Transport efficiency of vacuum arc plasma in a curved magnetic filter

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We describe two methods for increasing the transmission efficiency of vacuum arc plasma through curved magnetic filters. In the first method the substrate is connected to the anode or biased to a negative voltage. In the second method a metal grid is placed between the substrate and the exit of the magnetic filter, and biased to a positive voltage whereas the substrate is biased negatively. The ion saturation current and electron saturation current of the plasma between the filter exit and the substrate were measured using a current collector plate and a Langmuir probe, respectively, and the ion density estimated. For the experimental conditions of the work described here, the measured ion flux (ion saturation current) near the duct exit was increased by up to about 80% (from 140 to 250 mA), and the measured ion density was increased by up to about 40% (from $3.7 \times 10^{11}$ to $5.2 \times 10^{11} \text{ cm}^{-3}$). These results can be explained by the ambipolar influence of enhanced electron flow on the accompanying plasma ion component, leading also to enhanced ion flow. © 2005 American Institute of Physics. [DOI: 10.1063/1.1848492]

I. INTRODUCTION

The cathodic vacuum arc produces a highly ionized, energetic, plasma stream from the cathode material which can be used for thin film deposition onto an appropriately positioned substrate. The process is often used to form films of metals, oxides, nitrides, semiconductors, and amorphous carbon. Similar plasma hardware is also used for beam-line metal ion implantation as well as for plasma immersion ion implantation (PIII). However, a negative feature of the use of this metal plasma formation process is the generation of “macro-particles” from the cathode—roughly micron-size droplets of cathode debris—that can act as a particulate contamination to the plasma stream. Even though the technique has found many applications in metallurgical and tribological applications, the presence of macroparticles has hindered the use of the method in more demanding areas such as microelectronics and optoelectronics. In order to circumvent the problems, macroparticle filters such as curved magnetic ducts are used to separate and remove particles from the plasma stream. Attempts have also been made to eliminate the particulate fraction by locating the cathode out of sight from the substrate. In a curved magnetic filter, the plasma particles (i.e., ions and electrons) are spatially separated from the macroparticles by virtue of the huge difference in their charge-to-mass ratios. While the plasma stream can easily be bent by a modest guiding magnetic field, the relatively massive macroparticles, which are (relatively) electrically neutral, move along almost straight trajectories unaffected by the magnetic field. Since Aksenov and co-workers introduced the 90°-duct magnetic filter in the late 1970s, this kind of curved filter has been the most common approach used and also one of the most successful.

While a curved magnetic filter offers many advantages, it also results in a significant loss of plasma ion flux, adversely affecting the rate of deposition or implantation. The plasma transmission efficiency through the magnetic filter is affected by the duct bias, magnetic field, arc current, and other factors. For good plasma transport, the duct must be biased positively by about 10 to 20 V. Bilek proposed and demonstrated inserting a positively biased plate near the outer wall of the magnetic duct to reflect positive ions and reduce electron loss to the duct. In another study, it was...
observed that this biasing mode resulted in a lower plasma transmission through the filter than for the case when the entire duct was biased.9

In most previous studies, the duct bias has been considered to be one of the most important factors for improving the plasma transmission, and few researchers have paid attention to the influence of external electric fields. In the work described here, we have investigated two different approaches for improving the plasma transmission through the 90°-duct filter, based on establishing an electric field in the post-duct region. The parameters of the plasma that exits the duct have been measured using a Langmuir probe and biased current collector plate.

II. EXPERIMENTAL SETUP

In our experiments, a dc (direct current) cathodic arc plasma source with an 84 mm diameter cathode was used, driven by an arc current of 81 A. A curved magnetic filter was inserted between the vacuum arc anode and the main vacuum chamber so as to suppress the transported macroparticle flux. The curved magnetic filter consisted of a 90° stainless steel duct with an inner radius of 155 mm, about which a coil was wrapped to produce a guiding magnetic field when a dc current was passed through the coil. The magnetic duct was electrically floating, and the magnetic field strength in the main part of the duct was fixed at 20 mT. The base pressure in the vacuum chamber was 2.8 × 10⁻³ Pa. Argon gas was 99.99% pure and was bled into the chamber by the inlet on the top of cathodic plasma source (Fig. 1) and the working pressure was maintained at 1.8 × 10⁻¹ Pa.

Two methods were explored to improve the efficiency of transmission of the plasma through the duct. In the first method, the substrate was connected to the anode or biased to a negative voltage. Alternatively, a metal grid was connected to the anode and positioned about 40 cm from the exit of the filter as shown in Fig. 1. The dimension of the wire grid was 35 cm × 35 cm, and the negatively biased substrate was of diameter 40 cm.

A Langmuir probe and an ion current collector plate measured the plasma parameters. The probe was located at the exit plane of the filter as indicated in Fig. 1. The probe was made of molybdenum wire of diameter 0.18 mm; the probe was of tip length 10 mm. The ion current collector plate was positioned at the duct exit (Fig. 1) and biased at a voltage of from 0 to −120 V, until the measured ion current saturated. In this work, the plasma Debye length \( \lambda_D \) was in the range of 3−5 × 10⁻⁴ m and larger than the probe radius \( r_p \) (\( r_p/\lambda_D < 1 \)). Thus an orbital motion limited analysis could be applied in interpretation of the Langmuir probe data.14,15

The ion current collector plate was made of copper board of diameter 30 mm. Comparing to the radius of duct the dimension of current collector plate is adequately small, the shading of current collector to the substrate could be neglected. In the results presented in the following, the electron saturation current was determined from the Langmuir probe measurements, the ion saturation current was determined from the current measured to the ion current collector plate, and the ion density was determined from the ion saturation current and the electron temperature obtained from the Langmuir probe measurements.
III. RESULTS AND DISCUSSION

A. Electron saturation current

The electron saturation current to the Langmuir probe was measured for the two filter configurations investigated, and the results are shown in Fig. 2. The electron saturation current without the wire grid in place is about 140 mA, remaining approximately unchanged as the substrate bias is varied from 0 to \(-100\) V; thus the negative bias voltage has little effect on the electron saturation current in this case. However when the substrate is directly connected to the anode and thus biased to \(+20\) V, the electron saturation increases to 160 mA as the probe bias is varied from 0 to \(-100\) V. When the wire grid is employed, the electron current increases slowly with increasingly negative substrate bias, to a maximum value of about 190 mA at a substrate bias of \(-100\) V. The increase in the electron saturation current is related to the location of the grid with respect to the substrate, as our results show different results for different positions of the grid.

B. Ion saturation current

The ion saturation current collected by the current collector plate in the two different experimental configurations is shown in Fig. 3. For the first method (substrate bias), the negative substrate voltage has almost no effect on the ion saturation current at the filter exit and the ion saturation current remains fixed at about 180 mA. These results imply that the negative voltage applied to the substrate has no significant effect on the ion motion. However, when the substrate is connected to the anode, the ion saturation current increases to 220 mA. Because the substrate is connected to the anode, electrons that are confined by the duct magnetic field are not reflected by the substrate and do not return to the anode. When the substrate is at the same potential as the anode, the
electron flux from the filter exit to the substrate can be
greater than for the case of a negatively biased substrate.
Electron loss to the duct wall may also diminish. This has
been corroborated by the electron saturation current behavior
shown in Fig. 2. It is now well known that ions in a macro-
particle filter are not magnetized because their gyration ra-
dius is usually greater than the characteristic filter size
(filter inner radius), but the unmagnetized ions follow the plasma-
confined electrons so as to maintain plasma quasi-neutrality
(i.e., ambipolar flow). Thus for the case when a greater elec-
tron flux is caused to flow from the duct, so also does the ion
flux (ion saturation current to the collector plate) increase.

In the second method (use of a wire grid), the measured
ion saturation current increases slightly when the negative
substrate bias is increased from 0 to −100 V. As mentioned
above, the position of the grid is an important factor because
it attracts more electrons and gives rise to a higher ion satu-
ration current. The ion saturation current increases slowly
with increasingly negative substrate bias, as would be ex-
pected from a model in which ion flow is due to an ambipo-
lar field established by increased electron flow. We point out
that in both the first and second methods of increasing duct
transport, positive substrate bias increases the measured ion
saturation current.

C. Ion density

Figure 4 shows the ion densities measured for the case of
the two different approaches to increasing the filter transport
efficiency. The maximum ion density is $5.2 \times 10^{11}$ cm$^{-3}$ at a
substrate bias of about −60 V for method 2. In the first
method the measured ion density does not change with nega-
tive substrate bias, and is a maximum when the substrate is
connected electrically to the anode. This behavior is similar
to that for the ion saturation current, as expected. The ion
density measured in the second method is greater than in the
first method, and can be explained by the position of the wire
grid. The grid is placed between the curved duct and the
substrate, and thus provides a strong attractive influence on
the electron flow and also the ambipolar ion flow.

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