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GUIDING OF PLASMA BY ELECTRIC FIELD AND MAGNETIC FIELD*

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The relationship between the transported ion current and the cathodic arc current is determined in a vacuum arc plasma source equipped with a curved magnetic filter. Our results suggest that the outer and inner walls of the duct interact with the plasma independently. The duct magnetic field is a critical factor of the plasma output. The duct transport efficiency is to maximize at a value of bias plate voltage in the range +10 V to +20 V, and independent (within our limit of measurement) of the magnetic field strength in the duct. The plasma flux is composed of two components: a diffusion flux in the transverse direction due to particle collisions, and a drift flux due to the ion inertia. The inner wall of the magnetic duct sees only the diffusion flux while the outer wall receives both fluxes. Thus, applying a positive potential to the outer duct wall can reflect the ions and increase the output current. Our experimental data also show that biasing both sides of the duct is more effective than biasing the outer wall alone.

Keywords: cathodic arc, plasma, transport, magnetic filter
PACC: 5275, 5230, 5280, 2925

I. INTRODUCTION

Cathodic arc plasma becomes more important in thin-film deposition of metals, oxides, nitrides, semiconductors and amorphous carbon,[1−5] metal ion implantation using line-of-sight implantation with a three-electrode system,[6] as well as metal plasma immersion ion implantation (PIII).[7−9] The favourable characteristics of a cathodic arc plasma source are the high flux and large fraction of ions in the metal plasma. However, cathodic arc plasma sources suffer from macro-particle contamination, and the reduction or elimination of macro-particles has been studied.[10,11] The most common method to remove macro-particles is to use a curved magnetic filter (duct). Unfortunately, it has been found that a curved magnetic filter also results in significant losses of the ion flux, thereby adversely affecting the metal film deposition rate and metal ion implantation rate. Several methods have been proposed to optimize the ion flux transport efficiency through the curved magnetic filter.[12,13] A prominent technique was proposed by Bilek,[14] in which a positively biased plate is inserted near the outer wall of the magnetic duct to reflect positive ions and reduce electron loss to the duct. In this configuration, a small bias on the plate will suffice. This method is especially useful when the duct is electrically connected to the main chamber which is grounded, and biasing the duct itself is impossible.[15] 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 than when the plate is positively biased.

In the work described here, we have investigated the enhancement mechanism of the magnetic duct using a specially designed curved magnetic filter. Using two different biasing modes, the output current as a function of the bias voltage and magnetic field is determined. The relationship between the output current and cathodic arc current is also evaluated to investigate the interaction between the plasma and the duct walls.

II. EXPERIMENTAL DETAILS

The cathodic arc plasma source consisted of a negatively biased titanium electrode (1cm in diameter) and a zero-potential anode positioned about 16 mm in front of the cathode. The anode aperture was 56 mm in diameter and a tungsten mesh was attached to the anode hole to stabilize the cathode arc triggered by

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a high voltage spark. The cathodic arc discharge was operated in a pulsed mode with a frequency of 60 Hz and fed by a 0.3 ms pulse-forming network at a maximum charging voltage of 200 V. A special curved magnetic filter was inserted between the plasma source and the main chamber to remove macro-particles produced in the cathode arc plasma and to perform the biasing experiments. The curved magnetic filter consisted of a 90° stainless steel pipe with a minor radius, r, of 40 mm and major radius, R, of 100 mm. It was insulated from the anode and 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 passed through it. As the distance between the end of the cathodic arc discharge and the entrance of the coil was only 20mm, the coil also produced a focusing magnetic field near the cathodic arc.

An aluminium 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 was insulated from the duct wall by a sheet of plastic. The magnetic duct 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 when the duct was positively biased.

A 160 × 220 mm large area plane collector plate was positioned in the vacuum chamber about 20cm 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.[9] The vacuum chamber pressure was about 5×10^{-3}Pa. A simplified schematic diagram of the experimental configuration is shown in Fig.1. In our experiments, we monitored the collecting plate current (transported plasma ion current) as a function of the Bilek bias plate voltage or duct voltage at different duct magnetic field strengths. To keep the arcing spots stable and to limit the number of variables, the titanium arc discharge current was fixed at 100A, except when the cathodic arc current was varied to investigate the influence of the arc current on the plasma transport efficiency. 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 100A while varying the other parameters. The cathodic arc and ion currents measured were their peak pulse values.

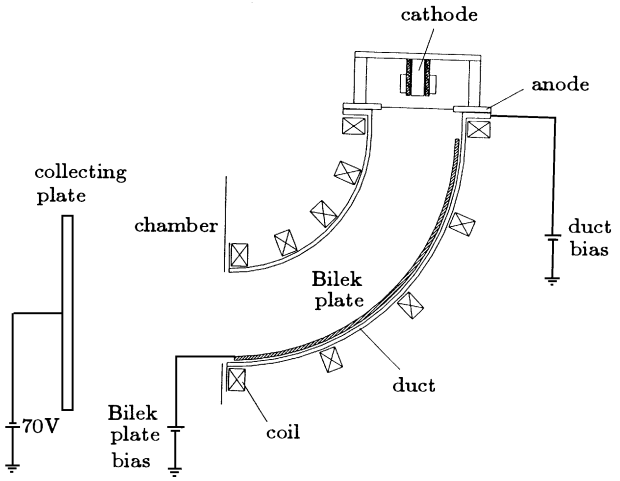


Fig.1. Schematic diagram of the experimental apparatus showing the cathodic arc plasma source, magnetic filter with the Bilek plate, and collecting plate.

III. RESULTS AND DISCUSSION

The results shown in Fig.2 indicate that the ion current is higher when the entire duct rather than the Bilek plate alone is biased.

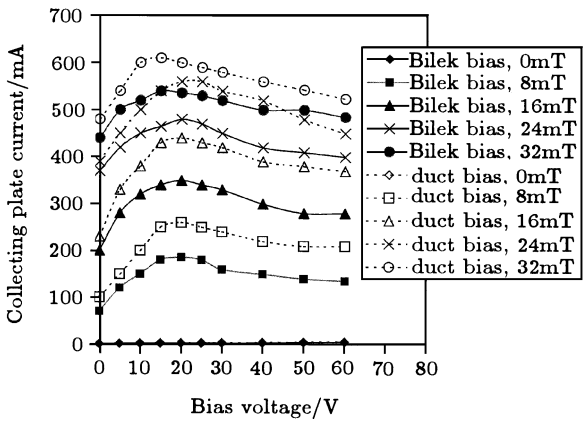


Fig.2. Ion current as a function of the Bilek bias or whole duct bias for various magnetic field strengths. Solid data points with solid lines are for Bilek plate bias only, and empty data points with dotted lines represent biasing both the inner and outer wall of the duct.

The duct transport efficiency is going to maximize at a value of bias plate voltage in the range

+10V to +20V, and is independent (within our limit of measurement) of the different values of magnetic field strength in the duct. The optimal improvement in plasma transport can be described by the plasma transport efficiency enhancement factor. The factor which equals the ratio of maximum collecting plate current by using the Bilek bias plate to the collecting plate current at zero bias is depicted as a function of duct magnetic field shown in Fig.3. The maximum transport efficiency enhancement is about a factor of four.

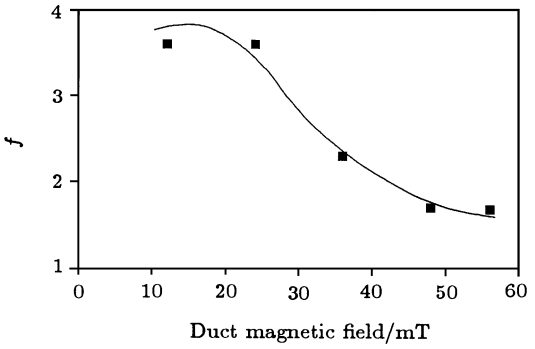


Fig.3. Plasma transport efficiency enhancement factor $f = I_c(\max)/I_c(V_B = 0)$, as a function of the magnetic duct field strength. I_c is collecting plate current, and V_B is the magnetic field in the duct.

The plasma output 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 increases as the duct magnetic field increases when the Belik plate is grounded.

We measured the current to the grounded or positively biased duct or the Bilek plate and found that there was a net electron current through the duct or the Bilek plate for the magnetic field used in this work. Our work showed the same result as that in Ref.[12] that the electron current to the duct or the Bilek plate increases with the bias voltage. Interestingly, at the same bias, the electron current through the duct is higher than that through the Bilek plate. It is reasonable that the interaction between the plasma and the duct wall is independent of the interaction between the plasma and Bilek plate when the duct is filled with plasma. This is because the Debye length of the cathodic arc plasma is small and the plasma shields the external electric field, although the duct shields the Bilek plate when they are connected in parallel and there is no plasma in the duct. The positive bias on the duct or the Bilek plate will give rise to an electric field between the plasma and the duct wall or the Bilek plate. This electric field prevents the ions from colliding with the duct wall or the Bilek plate. A positive bias promotes the reflection of ions back into the plasma. Hence, biasing both sides of the duct is more effective than biasing the Bilek plate alone, as far as the transported ion current is concerned. If the magnetic field is high enough, the inner wall of the duct will receive an equal flux of ions and electrons, but the outer wall will receive an additional ion flux due to the ion inertia drift.[12,16] Based on our results, we believe that the ion flux impacting the duct wall has two components. The first component is the transverse diffusion ion flux due to particle collisions in the plasma, and the second is the ion inertial drift flux. The outer wall of the duct is the main surface facing the ion inertial drift flux. Hence, a positively biased Bilek plate is quite effective in increasing the transported ion current. However, if the positive bias is too high, both the Bilek plate and the inner wall of the duct will collect a high electron flux from the plasma. These plasma electrons play an important role in guiding the ions, and an excessively high positive bias will result in decreasing of ion transport, as illustrated in Fig.2.

In order to investigate the influence of the cathodic arc current on the transported ion current, the bias of the duct or the Bilek plate was fixed at +20V. As shown in Fig.4, the transported ion current initially increases rapidly with the arc current. The increase becomes smaller at higher arc currents for both biasing modes (Bilek plate alone or both sides of the duct). The diminished increment in the transported ion current is due to ions impinging on the duct wall, resulting from both the transverse ion diffusion flux and the ion inertial drift flux. The transverse 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 ∇n is the gradient of the plasma density, $D = kT_e/16B$,[17] k is Boltzmann's constant, T_e the electron temperature, and B 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, i.e. electron–electron, electron–ion, ion–electron and ion–ion, has been described by Anders.[12] In our work, $\rho_e \ll r$ and $\rho_i > r$, where ρ_e and ρ_i are the electron and ion Larmor radii, respectively, and r is the

minor radius of the duct. Therefore, electron–electron collisions give rise to very little diffusion, since the centre-of-mass of the guiding centres of the colliding electrons remains stationary. Ion–ion collisions cause a radial, ambipolar electric field. For electron–ion and ion–electron collisions, we mainly consider electron–ion collisions because $\upsilon_{ie} = (m_e/m_i)\upsilon_{ei}$ due to momentum conservation. A high cathodic arc current results in a high electron density n_e in the duct. When n_e is high enough, the electron–ion collision will play a considerable role in transverse plasma transport. Thus, the ion inertial drift flux has a major effect on the transport of the plasma through the duct only when the cathodic arc current is low. When the cathodic arc current is high, both the transverse ion diffusion flux and ion inertial drift flux have an evident effect on the transport of the plasma through the duct.

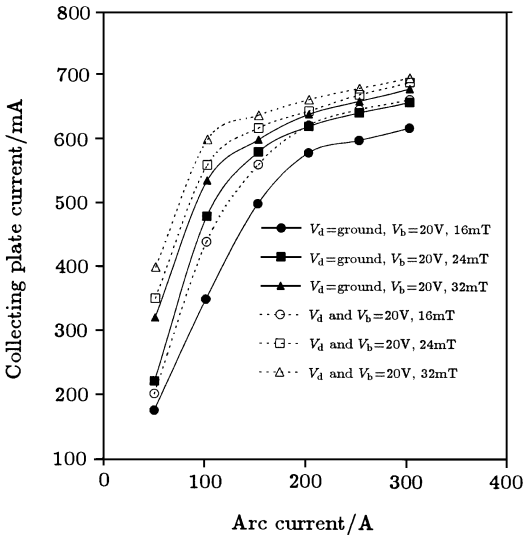


Fig.4. Transported ion current as a function of cathodic arc current for different biasing modes (Bilek plate or whole plate) and magnetic field. Solid data points with solid lines are for Bilek plate bias only, and empty data points with dotted lines represent biasing both the inner and outer wall of the duct. V_d is bias on the duct and V_b is bias on the Bilek plate.

The plasma is guided when the electrons are magnetized, i.e. when the electron cyclotron radius is much smaller than the minor duct radius, and the collision frequency is smaller than the electron cyclotron frequency. The magnetic field strength is not sufficient to magnetize ions in this experiment. The feature of cathodic arc is that the ions drift velocity is (1–2)×10^{4}m/s, nearly independent of their mass.[18] The ion flux in the space near the cathode is an inertial ion flux, which is hardly confined by magnetic field line, and the ions move along almost straight lines.[14,19] This means that the ions in the cathodic arc plasma move across the magnetic line much faster than electrons and the plasma internal electric fields have little confinement on the ion motion. The magnetic field confines the electrons and these electrons shield the Coulomb repelling between ions. Thus the magnetic field indirectly prevents the ions from increasingly moving to the wall. The ion trace in the space near the cathode is mainly determined by ion–ion thermal collisions. Collisions between ions and electrons have little influence on the ions trace when the ions are not magnetized and the ion drift energy is high in the space near the cathode. The ion–ion collision frequency is

$$\upsilon_{ii} = \frac{8\sqrt{\pi}e^4 n_i L_i}{3m_i T_i^{3/2}}. \quad (1)$$

In this equation, e is the elementary charge, n_i the ion density, m_i the ion mass, T_i the ion temperature, and L_i is a constant. The ion density in the space near the cathode is usually below 10^{20}cm^{-3}.[20] So the ion–ion collision frequency in the cathodic arc plasma is below 10^5/s (Fig.5).

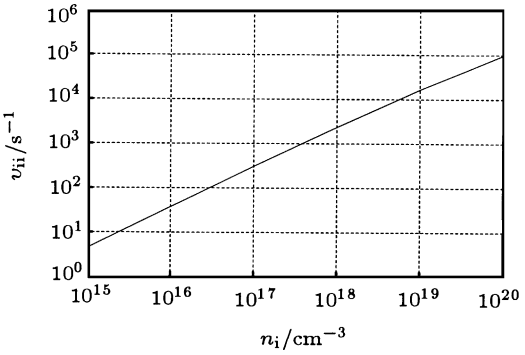


Fig.5. Ion density n_i versus ion collision frequency υ_{ii} in the cathodic arc plasma. The ion is titanium and the ion temperature is 3eV.

With the typical ion drift velocity of (1–2)×10^4 m/s in the cathodic arc plasma, the drift distance of most ions between two collisions will be 0.1m or more. This distance is larger than the duct minor radius r. So the ions originating from the cathodic spots and having big emission angle (the ion emission angle is 0 when the ions shoot along the axis of the duct) will reach the duct wall without ion–ion collisions. The ion loss to the duct wall near the cathode is very severe and holds the best part of the total ion loss to the duct wall, because most ions in this section of the duct have the favourable energy and incident angle to strike the duct wall. The positively biased duct wall

reflects the ions and increases the transport efficiency. The initial distribution of the drift velocity and direction of the ions from the cathodic spots are decided by cathodic arc process only. The magnetic field has little influence on the ion motion and the ions move along nearly straight lines in the space near the cathode. So the maximum ion current on the collecting plate would appear at an optimum bias voltage which is independent of the magnetic field (see Fig.2). This optimum voltage is a tuned result to reflect the ions, which have different energy and incident angle, and let as many as possible ions finally reach the exit of the duct. On the other hand, from the point of the whole duct, the optimum voltage should be the minimum voltage on the condition of effectively reflecting the ions.

IV. CONCLUSIONS

The plasma ion flux transported through a magnetic filter can be separated into two components: a transverse ion diffusion flux due to particle collisions in the plasma and an ion inertia drift flux. These components interact in different modes with the magnetic and electric fields in the duct. The inner wall of the duct sees mainly the transverse ion diffusion flux, whereas the outer wall receives both the transverse ion diffusion flux and the ion inertia drift flux. The outer wall is the main surface facing the ion flux, and so a positive potential on the outer wall increases the transported ion current. Our results indicate that biasing the inner and outer walls of the duct positively is more effective than biasing only the Bilek plate, although a positively biased duct absorbs more electrons than the positively biased Bilek plate alone. The plasma transport efficiency through the duct is lower for higher cathodic arc current because the transverse ion diffusion is strong.

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