Characterization of the Low-Voltage, High-Current Single-Cell Ion Source

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ABSTRACT

Advanced Energy has recently expanded the technology available for anode layer ion sources for industrial applications by introducing a round, single-cell ion source (Figure 1). The previously available technology included linear and round, multi-cell ion sources, the former for in-line coaters and the latter to process one substrate at a time.

Similar to linear and multi-cell sources, the single-cell ion source can operate without external electron emitters and, therefore, is compatible with reactive gas environments. In particular, oxygen can be used as a working gas.

The main advantage of the new single-cell ion source over the existing multi-cell source is its ability to deliver much higher ion currents at lower discharge voltages. This makes it especially appropriate for applications where high ion energy is a concern, such as hard disk manufacturing (disk cleaning and high-rate DLC deposition), ophthalmic, and optical applications.

This article presents experimental results–volt-ampere and gas characteristics, ion beam angular distribution, rate, and uniformity of DLC deposition.

INTRODUCTION

Advanced Energy has recently introduced a new product line of gridless ion sources with anode layers [1,2]. These sources are developed for industrial applications and based on the so-called closed drift thruster design. The anode layer ion sources are very robust by nature; they don't have accelerating grids and don't need an electron emitter. They would work in reactive gas environments; they have no parts that can burn off.

The new product–single-cell round ion source (Figure 1) can also be classified as closed drift type with anode layer [3]. It is well suited for industrial applications because it can work without an electron emitter and has a simple design.
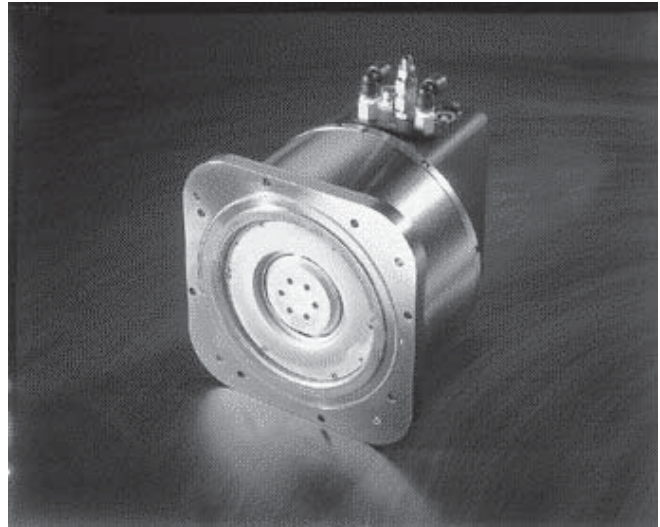

Figure 1. Round single-cell ion source.

As with other AE ion sources, the single-cell source can run in pure oxygen for a long time without any degradation or need for maintenance. At the same time, maintenance of gridless ion sources is much easier than that of gridded sources.

DESCRIPTION OF THE ION SOURCE

The single-cell ion source resembles the Advanced Energy multi-cell ion source, except it has one round emission slit instead of many small cells. The electrodes geometry of the new source is the same as that of linear ion source, except the emission slit is round as opposed to an elongated, racetrack-like slit of the linear source. Discharge parameters and operational characteristics are also similar to the linear source.

The power supply (a modified Pinnacle™ II, maximum voltage is 1500 V, maximum current 8 A, and maximum power 6 kW) is connected to the anode. Working gas is fed directly to the ion source. The source has a gas distributor that distributes gas evenly along the round slit. The magnetic system of the single-cell source can utilize permanent or electromagnet. Edges of the emission slit are made of soft iron, and the anode is made out of aluminum. The ion source can be flange-mounted or remote-mounted inside the vacuum chamber.

The flange-mounted ion source bolts to the flange on atmosphere side. Most parts of the source are at atmosphere and can be easily water-cooled without using vacuum feedthroughs. The magnetic system has an electromagnet that provides additional flexibility. The magnet coil is at atmosphere and is air-cooled. The ion source has two electrical connectors, one for the anode (high voltage up to 1500 V) and the other for the magnet (up to 10V, 3A). It also has fittings for the gas and water.

The remote-mounted ion source can be installed inside the vacuum chamber. The magnetic system utilizes permanent magnet. The ion source is designed in such a way that it has atmospheric pressure inside, where all water and electrical connections are located. Internal volume of the source is connected to the atmosphere by flexible stainless steel hose, which also carries water hoses, gas line, and electrical cable. This design eliminates exposure of high-potential parts into vacuum and allows using plastic water lines to insulate water-cooled anode. In the case of the water line failure, water would flow not into the vacuum chamber, but to the atmosphere.

Similar to the linear source, the round single-cell source can work either in collimated-beam mode with high discharge voltage and lower current or in diffused-beam mode with higher current. The diffused-beam mode could be used to process one substrate (e.g., a magnetic disc) at a time or process many substrates in carousel-type systems, like systems for ophthalmic applications. The collimated-beam mode is best suited for carousel-type systems.

EXPERIMENTAL RESULTS

Discharge and beam measurements

Volt-ampere characteristics of the round single-cell ion source are summarized in Tables I and II. Ion beam current data should be considered with some cushion because the ion source works at high gas pressure (usually 1 to 4 mtorr) and some ions in the beam are converted to fast neutrals due to charge exchange with background gas. From the process point of view fast neutrals are as good as ions, however they don't contribute to the measured beam current. On the other hand, the slow ions that are produced at the same time from the background gas tend to drift away in all directions and produce an ion current signal outside the beam.

Table I. Oxygen, 25.5 sccm, collimated beam mode

Discharge Voltage, V	800	900	1100	1300	1500
Discharge Current, mA	30	37.8	54.5	70.8	88
Beam Current, mA	19.1	25.8	41	57.8	75.8

Table II. Oxygen, 60 sccm, diffuse beam mode

Discharge Voltage, V	294	289	292	288	316
Discharge Current, A	0.5	2	4	8	10
Beam Current, A	0.07	0.31	0.66	1.46	1.86

The round ion source can work in two distinct modes: collimated-beam and diffused-beam. Collimated-beam mode (Table I) can be achieved at low gas flow. In this mode, discharge voltage significantly increases with increasing discharge current. The ion beam in this mode is well collimated and has a tubular shape that can be readily observed by naked eye.

By increasing the gas flow or pressure, ion source can be switched into the diffused-beam mode with much higher discharge current and almost constant discharge voltage (Table II). In this mode, the ion beam is very diffuse, and it looks like a plasma cloud.

We think that in collimated-beam mode the electron space charge isn't compensated by ions. Thus hall current and ion current increase with discharge voltage. In a diffused-beam mode, the electron space charge is compensated by ions, so the discharge current is limited by only by power supply.

Angular distribution

Figure 2 and Figure 3 show angular current distribution, measured on the distance 1050 mm from the source. In Figure 2, the ion source was running in a diffused-beam mode at 80 sccm of oxygen at pressure 2.2 mtorr. The top curve corresponds to discharge voltage 341 V and discharge current 7.34 A. The bottom curve corresponds to discharge voltage 183 V and discharge current 8.18 A. There is a minor dependence of angular distribution of ion source operation parameters, such as gas flow, discharge power, and magnet current.
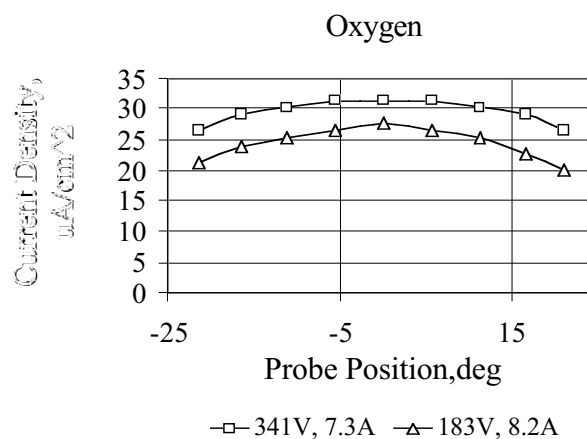

Figure 2. Angular current distribution in diffused-beam mode.

In Figure 3 the ion source was running in a collimated beam mode on 35 sccm of oxygen at pressure 1.13 mtorr, discharge voltage was 3000 V and discharge current was 0.17 A. It is obvious from the current density distribution that in a diffused-beam mode the source generates broad diffuse ion beam and in a collimated-beam mode tubular-shaped collimated ion beam. Beam uniformity is usually better in a low-voltage diffused-beam mode.
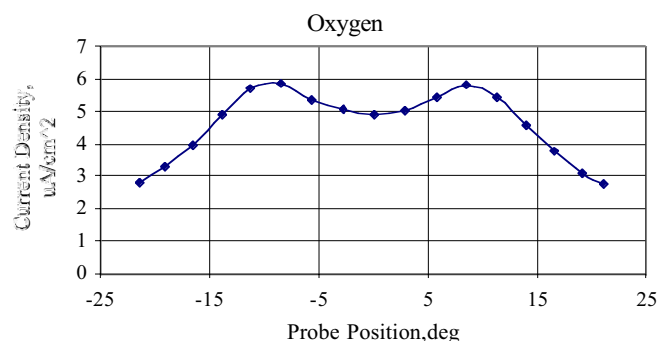

Figure 3. Angular current distribution in collimated-beam mode.

Energy distribution

The energy distribution was measured with the linear ion source in collimated-beam mode. Since local geometry of discharge area (anode-cathode distance, cathode slit width, and magnetic field strength) is the same for round and for race-track shaped slits, the energy distribution should be the same for the round and linear ion sources. The energy distribution measurements were performed using a four-grid analyzer. Typical energy distribution for the discharge voltage 1500 V is shown on Figure 4. Typically, average ion energy is approximately equal to 1/2 of discharge voltage.
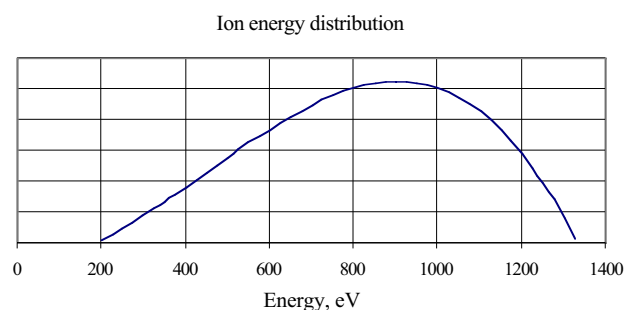

Figure 4. Energy distribution of oxygen ions at 5 sccm oxygen gas flow into LIS-65 at discharge voltage of 1500 V and gas pressure in the vacuum chamber of 0.21 mtorr.

Etching and film deposition

Using the round single-slit ion source, we etched DLC films on silicon wafers with an argon beam. The DLC thickness before and after etching as measured by optical methods in the center and at the edge of the wafer.

The typical DLC etch rate with oxygen was 5.2 nm/sec with uniformity ±7% over 95 mm diameter substrate. With argon, the DLC etch rate was 1.5 nm/sec with uniformity ±8% over the same substrate. Etching experiments were done at low pumping speed 25 L/sec. We expect higher etch rate at higher pumping speed, similar to behavior of deposition rate below.

In the same arrangement, we deposited DLC films with the round slit ion source. We used ethylene and butane as precursor gases. With ethylene, the typical deposition rate at high pumping speed 300 L/sec was 4 nm/sec with uniformity better than ±1% over 95 mm diameter substrate. At the pumping speed 25 L/sec deposition rate went down to 1.6 nm/sec.

With butane, the deposition rate was about the same as for ethylene, but uniformity was unacceptable low, about ±30%.

In addition to DLC, the single-cell ion source has also been used to deposit chemically modified carbon films which may prove useful for a variety of applications. While DLC is the material of choice for many protective overcoat applications, it is not without problems. DLC films are subject to great amounts of internal stress. This is a severe limitation to growing very thick (>1-2 micron) films for protective overcoats due to delamination and poor film integrity. From experiments performed here and results in the literature, a number of processes suggest themselves whereby a thick, hard carbon layer can be deposited having many of the same mechanical properties of DLC, but with a different chemical composition.

One possible method for reducing the internal stress of a DLC film is to incorporate a small amount of another chemical moiety into the film during deposition. Mentioned here are results for incorporation of Si and N into the DLC film. We have previously found that Si-doped DLC does not suffer from the internal stress of undoped DLC. This is evidenced by the ability to grow very thick (1-2 micron) Si-doped DLC films with no delamination or other signs of poor film integrity, problems often seen with thick DLC. Another chemical species that can be incorporated into a growing DLC film is nitrogen. We have experimented with $C_X N_Y$ films and found that nitrogen can have a similar effect in reducing the internal stress, again evidenced by stable thick films.

Recently, we have performed some experiments on Si-doped DLC and C_XN_Y (carbon nitride) using the Advanced Energy single-cell round ion source. Using HMDSO (hexamethyl disiloxane) and ethylene, we were able to deposit films having a thickness greater than 1 micron on Si substrates. The films exhibited no peeling, indicating good adhesion and lower film stress than normal DLC. Both ethylene and HMDSO were delivered through the ion source. Similar experiments using only ethylene and no HMDSO revealed deposition of a highly stressed film, indicating that using HMDSO could greatly enhance the fabrication of thick DLC films for protective overcoats.

While silicon doping can be an effective strategy for reducing internal stress, other methods are available. One method examined here is the incorporation of nitrogen into the growing DLC film. This was accomplished by flowing N_2 through the ion source simultaneously with ethylene. By varying the ratio of nitrogen to hydrocarbon (N_2/C_2H_4), a variety of film compositions can be attained. It has been shown in the literature that high nitrogen ion content in an ion-beam growth process for DLC can result in pyridine-like structures in the resulting film. The presence of these polymeric moieties can, of course, affect mechanical properties such as hardness and internal stress. However, even at low concentrations, nitrogen appears to reduce the internal stress of a deposited DLC film without sacrifice of the hardness. Using ethylene and nitrogen as precursor gases, we were able to deposit films of 1 micron thickness with no delamination from a silicon substrate, a great improvement over nondoped DLC films deposited under similar process conditions. Parameter studies could yield the optimum conditions for thick protective overcoat films, as even thicker films than 1 micron are likely possible, but were not attempted in this round of experiments.

For both Si-doped DLC and C_XN_Y, uniformity was good. The ion source also didn't have any problem associated with prolonged deposition of the films. Material characterization of these films is currently being performed to determine any effects on hardness or wear behavior as a result of the doping process. In addition, experiments to assess the merits of a gradient deposition scheme will possibly reveal insight into the best way to implement this technology to thick film fabrication.

CONCLUSION

A new industrial ion source with a single, round slit has been introduced. The source is of the anode-layer type and can operate without electron emitter. Virtually maintenance-free operation makes this type of source attractive for a wide range of industrial applications. Uniform, high-rate DLC deposition on hard discs had been demonstrated.

Possible applications of the single, round slit ion source are in hard disk industry for disk cleaning and deposition of the protective (DLC) coating. Other application could be in ophthalmic and optical industry in ion-assisted deposition, and tool coating (thick doped DLS, C_xN_y and other).

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