that involve treating substrates of large areas, it is more typical to use a linear ion source and translate the substrates in front of the beam. Examples include substrate cleaning of in-line web and industrial glass coating systems.

DESCRIPTION OF ION SOURCE

A sectional view of a linear ALS is shown in Figure 1. Conceptually, the ALS has three main components: (1) the anode, (2) the inner and outer cathodes, and (3) the magnets. The anode is the high voltage electrode of the system. It is biased to a large positive voltage, usually 1-3 kV. The cathodes are electrically grounded. The cathodes also serve as the pole pieces of the magnetic circuit, and they are, consequently, made of a magnetic material such as carbon steel. The magnets are placed inside the source. Their function is to produce a large magnetic field in the small gap between the inner and outer cathodes. The magnetic field vectors are primarily parallel to the surface of the anode.

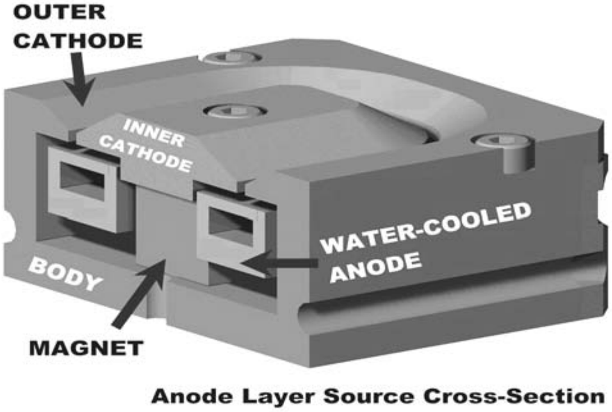

Figure 1: Schematic cross section of an anode layer ion source (ALS).

The plasma dynamics of the ALS are similar to those of a planar magnetron. The magnetic field between the inner and outer cathodes prevents electrons from traveling directly to the positively biased anode. Instead of moving towards the anode, the electrons move along the cathode gap in a Hall current that is perpendicular to both the magnetic field and electric field vectors. The gap between the cathodes must form a closed loop or "racetrack" so that the Hall current can flow continuously around the loop. The Hall current provides very efficient ionization of the working gas in the cathode gap, creating a dense plasma in that region. The electrons have very low mobility towards the anode due to the impedance to their movement perpendicular to the magnetic field lines. The potential gradient in the plasma created by the electrons' low mobility accelerates the ions out of the source. The kinetic energy of the individual ions leaving the source is some fraction of the voltage applied to the anode and is determined by the position in the potential field at which the ions are created. Most of the ion production and acceleration takes place in a thin layer adjacent to the anode called the "anode layer" which gives the source its name. The ion beam emitted by the source is neutralized by secondary electrons from the cathodes and downstream surfaces. Typically, a neutralizer is not needed.

The body of the anode layer ion source is electrically grounded and water-cooled. The anode is also water-cooled. The working gas is introduced into the body cavity behind the anode such that gas is uniformly distributed along the length of the source. The source components are compatible with argon, oxygen, nitrogen, hydrocarbons, and other reactive gases.

A useful feature of anode layer sources is that the length of the racetrack can be easily scaled to practically any length provided the gaps between cathodes and anode remain constant. The cross-section shown in Figure 1 forms the basic design for the two sources shown in Figure 2. These sources have been constructed so that the straight sections of their racetracks are 1500-mm and 340-mm, respectively. Operating characteristics from these two sources will be presented in the following section.

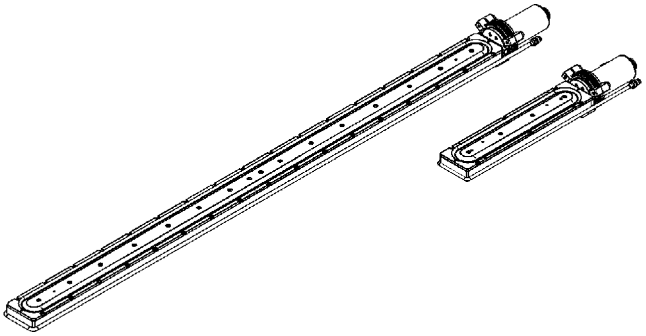

Figure 2: 1500-mm and 340-mm ALS.

OPERATING CHARACTERISTICS

An operator of an ion source using it to treat a substrate will be mainly concerned with three characteristics of the ion source: (1) How much ion current can be applied to the substrate? (2) What is the spatial distribution of the ion current at the substrate? (3) What is the energy of the ions when they reach the substrate? This section will examine these operating characteristics for the 340-mm and 1500-mm anode layer ion sources.

Total Ion Current Produced

One tool useful for characterizing an ALS is the dependence of discharge current and ion current on the amount of gas supplied to the ion source. Discharge current is defined as the electrical current flowing between anode and cathode. This current is measured at the power supply. Ion current is defined as the current of ions leaving the ion source and striking the substrate. This current is measured by a probe at the location of a substrate. Figure 3 shows discharge current and ion current plotted against oxygen flow for the 340-mm ALS. The ion current that could be measured at a substrate location 20 cm downstream from the source was 60-90% of the discharge current. This ion current fraction will vary with the operating condition of the source and the process conditions in the vacuum chamber. For example, increased system pressure (caused in this case by higher ion source flow rates) causes some ions to be scattered and/or charge exchanged so that they cannot be detected by the probe. An important metric illustrated by Figure 3 is that up to 15 mA of ion current can be developed per linear centimeter of ion source. The 1500-mm source produces similar ion current per unit length due to the scalability of the sources.

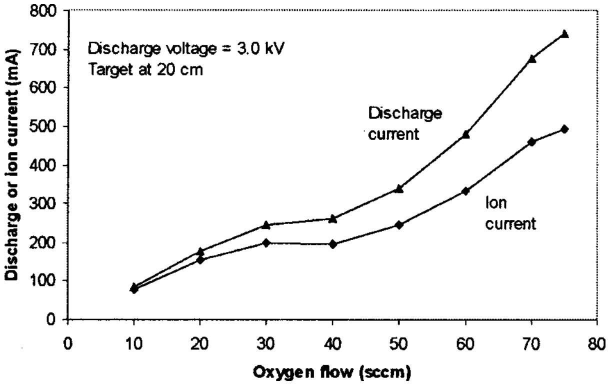

Figure 3: Discharge current and ion current vs. oxygen flow for an ALS 340L operating at a discharge voltage of 3.0 kV.

Ion Current Density Profiles

The spatial distribution of ion current emitted from an ion source is an important measure of its performance. The ion current density profile (or beam profile) of a linear ion source can be measured by sweeping a Faraday probe across the major or minor axis of the source and recording ion current density as a function of position. Figure 4 presents the beam current density profile across the minor axis of the 340-mm ALS operating at a discharge voltage of 3 kV and discharge currents of 250, 500, and 750 mA. The distance from the source to the probe was 10 cm. The minor axis beam profile of the 1500-mm ALS is characteristically similar due to the common cross section used for construction of both sources. Figure 5 presents the etch rate of glass as a function of position for the 340-mm ALS to demonstrate that the etch profile closely matches the ion current density profile.

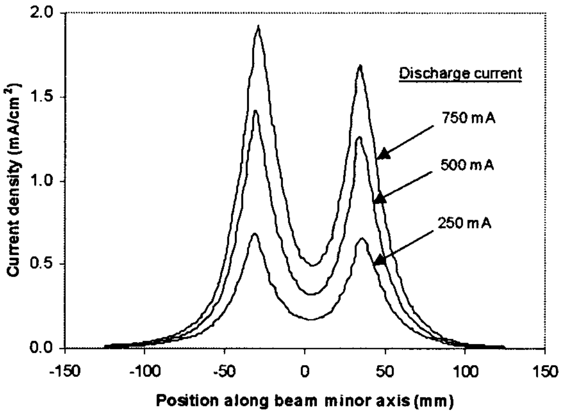

Figure 4: Ion current density profiles at various discharge currents across the minor axis of an ALS 340L operating at 3.0 kV discharge voltage.

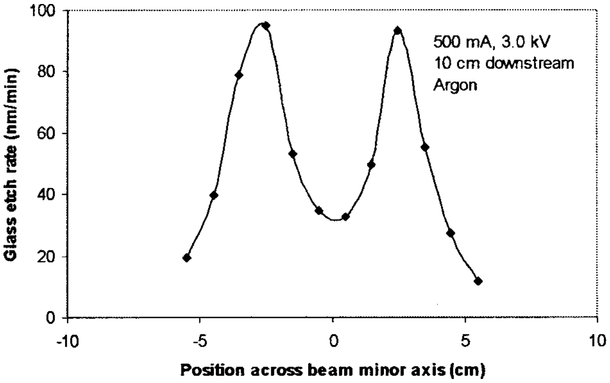

Figure 5: Etch rate profile of glass across the minor axis of an ALS 340L operating at 3.0 kV discharge voltage, 500 mA discharge current, normal incidence.

The uniformity of the major-axis ion current density is an important parameter of the ion source as it will directly influence substrate uniformity in an in-line system. Figure 6 presents the beam current density profile along the major axis of the 1500-mm ALS operating at 3 kV discharge voltage for 1.5 A and 1.0 A discharge currents. The shape of the Faraday probe aperture was a narrow rectangle extending across the full minor axis beam width that captured a slice of the beam at each position along the major axis of the beam. This type of Faraday probe is necessary for measuring the major-axis uniformity of a linear ion source, as it measures the relative "dose" (i.e., current per centimeter of beam length) that would be delivered to the substrate as it moved across the major axis of the beam. The uniformity of the beam current density "dose" for the two plots in Figure 6 is ±5% over the active length of the beam. The active length is defined as the straight section of the racetrack. The increase in current density at the ends of the source results from the curved portion of the racetrack delivering more current per linear centimeter of ion source. The size of the ion source for a particular application is selected so that the substrate fits inside the peaks at the edges of the profile.

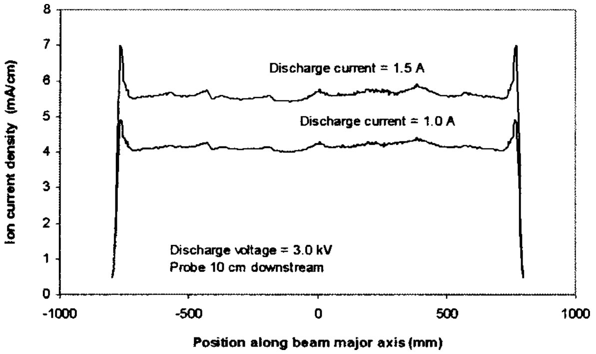

Figure 6: Ion current density profiles along the major axis of an ALS 1500L.

Ion Energy Distribution

Unlike with gridded ion sources, the energy of the beam ions produced by an ALS cannot be determined from discharge parameters and must be measured experimentally. A retarding potential analyzer (RPA) was used to measure the energy distribution of beam ions produced by the 340-mm ALS. Figure 7 shows the energy distribution function of argon ions produced by the source operating at a 3.0 kV discharge voltage. The mean energy of this distribution is 730 V. Figure 8 shows a plot of the mean ion energy as a function of discharge voltage. The mean ion energy ranges between 25% and 45% of the discharge voltage.

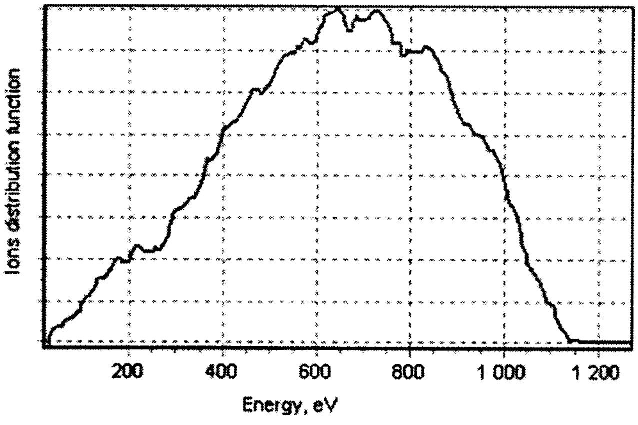

Figure 7: Argon ion energy distribution of an ALS 340L operating at 3 kV discharge voltage.

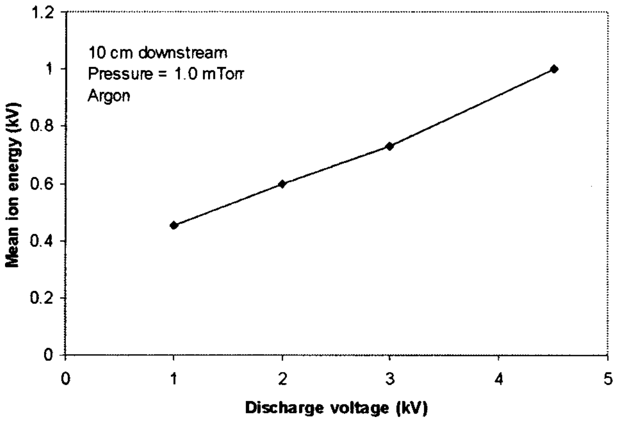

Figure 8: Mean ion energy vs. discharge voltage for an ALS 340L operating on argon.

PROCESS RESULTS

A 340-mm ALS was positioned in front of a rotating substrate holder so that substrates could be swept perpendicular to the major axis of the beam to simulate a substrate translating in front of the source in an in-line coater. Three different experiments were performed with this experimental arrangement. First, silica etch rates were measured at varying source conditions and source-to-substrate angles. Second, the ability of the ion beam to change water contact angles of glass substrates was examined. Finally, a measurement of residual contamination deposited on a moving substrate by the ion source was measured. In all tests, the speed of the substrate moving past the ion source was 10 m/min, which is a typical line speed of industrial glass coaters. The source-to-substrate distance was 11.5 cm.

Etch Rate of Silica

Silica (SiO_2) substrates were passed in front of the beam at a speed of 10 m/min. Repeated passes were made to produce a large etch for measurement accuracy. The amount of material removed was then measured optically with an ellipsometer. The source was operated on a gas mixture of 80% argon and 20% oxygen. The discharge current was controlled to 500 mA. This discharge current equates to an ion current of 10 mA per linear centimeter of substrate. The discharge voltage was varied between 1.0 kV and 3.0 kV. The source-to-substrate angle of incidence was varied from 0° (normal incidence) to 60° incidence. The tests were conducted at a constant pressure of 2.0 mTorr. The results of the etch experiments are plotted in Figure 9. The amount of silica etched per pass is plotted as a function of the discharge voltage. The etch rates of 1-10 A per pass represent a removal rate of 1 to 2 atomic layers per pass at a line speed of 10 m/min. It can be seen that increasing the angle of incidence from normal to a 60° glancing angle increases the removal rate by approximately a factor of (4) four.

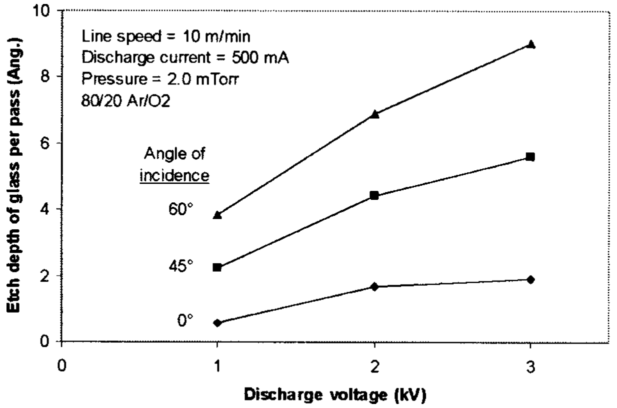

Figure 9: Etch depth per pass vs. ALS discharge voltage. An SiO_2 substrate moving at 10 m/min perpendicular to ALS major axis at different source-to-substrate incidence angles.

Contact Angle Modification

Experiments were also performed to measure the ability of the ALS to modify contact angles of water droplets on a glass substrate. The contact angle is the angle between the tangent of a droplet surface and the tangent of the solid surface at the point of contact. The contact angle gives an indication of the surface energy of the substrate. Smaller contact angles indicate higher surface energy and, therefore, better adhesion of applied coatings. Determining a surface's precise surface energy is a complicated process and is not attempted in this paper. However, the relative difference in contact angle between different samples does provide a useful relative comparison in the surface energies of the samples.

Nineteen samples of commercially available float glass were measured in this study. The contact angles of de-ionized water droplets were measured using a goniometer before treatment with the ALS. All measurements were made on the side of the glass that is not exposed to tin during the float process. The untreated contact angles of the 19 samples are displayed as squares in Figure 10. The untreated contact angles ranged from 18° to 38°. Significant variation also occurred at different measuring locations on a single sample.

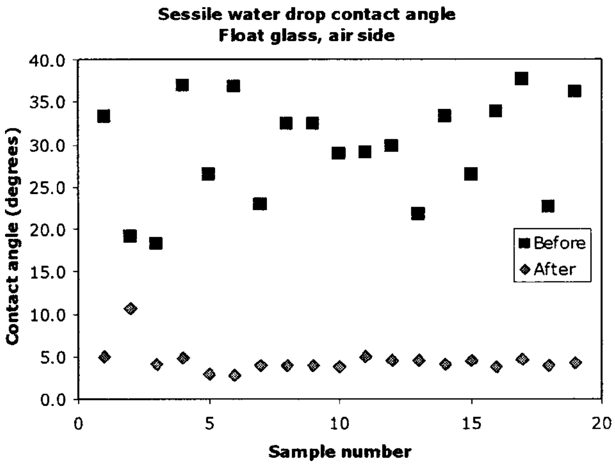

Figure 10: Water contact angle of float glass substrates before and after treatment by ALS. Treatment conditions listed in Table 1.

Table 1: Ion source operating conditions for contact angle modification.

Sample #	% O_2 (balance Ar)	Discharge voltage (kV)	Discharge current (mA)
1	50	2.5	300
2	80	2.5	300
3	80	2.5	300
4	80	2.0	300
5	80	3.0	300
6	80	2.5	390
7	80	2.5	200
8	20	2.5	300
9	80	2.5	300
10	80	2.5	300
11	0	2.5	310
12	100	2.5	240
13	80	1.0	180
14	80	1.5	133
15	0	1.5	133
16	100	1.5	133
17	20	3.0	200
18	80	3.0	200
19	80	3.0	200

The 19 samples were then treated by a single pass through the 340-mm ALS beam at a line speed of 10 m/min. Each sample was treated with a different ion source operating condition to find an optimum process for surface modification. Discharge voltage, discharge current, and working gas composition were varied. The working gas compositions consisted of different percentages of oxygen in argon from 100% oxygen to 100% argon. The operating conditions used in the study are listed in Table 1. After treatment with the ion beam, the contact angles of the samples were significantly reduced as shown by the diamonds in Figure 10. The variation in contact angle across the sample set was also significantly reduced with 18 of the 19 post-treatment contact angles reduced to less than 5°. No correlation between contact angle and ion source operating condition was evident, indicating a robust process.

Substrate Contamination

As discussed in the description of the anode layer ion source, the basic design of an ALS requires that the cathodes be positioned close to the ion beam to allow for some secondary electron emission. Since the cathodes function as magnetic pole pieces, it is also necessary that they be manufactured from carbon steel or some other magnetically permeable alloy. Thus, there exists the possibility for cathode material (mainly iron) to be sputtered from the cathodes onto the substrate by beam ions. The design of the cathode/anode geometry and magnetic field strength plays a large role in how much material is sputtered. The sources used for the tests described above were based on a carefully optimized design that minimized cathode sputtering.

To test the level of contamination produced by these ALS, a silicon witness piece was passed through the beam at a rate of 10 m/min. The source was operating at a standard operating condition of 3 kV discharge voltage, 400 mA discharge current and working gas of 80%/20% Ar/O_2. The surface of the witness piece was then analyzed with X-ray photoelectron spectroscopy (XPS) to determine surface elemental concentrations. The XPS survey scan is displayed in Figure 11. There was no evidence of iron in the survey scan. The arrow in the plot indicates where the iron line would be if it were strong enough to be detected. A high resolution scan of the iron line showed that iron concentration at the surface was 0.1 atomic percent, which is near the detection limit of the instrument.

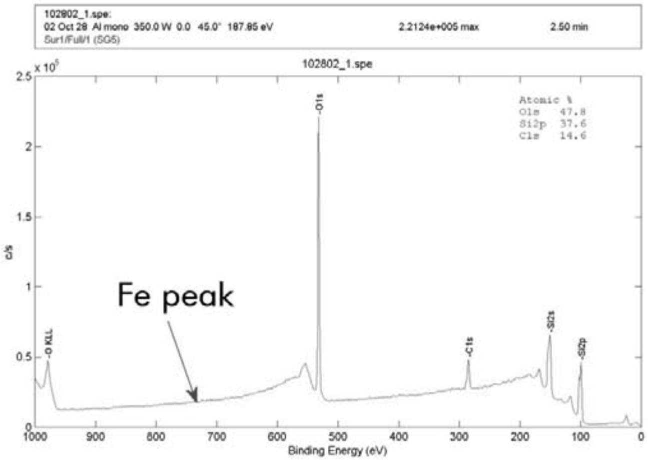

Figure 11: XPS survey scan of a silicon substrate treated by ALS at 10 m/min line speed.

CONCLUSIONS

Linear anode layer sources of 340-mm and 1500-mm lengths have been built and tested. Longitudinal beam uniformity of ±5% has been obtained over the active area of the ion source. Silica etch rates of 1-2 atomic layers (1-10 Å) per pass have been demonstrated at line speeds of 10 m/min. It was shown that ALS treatment of glass reduced water contact angle, indicating an increase in surface energy. Contact angles were reduced to <5° over a wide range of ion source operating conditions. Finally, XPS measurements of witness pieces showed substrate iron concentrations of only 0.1 atomic percent.

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