Guiding effects of electric and magnetic fields on the plasma output of a cathodic arc magnetic filter

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A magnetic filter was inserted between the cathodic arc plasma source and chamber to reduce the amount of macroparticles transmitted from the plasma to the sample. The plasma output of the magnetic filter was determined as a function of magnetic field and bias voltage, for the cases when the bias was applied to the entire duct wall or to a Bilek bias plate alone. The factors affecting plasma diffusion in the duct were investigated. As well as collisional and inhomogeneous magnetic field effects, our computer simulation and experimental results indicate that the \( \mathbf{E} \times \mathbf{B} \) drift results in an additional diffusion flux for the case when a Bilek bias plate is used. Hence the Bilek biasing mode results in a lower plasma output than for the case in which the entire duct is biased. © 2001 American Institute of Physics. [DOI: 10.1063/1.1330240]

I. INTRODUCTION

Cathodic arc plasma is of increasing importance in thin film deposition of metals, oxides, nitrides, semiconductors and amorphous carbon,\(^1\) beam-line metal ion implantation,\(^6\) as well as metal plasma immersion ion implantation (PIII).\(^7\)–\(^9\) The favorable characteristics of a cathodic arc plasma source are the high flux and high degree of ionization of the metal plasma. However, cathodic arc plasma sources suffer from macroparticle (cathode debris) contamination. Techniques for the reduction or elimination of macroparticles have been investigated.\(^10\),\(^11\) The most common method to remove macroparticles is to employ a curved magnetic filter (duct). Unfortunately, it has been found that a curved magnetic filter also results in a significant loss in the ion flux, adversely affecting the metal film deposition or ion implantation rate. Several methods have been proposed to optimize the ion flux transport efficiency through the curved magnetic filter.\(^12\),\(^13\) One such method involving inserting a positively biased plate near the outer wall of the magnetic duct to reflect positive ions and reduce electron loss to the duct was proposed by Bilek.\(^14\),\(^15\) In this configuration, a small bias on the plate suffices. This method is especially useful when the duct is electrically connected to the main chamber that is grounded and biasing the duct itself is thus impossible.\(^16\) It should be noted that the electron current collected by the positively biased “Bilek plate” is much higher than when it is at ground potential, but the plasma current exiting the duct is also much higher when the plate is positively biased.

In the work described here, we compare the Bilek biasing mode and the entire duct biasing mode with regard to the plasma output of the magnetic filter. Our computer simulation and experimental data show that the electron behavior is different when biasing the Bilek plate alone compared to that when the whole duct is biased. The experimental results can be explained by the electron behavior under the different biasing modes.

II. EXPERIMENT

The cathodic arc plasma source was composed of a negatively biased titanium electrode 1 cm in diameter and a zero-potential mesh anode positioned about 16 mm in front of the cathode. The cathodic arc discharge was sustained in a pulsed mode at a frequency of 60 Hz by a 0.3 ms pulse-forming network at a maximum charging voltage of 200 V. A curved magnetic filter was inserted between the plasma source and main chamber to remove macroparticles produced in the cathodic arc plasma and perform the biasing experiments. The curved magnetic filter consisted of a 90° stainless steel pipe with a minor radius \( r \) of 40 mm and a major radius \( R \) of 100 mm. It was insulated from the mesh anode and from the vacuum chamber so that it could be positively or negatively biased. A coil was wrapped around the duct to produce a guiding magnetic field when a dc current was passed through the coil.

An aluminum electrode (the “Bilek bias plate”) was positioned on the inside surface of the outer duct wall (large
radius) and biased to enhance the plasma transport through the duct. The plate covered a quarter of the outer duct wall and was insulated from the duct wall by a sheet of plastic. The magnetic filter was biased in two ways: (a) biasing the Bilek plate only and (b) biasing the entire duct. In the second mode, the duct and the Bilek plate were connected in parallel, and so the plate became a part of the duct wall. The duct and the Bilek plate were biased via a capacitor bank of 22 mF. The large capacitance was needed to produce the high duct current during the arc pulse, otherwise the duct potential could change significantly during the arc pulse.

A 160 mm x 220 mm plane collector plate was positioned in the vacuum chamber about 20 cm from the duct exit to monitor the ion flux transported through the duct. The plate was negatively biased to -70 V to collect the ion current. This voltage was chosen by varying the bias voltage over a range to confirm that it was comfortably within the ion saturation current regime. The vacuum chamber pressure was about 5 x 10^-3 Pa. A simplified schematic of the experimental configuration is shown in Fig. 1. To limit the number of variables, the titanium arc discharge current was fixed at 100 A. The arc discharge current depends not only on the charging voltage of the LC pulse forming line, but also on the duct and Bilek plate voltages as well as the magnetic field near the arc region. The voltage of the pulse line was regulated to keep the discharge current at 100 A while varying the other parameters. The measured cathodic arc and ion currents were their peak pulse values.

The electron oscillation experiment was conducted with an insulating torus positioned inside the duct (Fig. 2). A hot filament generated the electrons. The duct was away from the line of sight of the filament, and so the electrons generated from the filament could not drift into the duct directly. An aluminum foil torus was affixed to the side of the insulating torus facing the cathode. The aluminum foil torus collected the electrons traversing from right to left but not the electrons from left to right (see Fig. 2). The cathode was charged to -90 V but did not produce a cathodic arc.

III. RESULTS AND DISCUSSION

The results shown in Fig. 3 indicate that the ion current on the collecting plate $I_P$ is higher when the entire duct is biased, rather than the Bilek plate alone. The duct transport efficiency attains a maximum value when the bias voltage is in the range of +10 to +20 V, independent of the magnetic field strength within our experimental error. The plasma output $I_P$ monotonically increases with the duct magnetic field. There is almost no plasma output when the duct magnetic field is zero. This indicates that the duct magnetic field is a critical factor of the plasma output. In contrast to the case of zero duct magnetic field, the plasma output $I_P$ increases with the duct magnetic field when the Bilek plate or the entire duct is grounded.

When the electrons are magnetized, the motion of electrons across the magnetic field is limited. When $\omega_e \gg \nu$, where $\omega_e$ is the electron cyclotron frequency and $\nu$ is the electron collision frequency, the ions have a much higher transverse motion rate than the electrons. Hence, a positive...
bias on the duct wall can reflect ions back and keep the plasma from diffusing towards the duct wall to some extent. The plasma output of the duct increases significantly when the magnetic field is on, and the positive bias increases the output further, as illustrated by the $B=80, 160, 240,$ and $320$ G curves in Fig. 3. However, an excessively high positive bias causes electrons to traverse faster. More electrons are lost to the wall and the plasma becomes unsteady. Thus an unduly high positive bias decreases the plasma output of the duct. When the magnetic field is off, the electrons are not magnetized and move rapidly towards the duct wall and are lost to the wall. In this case, the ions will collide with and deposit onto the wall due to bipolar diffusion. Consequently, the plasma output is very low, regardless of the positive bias, as shown by the $B=0$ G curve in Fig. 3.

The ion diffusion flux to the wall is caused mainly by collisions between the particles in the duct.12 The flux associated with cross-field diffusion is given by Fick’s law: \[ \Gamma = -D \nabla n \] where $\nabla n$ is the gradient of the plasma density, $D = kT_e/16B$,17 $k$ is Boltzmann’s constant, $T_e$ is the electron temperature, and $B$ is the magnetic field strength. Collisions with neutrals can be ignored because the vacuum arc plasma is almost fully ionized. The occurrence of several kinds of collisions in the filter, namely electron–electron, electron–ion, ion–electron, and ion–ion, has been described by Anders.12 The plasma output $I_p$ increases linearly and so $I_p \propto B$. The relationship of $I_p$ versus $B$ in this experiment deviates slightly from $I_p \propto B$ (Fig. 4) suggesting that there are other causes for the plasma diffusion besides collisions. The inhomogeneous magnetic field in the duct, with a higher magnetic field on the inner side of the duct torus, can give rise to a drift motion of the electrons and ions in the plasma. This can decrease the plasma output of the duct. When the entire duct is biased, the plasma output is higher, and so there is an extra diffusion mechanism in the Bilek biased duct. The electron velocity is typically about $10^6$ m/s and ion velocity $10^4$ m/s in the cathodic arc plasma.18 The electron density is usually several times the ion density.19 In the short time frame, the ions can be considered to be motionless compared to the electrons. A computer code has been developed to simulate the particle motion in the magnetic filter.20 The calculation results show that some electrons will oscillate in the duct in the presence of an axial magnetic field and positive bias (Bilek bias or entire duct bias). The magnetized electrons move along the magnetic field, and when the electrons leave the duct, the electric field at the duct outlet will pull the electrons back and reverse their direction. When the electrons are close to the cathode, the electric field of the negatively biased cathode pushes the electrons back and makes them move towards the duct outlet again. Thus the electrons oscillate in the duct. The initial position, velocity, and direction of the flying electrons must satisfy certain requirements to make the electrons oscillate. The oscillating requirements are more difficult to meet when the entire duct is biased and only a few electrons oscillate. On the other hand, the oscillating requirements are easier to meet for the Bilek biasing mode and a considerable number of electrons will oscillate in the duct. The oscillating electrons will produce a pronounced effect on the plasma motion for the Bilek biasing mode. While the electrons oscillate, the $E \times B$ force will drift the electrons towards the duct wall. Therefore the electrons oscillate, finally striking the wall and the plasma in bulk may drift towards the wall.

The electron oscillation test results are displayed in Fig. 5. The results indicate that the electric and magnetic fields trap the electrons in the chamber generated from the hot filament, causing the electrons to enter into and oscillate in the duct. The collected electron current on the aluminum foil torus $I_f$ increases with the bias voltage and decreases with the magnetic field. The electron drift rate $v_d$ is equal to $E/B$. The larger the $v_d$, the higher the number of electrons impinging onto the aluminum foil. The curves in Fig. 5 can be explained by the equation $v_d = E/B$.

**IV. CONCLUSION**

One of the purposes of inserting a biased plate covering a quarter of the outer duct wall instead of biasing the entire duct is to reduce electron loss to the duct wall, because the electrons play an important part in guiding the ions through the duct. However, our experimental results show that the entire duct biasing mode has a higher plasma output than that of the Bilek biasing mode. Our work indicates that besides the factors affecting diffusion in the plasma, for example, collisions and the effective area of the duct inner wall where there is a bias, the electron drift resulting from the $E \times B$ force contributes to the plasma diffusion in the duct for the Bilek biasing mode. The different electron behaviors result in the difference in the plasma output of the magnetic filter.

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