

Substrate Neutralization Methods for the Closed Drift Ion Sources

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ABSTRACT

This article investigates substrate neutralization methods for ion sources that do not use a hot-cathode neutralizer. Not requiring a hot cathode ionizer is a significant advantage for many industrial applications. However, in some of these applications, even though the ion source does not require a hot-cathode neutralizer for its operation, lack of electron source results in undesirable positive charging of the substrate and other surfaces. To address this problem, we developed two different neutralization methods that do not use an electron emitter:

- In one method, we biased the ion source negatively. Biasing the ion source allows complete control of the substrate potential and can keep it positive, zero, or even negative. However, this method requires two power supplies and insulation of the ion source.
- In the other method, we applied AC or rectified AC voltage to the anode, instead of DC. Applying AC decreases the floating potential of the substrate by more than an order of magnitude; however, the potential is always positive. This method requires only one power supply, and sometimes the ion source must be insulated from the ground.

This article discusses experimental results—volts-ampere, floating potential, and gas characteristics—for both methods as well as how to select the appropriate neutralization method for a particular application.

INTRODUCTION

The gridless closed drift ion sources manufactured by Advanced Energy (AE) don't require an electron emitter, like hollow cathode or hot filament, for operation. If the ion source works in a clean metal vacuum chamber, there is no problem with beam neutralization, even if the substrate is dielectric.

However, usually deposition chambers for optical coatings are covered inside with dielectric films, and those films can be charged by the ion beam to a high potential. During the ion source operation those films can experience electrical breakdown, and one can see small arcs on the chamber walls and sometimes on the substrate surface – a strong indication that

the ion beam is not neutralized. Arcs, even the small ones, generate microparticles, which can contaminate substrate.

There are well-known methods of ion beam neutralization. The electron emitter, like hot filament or hollow cathode, supplies electrons that neutralize the positive ion charge. However, electron emitters have disadvantages, making them unusable in some applications. Hot filament has a short lifetime, especially in oxygen. Hollow cathode is complicated and also requires periodic maintenance.

To address these problems, we developed new neutralization methods for gridless ion sources, where the ion source plasma itself is the source of electrons. One method utilizes pulsing or AC technology, reversing the polarity of the power supply makes possible the use of discharge plasma electrons for neutralization. In the other method, biasing the ion source negatively supplies electrons into the ion beam.

We apply both methods of neutralization to different gridless ion sources made by AE. To quantify the degree of ion beam neutralization, we measured the potential of the floating conductive substrate positioned in front of the ion source. We also measured ion energy distribution to see how biasing the ion source or using AC affects the energy of the ion beam.

SINGLE-CELL ION SOURCE (SCIS)

Ion Source Description

The single-cell ion source was developed as an assistant source for activated oxygen for E-beam and magnetron reactive deposition of thin films. The ion source can work on pure oxygen and delivers a wide circular beam. It has a round emission slit 5 mm in width and 80 mm in diameter. The source was described in details [1].

The SCIS can work either in collimated or diffuse beam mode [1]. In collimated beam mode discharge voltage is high (1,500 V), and current is low (up to 0.5 A). In diffused beam mode, the discharge voltage is much lower (300–400 V) and current is high—up to 4 A. As an assistant source, the SCIS was optimized to run in diffuse beam mode. However, operational characteristics of the SCIS resemble those of AE linear ion sources, so in order to get data for the linear ion sources, we

did neutralization experiments for the collimated beam mode as well.

Diffuse Beam Mode

In our experiments, we ran the ion source in diffuse beam mode with oxygen flow of 60 sccm and pressure of 1.8 mTorr. The anode power supply was in current regulation mode with anode current of 2 A. The typical floating potential of the substrate for this condition with the cathode grounded was about 220 V, and the potential depended very little on the discharge current.

A floating potential of 220 V is too high for many applications and can lead to surface arcing and damage of the substrate. To decrease the potential, we biased the cathode of the ion source negatively. In this case, the cathode, which has the same magnetic field configuration as a magnetron, also works as a magnetron, emitting electrons and reducing plasma potential.

By biasing the cathode negatively and keeping the anode current constant at the current regulation mode of the anode power supply, the floating potential of the substrate could be reduced to a very low value and even reverse polarity. If the cathode is biased negatively, the anode potential becomes lower, so the potential difference between anode and cathode was approximately constant.

The power supply for cathode biasing could operate in two different modes, either voltage or current regulation. In voltage regulation mode we were able to bias the cathode only up to -180 V with the cathode current up to 1.6 A. At higher biasing voltage, the discharge became unstable. The current regulation mode appeared to be more stable; we were able to bias the cathode in this mode up to -280 V with cathode current up to 2.4 A. With this bias, the negative current from the cathode exceeded the positive current from the anode, and substrate potential was -1.2 V. Figure 1 shows the dependence of floating potential, anode, and cathode voltages of the cathode biasing current.

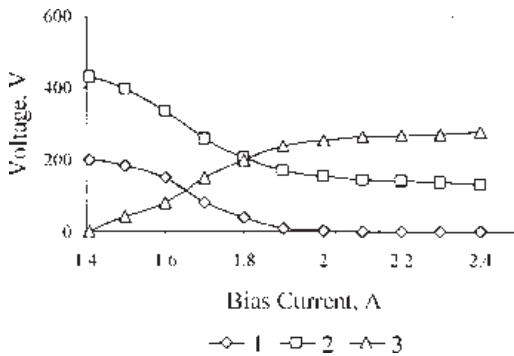


Figure 1. Dependence of floating potential (1), anode voltage (2), and cathode voltage (3) of the cathode biasing current.

It is important to know how the biasing of the cathode changes the energy distribution of the ion beam. We measured energy distribution using a four-grid energy analyzer with retarding potential. The first grid was biased to -60 V to prevent plasma electrons from entering the analyzer. The second and third grids were connected together and had the same positive retarding potential. Using two retarding grids has an advantage over using one grid, because retarding potential between two grids is much more uniform, than potential in the cells of the single grid. The fourth grid was biased to -60 V to suppress secondary electrons from the collector.

To get the energy distribution, one has to differentiate the collector current of the analyzer by retarding potential. Unfortunately, differentiation tends to amplify measurement errors and usually the final energy distribution curve is either very noisy or oversimplified due to excessive averaging. In our measurements, we used a digital oscilloscope to measure the retarding potential and collector current. The oscilloscope gives 10,000 data points for each energy scan, which allows plenty of room for averaging without losing important details. The energy distributions for diffuse beam mode for two different biasing cathode currents (and voltages) are shown in Figure 2.

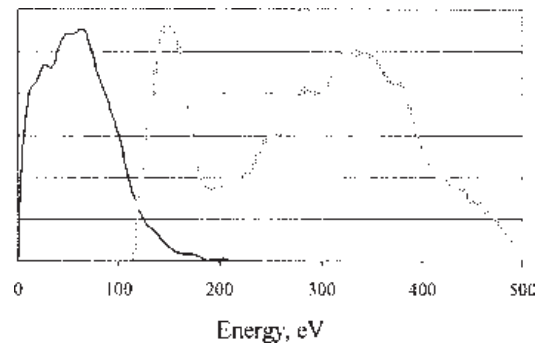


Figure 2. The energy distribution for the SCIS diffuse beam mode. Wide gray line – cathode grounded; anode current 2.4 A and potential 399 V. Thin black line – cathode current -2 A and potential -269 V; anode current 2 A and potential 159 V.

Our other method of neutralizing is to apply AC to the anode. The problem is, every time the anode potential turns negative, electrons can no longer be confined by the magnetic field, and discharge cannot be sustained. So for substrate neutralization, we can use only as many electrons as we had in the plasma cloud prior to the polarity change. In addition, every time the anode voltage turns positive again, we have to reignite the discharge, which gives an overvoltage spike.

To improve neutralization and facilitate the plasma ignition for every AC cycle, we applied AC to the anode and rectified unfiltered AC to the cathode. AC frequency was 375 kHz. The oscillograms of anode and cathode voltages are shown in Figure 3.

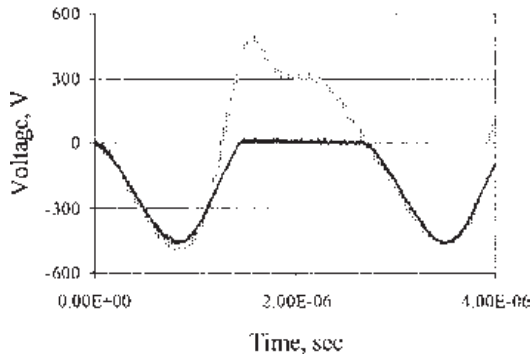


Figure 3. Anode and cathode voltages for AC operation of the SCIS in diffuse beam mode. Wide gray line – anode; thin black line – cathode.

During the positive cycle, there is a positive voltage on the anode, and the cathode has zero potential. At this time, the ion source works like a DC ion source, emitting ions. During the negative cycle, the anode and cathode are both negative, and the entire ion source works like a typical magnetron, emitting electrons. Discharge continues during this time between the ion source and grounded walls of the vacuum chamber; electrons are replenished, creating as much neutralizing electron current as necessary. Also, because transition between positive and negative voltages is very fast and there is no dead time, the plasma doesn't decay and the discharge reignites quickly every cycle and without a high voltage spike. Using this method for oxygen, we were able to reduce the floating potential of the substrate to 6 V. The energy distribution for AC operation, working on oxygen with an AC power of 950 W is shown in Figure 4.

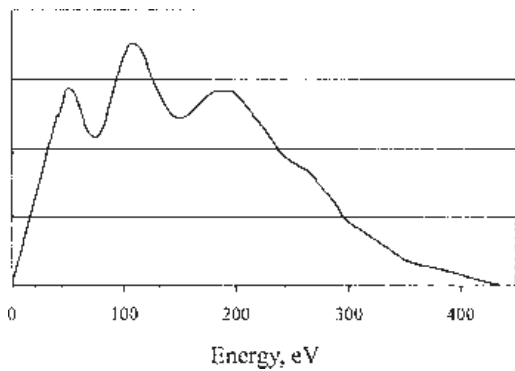


Figure 4. The energy distribution for AC operation of the SCIS in diffuse beam mode.

Collimated Beam Mode

In our experiments, we ran the SCIS in the collimated beam mode on oxygen and argon in order to simulate behavior of the linear ion source, which is intended to be run mainly in collimated beam mode.

The discharge voltage for the collimated beam mode was 1,500 V. The floating potential of the substrate in front of the ion source was up to 200 V for oxygen and up to 400 V for argon. The possible reason for different floating potentials could be the lower work function of oxidized metals (oxygen operation) compared to pure metals (as is the case in pure argon operation). The result is a higher secondary electron emission from the cathode and vacuum chamber walls, which allows better neutralization with oxygen.

It appears that the floating potential depends very little on the collector position, but rather on the gas flow and pressure. Figure 5 shows the dependence of the floating potential on the oxygen flow for the constant pumping speed.

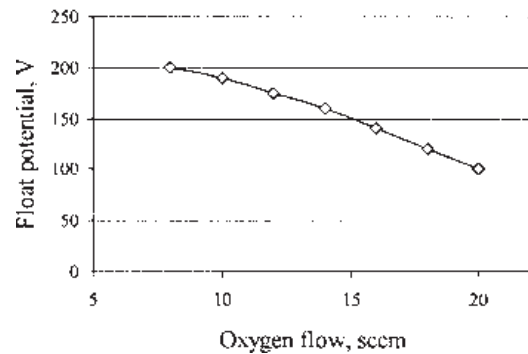


Figure 5. Dependence of the floating potential on the gas flow. The SCIS is running in collimated beam mode on oxygen, with a discharge voltage 1,500 V.

By negatively biasing the cathode of the ion source, we were able to reduce the floating potential of the substrate to 13 V. Dependencies of the floating potential on the cathode biasing voltage are shown in Figure 6 for 13 sccm of argon and 18 sccm of oxygen (both at a pressure of 1 mTorr). It is apparent that biasing the cathode significantly reduced the floating potential.

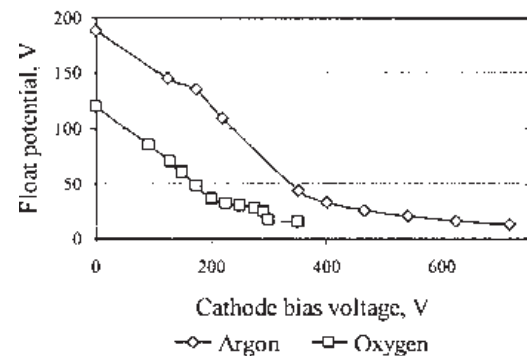


Figure 6. Dependencies of the floating potential on negative biasing voltage. Anode potential is 1500V.

The energy distributions curves for the cathode when biased and when unbiased are shown in Figure 7. The mean ion energies for different biasing options, calculated from energy distributions are summarized in the Table 1.

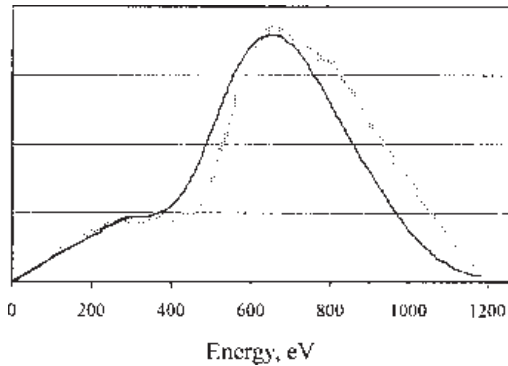


Figure 7. Energy distribution for the SCIS collimated beam mode. Wide gray line – cathode grounded, anode potential 1,500 V. Thin black line – cathode potential -250 V, anode potential 1,500 V.

Table 1. Mean ion energies for different biasing options.

Anode potential, V	1500	1500	1250
Cathode potential, V	0	-250	-250
Mean ion energy, eV	704	659	558

As mentioned above, the other method of neutralization is applying AC or pulsed DC voltage to the ion source, instead of straight DC. In the collimated mode, we tested the same method that was used for the diffused beam mode—applying AC to the anode and rectified AC to the cathode. The voltage oscillograms are reminiscent of the diffused beam mode (shown in Figure 3), but the maximum positive anode voltage was 1,400 V, and the minimum negative voltage was -200 V. The frequency was 375 kHz, and the maximum discharge power was 175 W. Using this method for oxygen, we were able to reduce the floating potential of the substrate to 12 V.

MULTICELL ION SOURCE (MCIS)

Ion Source Description

The multicell ion source was developed for hard disk cleaning and diamond-like carbon (DLC) film deposition. The ion source can work on pure oxygen and delivers a wide round beam. It has 61 cells; each cell is an individual small anode layer ion source. Cells fill the entire source aperture and share gas distribution and magnetic systems. The source was described in details in [2].

The MCIS can work only in collimated beam mode with a high discharge voltage (700 – 1500 V) and low current (up to 0.5

A). However, even though the mode is called collimated and the beamlet from each cell is well focused, the beam as a whole has a wide uniform spatial distribution due to divergence of individual beamlets.

Neutralization Experiments

In our experiments, we ran the ion source on argon and oxygen at the anode voltage of 1,500 V. For the argon operation, the flow was 25 sccm and discharge current was 0.2 A. The floating potential of the substrate in front of the source at the distance 50 mm was about 100 V. For the oxygen, the flow was 55 sccm and discharge current was 0.5 A. The floating potential of the substrate was only 18 V. We think that the much lower floating potential for the MCIS compared to the SCIS in collimated beam mode is due to a geometry factor. The cells of the MCIS are deep, and some ions from the beam strike the cells' walls, releasing secondary electrons. Those electrons reduce the floating potential of the substrate.

By negatively biasing the cathode of the ion source, we were able to reduce the floating potential of the substrate (collector) to zero, even making it negative. The graphs of floating potential versus biasing voltage for argon and oxygen are shown in Figure 8. The energy distribution for the unbiased source is shown in Figure 9.

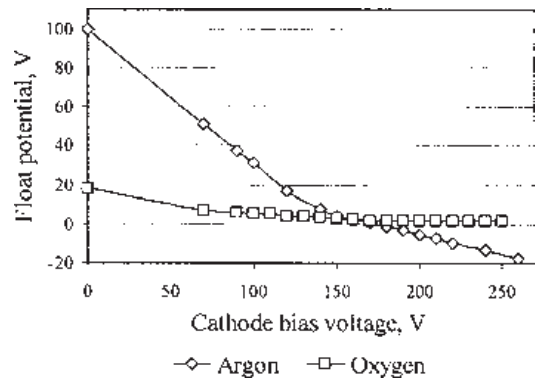


Figure 8. Dependence of the floating potential on biasing voltage. Anode potential 1500 V.

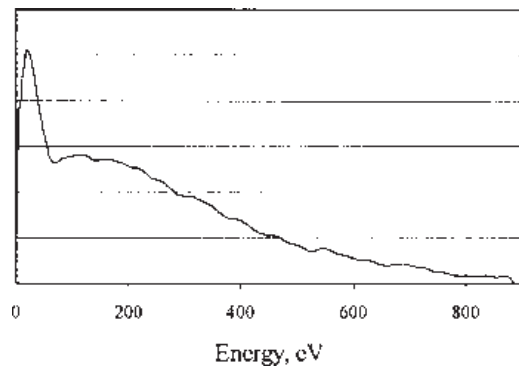


Figure 9. Energy distribution for oxygen. Anode potential 1500 V.

The other way of neutralizing the substrate was to apply half-rectified AC with frequency 400 kHz to the anode (the anode voltage oscillogram is shown in Figure 10). The dependence of the floating potential on the argon flow is shown in Figure 11. The lowest floating potential we were able to achieve was 2 V.

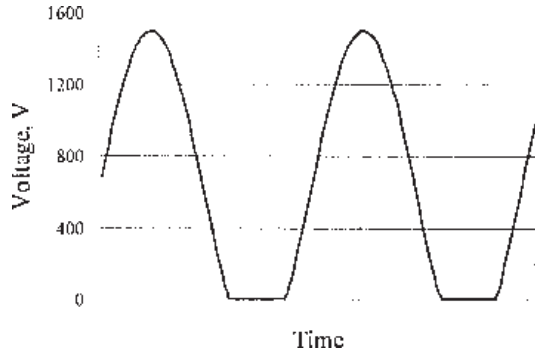


Figure 10. Half-rectified AC voltage applied to the MCIS anode. The frequency is 400 kHz.

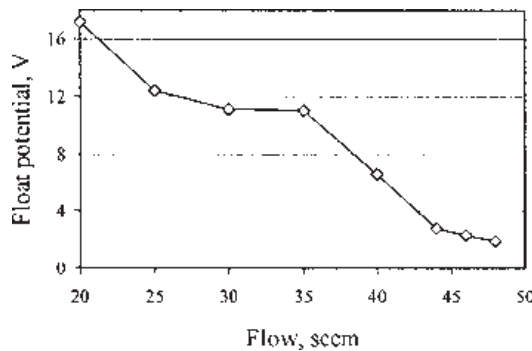


Figure 11. Floating potential versus argon flow for AC operation of the MCIS.

The MCIS appeared to work more stably with AC than with DC power at higher gas flow. The highest argon flow for the stable DC operation was 25 sccm, while with AC mode, it was 48 sccm.

There is a general concern about the lower average ion current with AC due to the less than 100% duty cycle as compared to DC. To address this, we measured the silicon oxide etch rates in AC and DC modes and didn't find a noticeable difference. This result could be due to the fact that even with the shorter duty cycle in AC mode, the higher available gas flow resulted in higher discharge peak current during AC positive cycle compare to DC.

SMALL 5 CM DIAMETER SINGLE-CELL ION SOURCE

Ion Source Description

For micromachining applications, we developed a small single-cell ion source with a 5 cm outer diameter. The ion source was designed to work in collimated beam mode. The emission slit of this source is 2 mm wide and inclined toward the ion source center, so the ion beam from the slit is focused on the axis. The focal distance is about 60 mm from the source. Working on argon, the ion beam density in the focal point could be up to 20 mA/cm² in the spot 5 mm diameter.

Neutralization Experiments

In our experiments, we ran the ion source on argon at the anode voltage of 1,500 V. The argon flow was 6.9 sccm, and discharge current was 0.1 A. The floating collector size 90 mm diameter was much larger than the ion beam size about 10 mm diameter (in our experiments with SCIS and MCIS the collector size was about the size of the ion beam).

Without biasing the source, the collector floating potential was 140 V. By negatively biasing the cathode of the ion source, we were able to reduce this potential to zero, even making it negative. The dependence of the floating potential on the bias voltage for argon is shown in Figure 12.

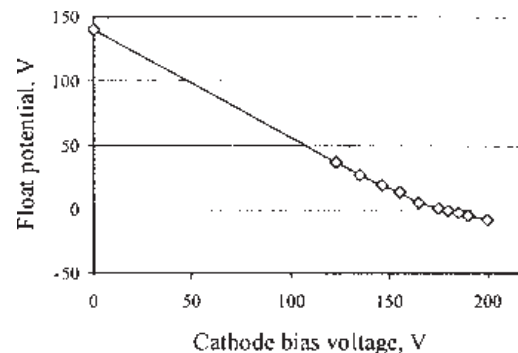


Figure 12. Dependence of the floating potential on negative biasing voltage. Anode potential 1,500 V.

When we tried using rectified AC for neutralization, it didn't work very well for this ion source. The floating potential with 400 kHz rectified AC was pretty high, 88 V.

CONCLUSION

Two new methods of ion beam neutralization for gridless ion sources have been introduced. One method is the biasing of the ion source cathode negatively, which enables creation of an electron beam from the discharge plasma simultaneously with the ion beam, and this electron beam neutralizes the substrate. The other method utilizes AC or rectified AC instead of DC. In this method, the reversed polarity of the power supply extracts the electrons from the discharge plasma. Both methods allow neutralization of the ion beam without using hot filaments or hollow cathodes. And both methods work well even in oxygen atmosphere.

Using AC appears to be simpler than biasing the cathode with a second power supply. However, biasing the cathode negatively provides more flexibility and reduces the floating potential to zero or even driving it negative. Also AC doesn't work well for some applications (e.g., the small 5 cm single-cell ion source).

The discussed methods of neutralization can be used in "hostile" environments with high oxygen pressure. Even though traditional electron emitters, such as hot filament or hollow cathode, are unavoidable in some applications, in many instances the newly developed neutralization methods are very attractive because of their simplicity and robustness.

REFERENCES

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