Mechanism of enhanced plasma transport of vacuum arc plasma through curved magnetic ducts

T. Zhang, Z. M. Zeng, X. B. Tian, B. Y. Tang, and P. K. Chu[a)]
Department of Physics and Materials Science, City University of Hong Kong, Kowloon, Hong Kong

I. G. Brown
Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720

H. X. Zhang
Institute of Low Energy Nuclear Physics, Beijing Normal University, Beijing Radiation Center, Beijing 100875, China

(Received 5 March 1999; accepted 9 April 1999)

The mechanism of the enhanced transport efficiency in a vacuum arc plasma source equipped with a curved magnetic filter is investigated. The relationship between the transported ion current and the cathodic arc current is determined, and our results suggest that the outer and inner walls of the duct interact with the plasma independently. 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 reflects the ions and increases the output current. Our experimental data also show that biasing both sides of the duct is more effective than biasing the outer wall alone.
[S0734-2101(99)03005-5]

I. INTRODUCTION

Cathodic arc plasma is of increasing importance in thin film deposition of metals, oxides, nitrides, semiconductors, and amorphous carbon,[1–5] metal ion implantation employing line-of-sight implantation with a three-electrode system,[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 large fraction of ions in the metal plasma. However, cathodic arc plasma sources suffer from macroparticle contamination, and the reduction or elimination of macroparticles has been studied.[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 significant losses of the ion flux, thereby affecting adversely 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 of 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 *et al.*[14] 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 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 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 was 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. EXPERIMENT

The cathodic arc plasma source consisted of a negatively biased titanium electrode 1 cm 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 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 main chamber to remove macroparticles 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 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 direct current (dc) current was passed through it. As the distance between the end of the cathodic arc discharge and the entrance of the coil was only 20 mm, the coil also produced a focusing magnetic field near the cathodic arc.

[a)]Author to whom correspondence should be addressed; electronic mail: paul.chu@cityu.edu.hk

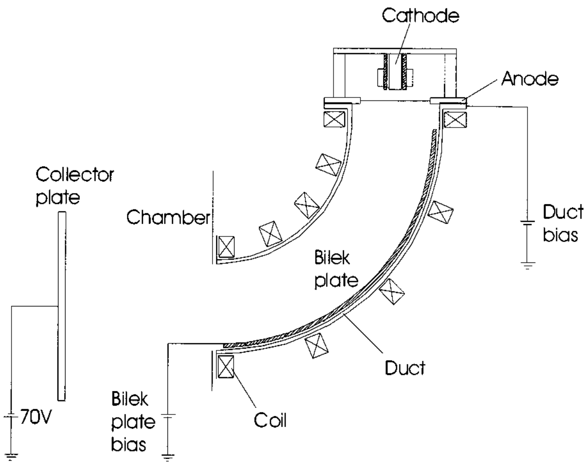

FIG. 1. Schematic of the experimental apparatus showing the cathodic arc plasma source, magnetic filter with the Bilek plate, and collector plate.

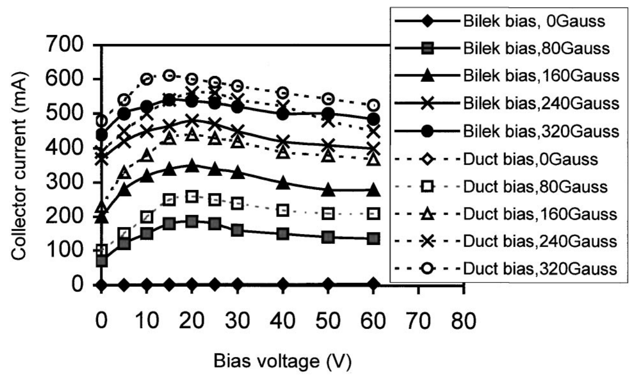

FIG. 2. Ion current as a function of the Bilek bias or whole duct bias for various magnetic field strengths. Solid data points with solid lines are for Bilek plate bias only, and empty data points with dotted lines represent biasing both the inner and outer wall of the duct.

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 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 mm$\times$220 mm large area 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.[9] The vacuum chamber pressure was typically about 5×10^{-3} Pa (4×10^{-5} Torr). A simplified schematic of the experimental configuration is shown in Fig. 1. In our experiments, we monitored the collector 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 100 A, 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 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 cathodic arc and ion currents measured were their peak pulse values.

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. We measured the current to the grounded or positively biased duct or 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. The electron current to the duct or the Bilek plate increases with bias voltage.[12] Interestingly, at the same bias, the 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 Bilek plate will give rise to an electric field between the plasma and duct wall or Bilek plate. This electric field prevents the ions from colliding with the duct wall or the Bilek plate. A positive bias thus 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 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 decreased ion transport as illustrated in Fig. 2.

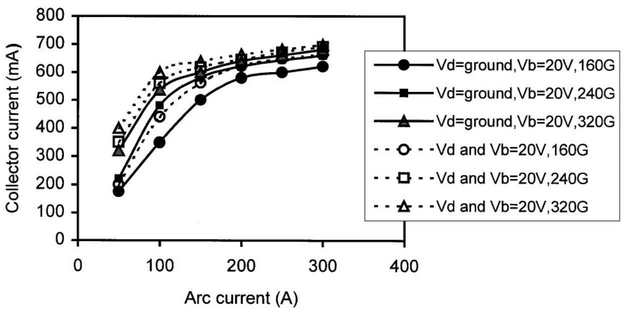

FIG. 3. Ion current as a function of cathodic arc current for different biasing modes (Bilek plate or whole plate) and magnetic field. Solid data points with solid lines are for Bilek plate bias only, and empty data points with dotted lines represent biasing both the inner and outer wall of the duct. V_d is bias on the duct and V_b is bias on the Bilek plate.

In order to investigate the influence of the cathodic arc current on the ion current, the bias of the duct or the Bilek plate was fixed at $+20$ V. As shown in Fig. 3, the transported ion current initially increases rapidly with 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 increase in the 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 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, i.e., electron–electron, electron–ion, ion–electron, and ion–ion, have been described by Anders, Anders, and Brown.[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 center-of-mass of the guiding centers 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 affect the transport of the plasma through the duct.

IV. CONCLUSION

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 as well as an ion inertia drift flux. These components interact differently 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 receives both the transverse ion diffusion flux and ion inertia drift flux. The outer wall is the main surface facing the ion flux, and so a positive potential on the outer 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 higher for lower cathodic arc current because the transverse ion diffusion due to particle collisions in the duct is strong or when the arc current is high.

ACKNOWLEDGMENTS

This work was supported by Hong Kong Research Grants Council Earmarked Grant Nos. 9040332 and 9040344.

[1]D. R. McKenzie, D. Muller, and B. P. Pailthorpe, Phys. Rev. Lett. **67**, 773 (1991).
[2]R. L. Boxman *et al.*, IEEE Trans. Plasma Sci. **23**, 939 (1995).
[3]A. Bendavid, P. J. Matin, R. P. Netterfield, and T. J. Kinder, Surf. Coat. Technol. **70**, 97 (1994).
[4]S. Anders, A. Anders, M. Rubin, Z. Wang, S. Raoux, F. Kong, and I. G. Brown, Surf. Coat. Technol. **76**, 167 (1995).
[5]A. Benshalom, L. Kaplan, R. L. Boxman, S. Goldsmith, and M. Nathan, Thin Solid Films **236**, 20 (1993).
[6]I. G. Brown, Rev. Sci. Instrum. **65**, 3061 (1994).
[7]I. G. Brown, X. Godechot, and K. M. Yu, Appl. Phys. Lett. **58**, 1392 (1991).
[8]I. G. Brown, A. Anders, S. Anders, M. R. Dickinson, I. C. Ivanov, R. A. MacGill, X. Y. Yao, and K. M. Yu, Nucl. Instrum. Methods Phys. Res. B **80/81**, 1281 (1993).
[9]Z. M. Zeng, T. Zhang, B. Y. Tang, X. B. Tian, and P. K. Chen, Surf. Coat. Technol. (to be published).
[10]R. L. Boxman and S. Goldsmith, Surf. Coat. Technol. **52**, 39 (1995).
[11]M. Chowalla, M. Weiler, C. A. Davis, B. Kleinsorge, and G. A. J. Amaratunga, Appl. Phys. Lett. **67**, 894 (1995).
[12]A. Anders, S. Anders, and I. G. Brown, J. Appl. Phys. **75**, 4900 (1994).
[13]V. N. Zhitomirsky, L. Kaplan, R. L. Boxman, and S. Goldsmith, Surf. Coat. Technol. **76**, 190 (1995).
[14]M. M. M. Bilek, D. R. McKenzie, Y. Yin, M. Chhowalla, and W. I. Milne, IEEE Trans. Plasma Sci. **24**, 1291 (1996).
[15]T. Zhang, B. Y. Tang, Q. C. Chen, Z. M. Zeng, P. K. Chu, M. M. M. Bilek, and I. G. Brown, Rev. Sci. Instrum. (to be published).
[16]M. M. M. Bilek, Y. Yin, D. R. McKenzie, and W. I. Milne, Proceedings of the 17th International Symposium on Discharges and Electrical Insulation in Vacuum, Berkeley, 1996, p. 962.
[17]F. F. Chen, *Introduction to Plasma Physics* (Plenum, New York, 1974).