High Current Density Anode Layer Ion Sources

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Introduction

Background

Commercial ion sources used for plasma processing can all trace their heritage to ion rocket engines, or ion thrusters. The ion sources we use today are cousins to the smaller ion thrusters designed to be put on satellites for the purpose of modifying their orbits. In the US the vast majority of the development work has centered on the electrostatic gridded ion thrusters of the Kaufman type[1]. In Russia the vast majority of the development efforts went into electrodynamic gridless ion thrusters. About a hundred of these types of thrusters have been used in satellites. Thousands of their cousins have been used in plasma processing in Russia. The plasma processing ion source versions of the electrodynamic thrusters fall into two broad categories, magnet layer ion sources and anode layer ion sources. Magnet layer ion sources have successfully used the in commercial systems[2] for the production of DLC. Anode layer ion sources have been commercially used for etching, pre-cleaning, ion assist during magnetron sputtering and direct deposition. Anode layer ion sources are also being investigated for ion assist during e-beam evaporation of optical coatings.

Description of the Anode Layer Source

The anode layer ion source is designed to produce a collimated flux of ions from practically any gaseous feed. It is capable of operating from a few milliamperes per meter of channel to more than 20 ma/cm of ion channel length. The mean ion energies vary with discharge voltage in the range of 250 eV to 1,800 eV. Anode layer ion sources do not need filaments or secondary electron sources to provide discharge current. In operation these devices accelerate the ions electrodynamicly so they do not need grids to extract and accelerate ions electrostatically. Finally, anode layer ion sources generally do not require separate electron sources to neutralize the beam.

As with magnetrons, anode layer ion sources may be mounted inside a vacuum chamber, onto flanges, or through the chamber walls using standard gas, water and high voltage feedthroughs. Anode layer ions sources can operate with gas flowing in the device only, in the device and the chamber, and in the chamber alone. Because of the broad range ion energy and the possibility of very high current density of the ionized species, the ability to use reactive and non-reactive working gasses and the simple, robust design; the Anode layer ion source is most often used for the following types of surface treatment applications:

1. Cleaning and activation of surfaces prior to coating to improve adhesion of coatings;
2. Ion assist during coating deposition;
3. Ion assist during reactive coating deposition (reactive gas introduced through the device);
4. Physical ion etching
5. Plasma-chemical ion etching with reactive gases, and
6. Direct deposition of amorphous carbon and other materials.

A rendering of a small anode layer ion source is shown in Figure 1. A distinguishing physical characteristic of these devices is their racetrack shaped ion channel geometry.

This anode layer ion source has a working channel length of 85 mm (race track length 200 mm), overall length of 120 mm, width of 90 mm, and depth of 55 mm. The utility lines illustrated are prepared for flange mounting. There are two anode and two body water cooling lines and a gas inlet line. Because the anode is at high voltage, the anode lines are electrically isolated from the body and the rest of the vacuum system using insulating feedthroughs.

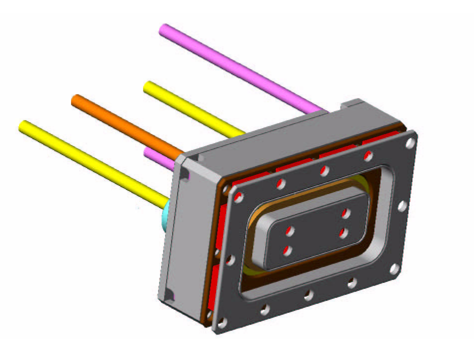

Figure 1 Anode Layer Ion Source

This ion source has permanent magnets on the outside surfaces of the inner and the outer cathodes protected by a retaining plate. The ions exit in a sheet from the channel between the inner and outer cathodes. As long as the closed loop topology is maintained, almost any channel geometry may be constructed. The most common channel shapes are race track and circular. The length of race track designs range from 100 mm to more than 2200 mm. Circular designs have been implemented from 70 mm diameter to 200 mm diameter. These devices have discharge powers of 100's of watts to more than 20 kW in the largest sizes.

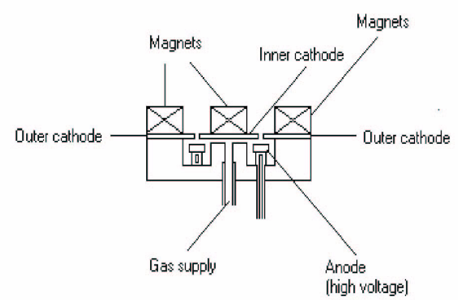

Figure 2 Cross Section View of a Typical Anode Layer Ion Source

Figure 2 is a schematic diagram of a central cross section of a typical anode layer ion source. The water-cooled anode is below the inner and outer cathodes. Together these three surfaces define the size of the ion discharge channel. The size of the discharge channel varies depending on application details. The anode is connected to a high voltage supply while the cathodes remain at ground potential.

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Operating Description

The key to the gridless operation of the anode layer ion source is the strength and arrangement of the electric and magnetic fields in the discharge channel. (For a more detailed theoretical overview of these issues, see the article by Zhurin, Kaufman and Robinson.[3]) The electrical and magnetic field configuration is shown in Figure 3. An electric field, E, is created between the grounded cathodes and the anode at a positive potential in the range of 0.7 kV to 3 kV. The magnets on the outer surfaces of the inner and outer cathodes provide magnetic induction, B, in the kiloGauss range. The cathodes are made from magnetic steel. They act as pole pieces to carry the magnetic flux into the cathode-cathode gap. This electrode configuration creates crossed electric and magnetic fields in the discharge channel. Under these conditions electrons are accelerated into and then trapped within the crossed field region in the discharge channel volume. When an adequate amount of working gas is introduced into this region it is impact ionized by the trapped gyrating electrons and a glow discharge is created.

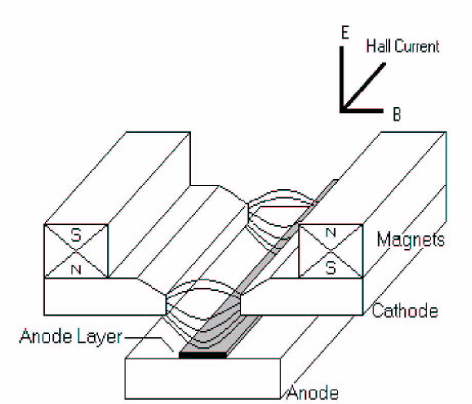

Figure 3 Electrical and Magnetic Configuration of One Channel of an Anode Layer Ion Source

The ExB or Lorentz Force acting on the trapped electrons in the discharge channel creates an electron current flowing parallel to it. This relationship is schematically illustrated in the Figure 3 where the axes represent the directions of the fields and current flow with the sign unspecified. Currents flowing under action of the Lorentz Force in crossed electric and magnetic fields are generally known as Hall Current, J_H. A closed circuit for the Hall Current flow is necessary, hence the requirement that the ion emission channel must have closed loop geometry.[4]

Figure 3 also illustrates the details of one side of the ion channel and the so-called anode layer region. The anode layer region is where the majority of the ionization is found. The anode layer is quite thin. In this region gyrating electrons are captured at the anode. The characteristic gyration radius is the electron Larmor radius. Thus the anode layer is only several Larmor radii thick. At the normal gas pressure operating conditions this is only a fraction of a millimeter thick. When the electron enters the anode there is a charge imbalance and a net repulsive force acting on the remaining ions. The ions created in the anode layer are accelerated away from the anode. The circulating Hall Current as it travels through the magnetic field provides further acceleration for the ions. The magnitude of this force is proportional to the produce of the Hall Current and the magnetic field and direction are given by the direction of $J_H x B$. Since the ions are created at different distances from the anode, the ions experience different total accelerations. With the usual discharge voltage between 0.7 kV and 3 kV, the average energy of the ejected ions is about 250 eV to 1800 eV.

The long electron path in the closed loop of the ion channel makes it possible for these devices to operate over a wide range of pressures and voltages. It is only necessary to have an appropriate gas pressure and adequate voltage difference between the anode and cathodes for initiation of the glow discharge and ion beam formation in the plasma channel.

Because the electron leakage current from the plasma plus secondary emissions from the environment substantially compensate the ionization of the working gas automatically, the ion currents accelerated out of the plasma channel in the anode layer ion source do not require any additional source of electrons to neutralize the beam.

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Operating Conditions and Performance Parameters

System Considerations

The planar sources can be installed in vacuum chamber walls and in the chambers themselves. Anode layer ion sources operate in the pressure range from about 0.1 mTorr to about 10 mTorr with gas flows up to about 2 sccm per centimeter of channel length. They are frequently used in magnetron and cathodic arc systems for pre-cleaning and deposition assist before functional and decorative coatings are applied

Table 1: Typical Discharge Parameters

Parameter	Units	Value
Discharge Voltage Range	KV	0.7 to 3.0
Maximum Discharge Current*	ma/cm	10 to 30
Maximum Discharge Power*	W/cm	33 to 100
Operating Pressure Range	MTorr	0.1 to 10
Maximum Gas Flow*	sccm/cm	3
Cooling Water Flow	L/min.	2

Table 2: Typical Ion Beam Parameters

Parameter	Units	Value
Mean Energy	keV	0.25 to 1.8
Energy Spread	% of Mean Energy	±15
Maximum Current*	ma/cm	10 to 30
Maximum Power*	W/cm	33 to 100
Beam Divergence at 1 mTorr	Degrees half angle	3 to 6

*Parameters are per centimeter of discharge channel

Current-Voltage Operating Characteristics

A typical characteristic curve for the dependence of discharge current on discharge voltage, and gas flow is shown in Figure 4. The anode layer ion source from which this data were taken has a 350 mm working channel length (850 mm total channel length). The coldtrapped diffusion pump pumping system provided about 2000 l/sec. pumping speed.

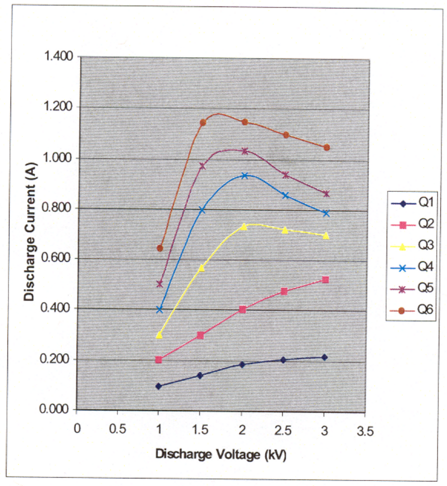

Figure 4 Discharge I-V Curve for 85 cm Channel Length Anode Layer Ion Source

Table 3: Gas Flow and Chamber Pressure

	Flow (sccm Ar)	Chamber Pressure (mTorr)
Q_1	8	0.10
Q_2	27	0.33
Q_3	48	0.59
Q_4	55	0.68
Q_5	66	0.81
Q_6	81	1.00

The shape of the I-V curves is worthy of comment. The peak in the discharge current and subsequent fall in current as voltage is increased is characteristic of anode layer ion sources and is the result of a complex interaction between the discharge and the magnetic field.[3] The discharge currents in Figure 4 extrapolate to zero at a value of discharge voltage of about 300 to 400 volts indicating a minimum voltage level necessary to initiate the discharge and create the collimated ion beam. This is characteristic of anode layer ion sources operating in the beam mode. It is possible to increase the gas flow and chamber pressure so that a diffuse plasma is ejected from the discharge channel. In this case the I-V curves extrapolate closer to zero voltage at zero discharge current. This diffuse mode of operation is not favored for these devices. In the diffuse mode no ion beam is being generated and accelerated, only a plasma is being formed.

In Figure 5, we show the dependence of ion current on discharge voltage for the same anode layer ion source and operating conditions.

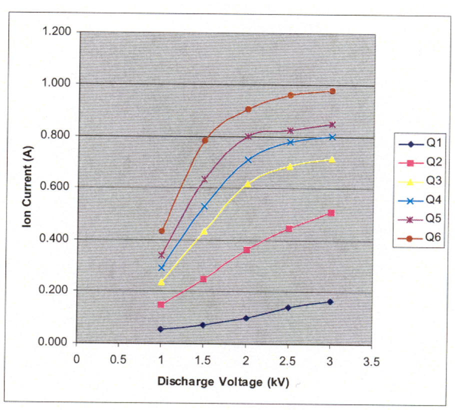

Figure 5 Ion Beam Current I-V Curve for 85 cm Channel Length Anode Layer Ion Source

It is notable that the ion generation efficiency is lowest where the discharge current peaks at intermediate discharge voltages. As seen in the for the case of Q_1 the ion generation efficiency is nearly 90% at 3 kV.

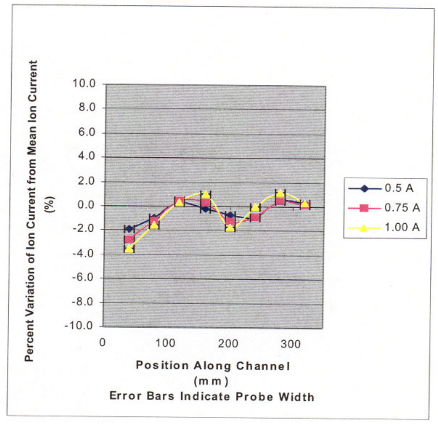

Figure 6 Ion Current Variation

In Figure 6 we see the variation in ion current at three operating currents for a 35 cm working channel length ion source. The variation from the mean ion current is generally less than 2%. This measurement was made with a grounded electrode of 1.5 cm width. Generally, pumping speed variations, gas distribution in the discharge channel, discharge channel geometry and magnetic field variations account for this variation. In special cases sub 1% variation in ion current can be achieved.

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Application Data

Pre-Cleaning

In pre-cleaning and sputter etching it is important to be able to remove materials that are loosely bonded to the substrate surface like water and organic vapors as well as be able to remove substrate material and native oxides of the substrate material. These jobs require different ion source operating conditions. Removing loosely bound material is efficiently done at low ion energies with high ion current density. Anode layer ion sources can provide mean ion energies up from below sputtering threshold to 1800 eV are provided by these sources and current densities in excess of 20 ma/cm2 at 10 cm source substrate distance can be achieved.

For non-metallic substrates, argon is typically used as the cleaning gas with discharge voltage at 3 kV and ion initial energies of about 1.5 eV. For metallic substrates, a two step cleaning process is frequently used. First an oxygen reactive etch is performed with a 2.3 kV discharge and followed by an argon ion non-reactive etch at 3 kV. The oxygen reactive etch removes hydrocarbon molecules and reactively removes metal ions as well.

This two step process is easily implemented with a single planar source in a drum coating system. In wear resistant film coaters it has been demonstrated that it is sufficient to have all areas of the substrate pass through the ion beam at a distance of 5 cm and speed of about 1 cm per second for the reactive and non-reactive steps to achieve complete cleaning on most metal substrates. In a linear flat pass system, two planar sources are frequently used with similar dose levels.

SiO2 Etching

In Figure 7 we show some typical SiO2 etch data from a field application with a low current density source operating at about 1 to 3 ma/cm. The deposition system is a batch type magnetron sputtering specialty multilayer coating system. The substrates are 4" silicon wafers being etched to remove native oxide prior to coating. Each carousel facet can hold two wafers. There are 4 to 8 facets on the carousel.

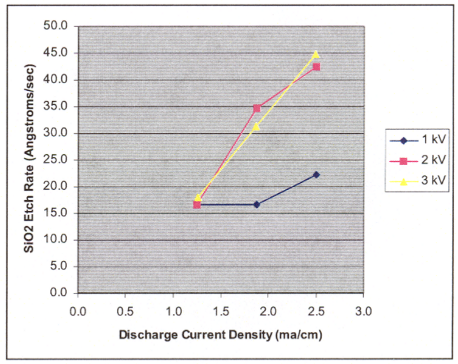

Figure 7 SiO2 Etch Rage as a Function of Discharge Current for

Boron Carbide Ion Assisted Sputtering

Anode Layer ion sources are also used in ion assist for magnetron sputtering. In the case of boron carbide (B_4C) it is important to make the coating as dense as possible to maximize the hardness and corrosion resistance of the film. The data in Figure 8 were taken at a fixed discharge current current density of 1.3 ma/cm of discharge channel. In this application it was determined that the maximum benefit of ion assist was obtained at about 1.5 kV discharge voltage. For voltages higher than this significant reduction in deposition rate became apparent. This deposition rate reduction was associated in sputter removal of coating.

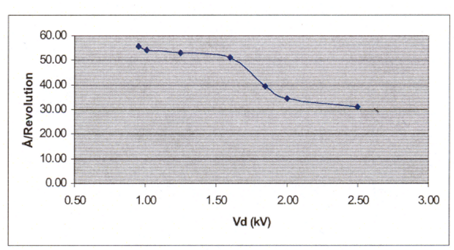

Figure 8 Deposition Rate of B4C as a Function of Anode Layer Ion Source Discharge Voltage

DLC Direct Deposition

Planar ion sources can also be used to make direct deposition of DLC. Any hydrocarbon gaseous source may be used in this device, including fluorinated hydrocarbons. The following table illustrates typical operating parameters and properties for experimental DLC depositions made using acetylene gas.

Table 4: Deposition Parameters and DLC Film Properties

V_d (kV)	I_d (mA)	Flow (sccm)	Pressure (mTorr)	Rate Å/sec.	Thickness (Å)	Stress (MPa)
2	400	105	6.80	11.20	1011	-675
2	800	140	0.35	6.10	550	-1411

In Table 5 we show a number of commercial coatings produced using anode layer ion sources in magnetron sputtering systems.

Table 5: Coatings and Process Parameters

Coating	System	Process	P (mTorr)	Ion Energy (keV)	Gases
TiN	Drum	Sputter	1	0.5-0.7	Ar-N_2
TiCN	Drum	Sputter	1	0.5-0.7	Ar-acet-ylene-N_2
CrN	Drum	Sputter	1	0.5-0.7	Ar-N_2
MEC	Drum	Sputter	5	0.3-0.5	Ar-acet-ylene
MoS2	Drum	Sputter	0.5 to 2.0	0.1-1.5	Ar
MgO	Flat Pass	Sputter	0.5 to 2.0	0.5-1.2	Ar-O_2

In the production of these coatings the presence of ion assist during the deposition eliminates the need for separate substrate biasing. Direct temperature measurements on substrates demonstrates that the process is performed at less than 100 C. This low temperature may be maintained and good coatings produced because the surface activation normally provided by heating and bias is provided by the ion assist current directly to the surface of the part much more efficiently that optical heating or biasing. Finally, there is no need to take special precautions to balance the loading of the chamber because there is no pre-heating required which influences the temperature of large and small substrates differently.

Maintenance

Maintenance is performed approximately every 100 hours of operation. This includes general cleaning of the electrical discharge surfaces and inspection. At longer intervals depending on the details of use, cathode electrode replacement is required. This process takes approximately 1 hour.

Conclusion

Anode layer ion sources provide high ion current density ion beams with a broad range of energies over a wide range of operating conditions and pressure ranges extending from the e-beam evaporation pressures to sputter pressures. They provide a simple, robust process element with great opportunity to simplify and improve a large range of commercial vacuum deposition processes.

References

1. J. Beeattie, “XIPS keeps satellites on track,” The Industrial Physicist, pp. 24-26, June 1998.
2. L. Mahoney, B. Daniels, R. Petrmichl, R. Venable and F. Fodor, U.S. Patent Pending, “Hall-Current ion source and method for processing materials.”
3. V.V Zhurin, H.R. Kaufman and R.S. Robinson, “Physics of CLosed Drift Thrusters,” Plasma Sources Sci. Tech-nol., 8, pp. R1-R20, 1999.
4. This feature gives rise to the term “Closed Drift Hall Current Sources sometimes seen in the literature.

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