Enhancement and Stabilization of Cathodic Arc Using Mesh Anode

Tao Zhang, Baoyin Tang, Zhaoming Zeng, Qingchuan Chen, Paul K. Chu, *Member, IEEE,* and Ian G. Brown, *Fellow, IEEE*

***Abstract*—The performance and characteristics of a cathodic arc deposition apparatus consisting of a titanium cathode, an anode with and without a tungsten mesh, and a coil producing a focusing magnetic field between the anode and cathode are investigated. The arc voltage V_a is measured with a fixed arc current for an anode diameter of 40 mm. The relationship between V_a and the magnetic field B with and without a mesh is obtained. In addition, the relationship between the arc current I_a and V_c, the voltage to which the artificial transmission line was charged, is measured with and without the mesh to determine the minimum ignition voltage for the arc when the anode hole diameter is 40 mm. The arc resistance increases with the focusing magnetic strength B and decreases when using the mesh. Our results indicate that the high transparency and large area of the mesh allows a high plasma flux to penetrate the anode from the cathodic arc. The mesh also stabilizes the cathodic arc and gives better performance when used in concert with a focusing magnetic field.**

***Index Terms*—Anode, cathodic arc, plasma.**

I. Introduction

CATHODIC arc plasma sources have been shown to give excellent results in surface modification of materials and industrial components [1]–[4]. However, for both coating deposition and metal plasma immersion ion implantation (PIII), cathodic arc sources are prone to release "macro-particles" (particulates of the cathode material of size on the order of a micrometer) that are detrimental to the treated materials. Hence, a filtering system is sometimes employed to eliminate these macro-particles from reaching the treated materials. Currently, the most common configuration providing an acceptable plasma transportation efficiency is the curved magnetic filter duct developed by Aksenov *et al.* [5], [6].

In order to increase the output plasma flux, a magnetic field is imposed between the cathode and anode in a cathodic arc to better focus the plasma in the axial direction. For a long-pulse or DC current arc source, the focusing magnetic field tends to make the arc unstable. Two interrelated factors are believed to be the cause: 1) the movement of the cathode spots to the side of the cathode and 2) an increase in the plasma resistance due to the flow of electrical current across the magnetic field lines [7], [8]. An arc-stabilizing magnetic field can prevent the cathode spot from wandering off the working surface of the cathode. In the pulsed mode, confinement of the arc spot to the working surface of the cathode is less of a problem, as the duration of the cathodic arc is short enough that there is insufficient time for the cathodic arc spot to move away from the front surface of the cathode. Hence, an arc-stabilizing magnetic field is less important in this case, but a focusing magnetic field can still be beneficial. However, owing to the second factor aforementioned, the magnetic field exacerbates the arc instability and decreases the arc current, especially when a hollow or annular anode is used (a hollow anode can increase the plasma flux). In this unstable condition, a higher arc voltage is needed to keep the arc on. The higher arc voltage is caused by the larger plasma voltage drop due to an increase in the electrical resistance of the plasma for conduction across the magnetic field lines. In this paper, we describe the use of a mesh anode to stabilize and increase the efficiency of the cathodic arc. The characteristics of the mesh anode are also discussed.

Manuscript received November 5, 1998; revised March 30, 1999. This work was supported by the Hong Kong Research Grants Council Earmarked Grants 9040332 and 9040344 and the City University of Hong Kong Strategic Research Grant 7000964.

T. Zhang, B. Tang, Z. Zeng, Q. Chen, and P. K. Chu are with the Department of Physics and Materials Science, City University of Hong Kong, Kowloon, Hong Kong (e-mail: paul.chu@cityu.edu.hk).

I. G. Brown is with Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720 USA.

Publisher Item Identifier S 0093-3813(99)05499-5.

II. Experimental Method and Apparatus

The arc source was composed of a negatively biased titanium electrode 1 cm in diameter and a zero-potential anode with a hole in the center. The anode was 16 mm from the cathode and consisted of a hole in the center 15 or 40 mm in diameter. A tungsten mesh (4 mm mesh size and 0.2 mm diameter tungsten wire) was mounted on the anode hole and the distance from the mesh to the cathode was 15.8 mm. The optical transparency of the mesh was about 90%.

The cathodic arc source was operated in a pulsed mode with a triggering frequency of 60 Hz. The duration of the arc current pulse was 0.24 ms and the trigger voltage was 3 kV. The focusing magnetic field B was produced by an external coil positioned just in front of the anode. The magnetic field strength was measured at the axis of the system and very close to the cathode surface. The vacuum chamber pressure was typically about 5×10^{-3} Pa.

The cathode arc was powered by a charged artificial transmission line [Fig. 2(c)] with $C = 20$ μF and $L = 0.2$ mH. The arc current was characterized by the peak current I_a, measured 30 μs after the beginning of the arc pulse (Fig. 1). The arc

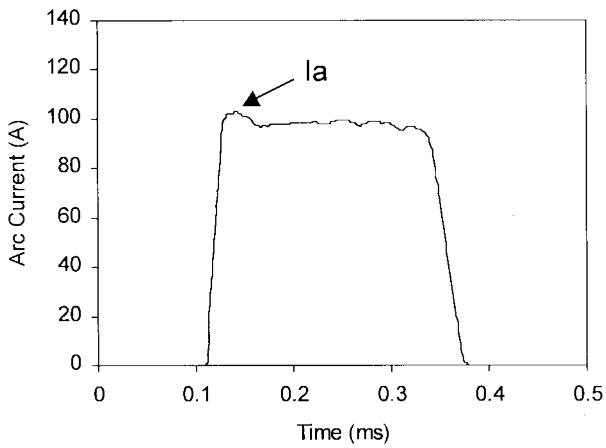


Fig. 1. Waveform of the arc current.

voltage V_a was measured at an arc current I_a of 100 A and with an anode hole 40 mm. The relationship between V_a and the focusing magnetic field B with and without the tungsten mesh was determined. The relationship between the arc current I_a and V_c, the voltage to which the artificial transmission line was charged, was measured with and without the mesh to obtain the minimum ignition voltage for the arc when the anode hole diameter was 40 mm. During ignition, the voltage of the cathode changed rapidly from V_c to V_a. Both I_a and V_c were the initial values of the current and voltage of the cathode arc.

In our experiments, a 100-mm silicon wafer was put in the vacuum chamber at a distance of 100 mm from the anode facing the exit of the arc source. A smaller distance between the silicon and arc source increased the deposition–implantation efficiency but made high voltage implantation more difficult due to arcing between the wafer and arc source. The distance of 100 mm was selected for convenience. The silicon wafer was partially covered in several places so that the thickness of the deposited film could be measured on the steps formed using a stylus profilometer. The film thickness was measured at four positions on the Si wafer (center, 17 mm from center, 33 mm from center, and close to the edge) as shown in Fig. 2(b); the deposition rate was calculated on the basis of the mean value of these four measurements. The experiment was repeated for different anode configurations while using the same arc current and trigger frequency settings to assess the deposition efficacy. A simplified schematic of the experimental configuration is exhibited in Fig. 2(a).

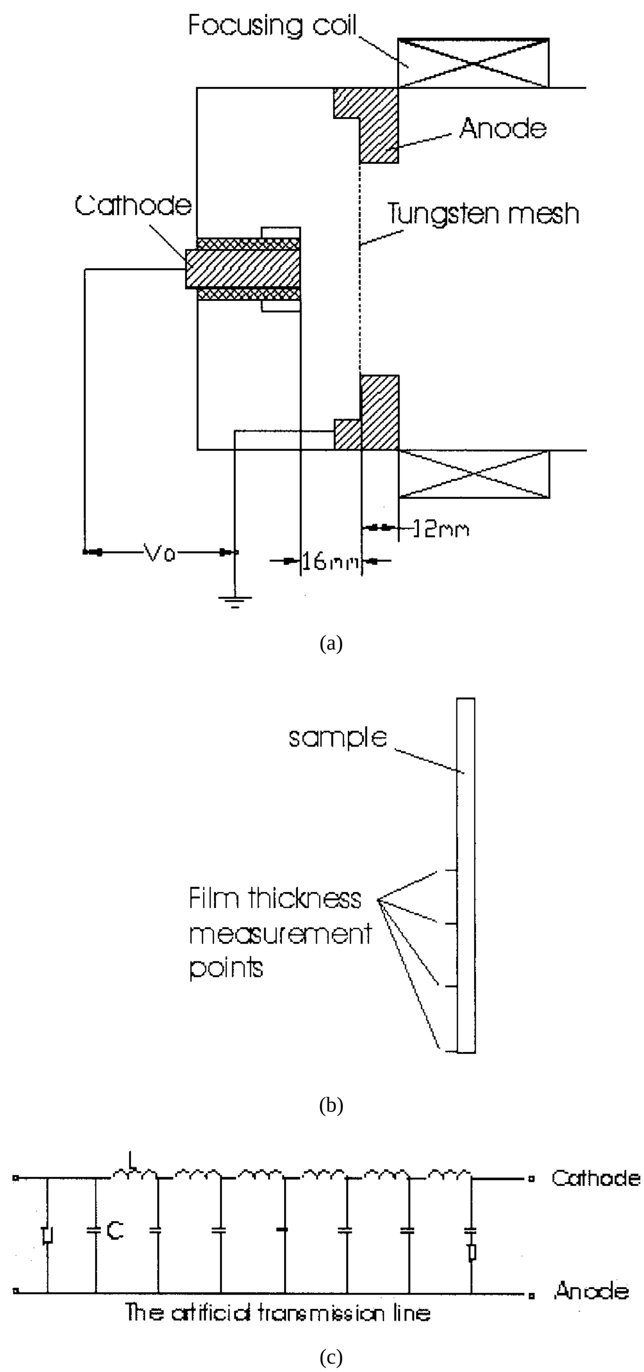


Fig. 2. (a) Schematic of the experimental apparatus with the anode center hole diameter being 40 mm, (b) thickness of the deposited film on the 100-mm silicon measured at four different places: center, 17 mm from center, 33 mm from center, and close to the edge, and (c) artificial transmission line.

III. Results

Using a 40-mm anode, the mean deposition rate was 18 Å/s and almost the same with and without the tungsten mesh when the focusing magnetic field was off. Hence, the mesh had very little effect on the plasma flux. For a 15-mm anode, the mean deposition rate was 4 Å/s when the focusing magnetic field was off. This implies that the bigger the anode aperture, the higher is the plasma flux through the anode.

The arc voltage V_a value with or without the mesh was 22 V when $B = 0$ (Fig. 3). V_a increased with B both with and without the mesh. With the mesh, V_a increased with B slowly and reached a steady value when B exceeded 400 G. On the other hand, for the case without the mesh, V_a increased quickly as the focusing magnetic field B went up. The mesh acted to slow down the increase in V_a with higher B. The arc current I_a increased with V_c but decreased with the focusing magnetic field B both with and without the mesh for the 40-mm anode (Fig. 4). The curves for $B = 160$ G and $B = 320$ G showed a similar trend and were thus not plotted in Fig. 4. The I_a value with the mesh was higher than

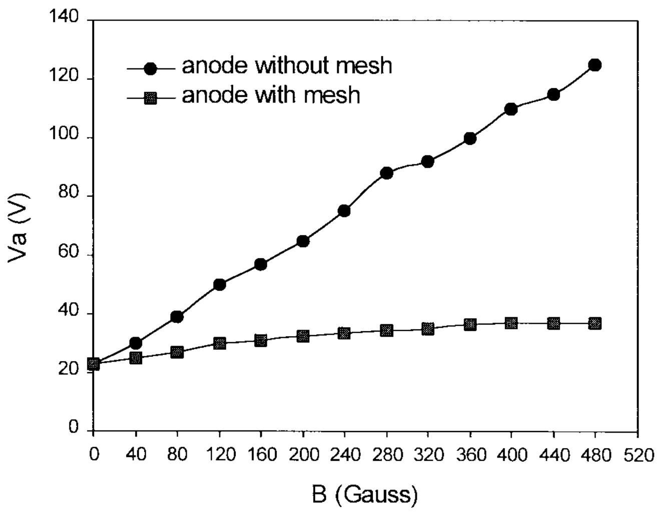


Fig. 3. Arc voltage V_a versus the focusing magnetic field B with the mesh and without the mesh at an arc current I_a of 100 A and with an anode hole diameter of 40 mm.

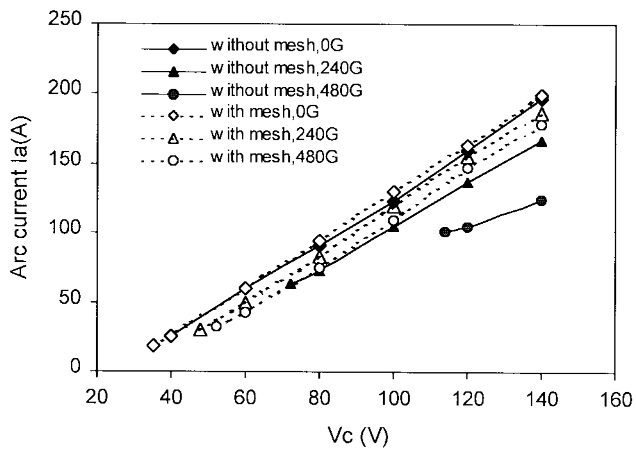


Fig. 4. V_c, the voltage to which the artificial transmission line was charged, versus arc current I_a at different focusing magnetic field settings for an anode hole diameter of 40 mm.

that without the mesh at the same V_c and focusing magnetic field B.

The relationship between B and the minimum ignition voltage of the arc is exhibited in Fig. 5. When the focusing magnetic field B was off, the minimum ignition voltage with the mesh was the same as that without the mesh. When the focusing magnetic field B was increased, the minimum ignition voltage without the mesh increased much faster than that with the mesh. Hence, our results indicate that the mesh makes arc ignition easier at high B.

IV. Discussion

Without the focusing magnetic field, the plasma extends in all directions from the cathode [Fig. 6(a)]. The plasma can touch the rim of the anode as easily as the mesh. Therefore, the mesh does not play a significant role in altering the minimum igniting arc voltage and V_a when $B = 0$. When the focusing magnetic field is on, the plasma from

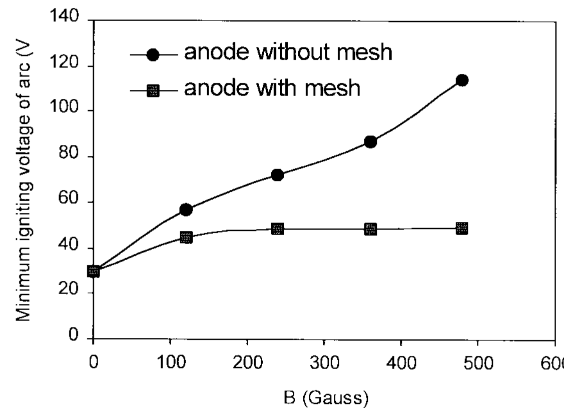


Fig. 5. Minimum arc-ignition voltage between the anode and the cathode versus the focusing magnetic field B with the mesh and without the mesh for an anode hole diameter of 40 mm.

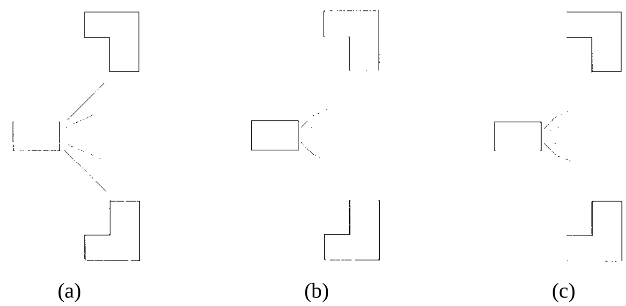


Fig. 6. Dispersion of the plasma flux in the anode-cathode gap: (a) without magnetic field but with mesh, (b) with magnetic field but without mesh, and (c) with magnetic field and with mesh.

the cathode arc is confined [Fig. 6(b)]. V_a without the mesh includes a component that overcomes the resistance of the plasma to penetrate across the magnetic field lines. Thus, the combination of an axial focusing magnetic field and a big anode hole increases the minimum ignition voltage, and when the arc current is constant, V_a increases. We have also observed that the cathodic arc without the mesh becomes very unstable when B is larger than 300 G. A focusing magnetic field and large anode aperture increase the plasma flux through the anode hole, but these two factors also affect the ignition of the cathodic arc adversely. The situation can be improved by adding a mesh on the anode. As shown in Fig. 6(c), the mesh is a part of the anode, and the confined plasma flux from the cathodic arc can easily reach the mesh. The mesh thus reduces substantially the deleterious effects on the ignition of the cathodic arc caused by the magnetic field and large anode hole size. It can also be observed that the cathodic arc discharge was quite steady for the entire range of B used in this experiment.

V_a consists of the voltage drop at the electrodes (mainly cathodic drop) and across the bulk of the interelectrode plasma. The focusing magnetic field B raises the part of V_a related to the plasma voltage drop due to an increase in the electrical resistance of the plasma for conduction across the magnetic field lines. The increase in the plasma resistivity with the introduction of a transverse magnetic field B can be described by [8]

$$\rho(B) - \rho(0) \approx k\rho(0)(\omega\tau)^2 \propto B^2 \tag{1}$$

where $\rho(B)$ is the electrical resistivity perpendicular to the magnetic field lines, $\rho(0) = \rho(B = 0)$, $\omega = eB/m$ is the electron cyclotron frequency, e and m are the electron charge and mass, respectively, τ is the mean free time between collision, and k is a constant that depends on the mean ion charge Z. V_a increases with the focusing magnetic field B as

$$\Delta V \approx cB^2 \tag{2}$$

where $\Delta V = V_a(B) - V_a(0)$ and c is a constant. In this work, the relationship between V_a and B without the mesh displayed in Fig. 3 deviates slightly from that predicted by (2). The focusing magnetic field here becomes concentrated between the cathode and the anode in the axial direction. In the interelectrode space, both the value and the direction of the focusing magnetic field vary from point to point. We have characterized the magnetic field with a one-point measurement near the cathode for simplicity. However, the magnetic field measured in this way is not exactly suitable for (2), even though the trend of B versus V_a is correctly disclosed.

The axial magnetic field increases the plasma resistance for conduction across the magnetic field lines, or equivalently, increases the distance between the cathode and anode [9], and so the voltage drop across the plasma is increased. When the mesh is added onto the anode hole, the anode-to-cathode distance for the axial plasma confinement is almost unchanged when the focusing magnetic field increases. Hence, with the mesh, V_a only changes slightly when the focusing magnetic field B is varied (Fig. 3).

Several kinds of metal mesh are used in our experiments. It is found that a brass mesh is ruined due to overheating when the time average arc current is over 2 A, and a stainless mesh suffers damage at a time average arc current over 5 A after a one-hour experiment. The damage manifests in the form of a hole 0.5–2 cm in diameter in the center of the mesh. On the other hand, when a tungsten mesh is used, no damage can be observed even for a time average arc current of 8 A after one hour of operation. We have also noticed that the center of the W mesh is clean but the area close to the rim is clogged up with the cathode materials. This decreases the optical transparency of the mesh. However, by selecting the mesh size in the center and the rim areas properly, the seriousness of the problem can be minimized.

V. Conclusions

A focusing magnetic field together with a large anode aperture is an effective way to increase the plasma flux of a cathodic arc source. Unfortunately, it makes the ignition of the cathodic arc more difficult, and the magnetic field can result in a lower arc current if the artificial transmission line power is unchanged. Moreover, the cathodic arc tends to be unstable in a strong magnetic field. Placing a metal mesh onto the anode hole stabilizes the cathodic arc and reduces the minimum igniting arc voltage, thereby enabling the use of a larger magnetic field and anode diameter. As an integral part of the anode component, the mesh has the same voltage as the anode, and the plasma from the cathodic arc can reach the mesh easily. The mesh minimizes the electrical resistance of the plasma. We also found that a tungsten mesh has the best durability, perhaps due to its high melting point.

References

[1] A. Anders, "Metal plasma immersion ion implantation and deposition: A review," *Surf. Coatings Technol.,* vol. 93, pp. 158–167, 1997.

[2] S. Anders, A. Anders, and I. G. Brown, "Macroparticle-free thin films produced by an efficient vacuum arc deposition technique," *J. Appl. Phys.,* vol. 74, pp. 4239–4241, 1993.

[3] J. Koskinen, A. Anttila, and H. P. Hirvonen, "Diamond-like carbon coating by arc-discharge methods," *Surf. Coatings Technol.,* vol. 47, pp. 180–187, 1991.

[4] I. I. Aksenov and V. E. Strelnitskij, "Properties of diamond-like coating prepared by vacuum arc deposition," *Surf. Coatings Technol.,* vol. 47, pp. 98–105, 1991.

[5] I. I. Aksenov, S. I. Vakula, V. G. Padalka, V. E. Strel'nitskii, and V. M. Khoroshikh, "High efficiency source of pure carbon plasma," *Sov. Phys. Tech. Phys.,* vol. 25, pp. 1164–1166, 1980.

[6] I. I. Aksenov, V. A. Belous, V. G. Padalka, and V. M. Khoroshikh, "Transport of plasma streams in a curvilinear plasma-optics system," *Sov. J. Plasma Phys.,* vol. 4, no. 4, pp. 425–428, 1978.

[7] V. N. Zhitomirsky, R. L. Boxman, and S. Goldsmith, "Influence of an external magnetic field on cathode spot motion and coating deposition using filtered vacuum arc evaporation," *Surf. Coatings Technol.,* vol. 68/69, pp. 146–151, 1994.

[8] ——, "Unstable arc operation and cathode spot motion in a magnetically filtered vacuum-arc deposition system," *J. Vac. Sci. Technol. A,* vol. 13, no. 4, pp. 2233–2240, 1995.

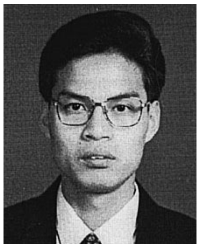
[9] V. N. Zhitomirsky, B. Alterkop, U. Kinrot, R. L. Boxman, and S. Goldsmith, "Role of the magnetic field in the acthode region during vacuum arc operation," in *XVII Int. Symp. Discharges and Electrical Insulation in Vacuum,* Berkeley, 1996, pp. 876–880.

Tao Zhang received the B.Sc., M.Sc., and Ph.D. degrees in materials science from the Dalian University of Technology, China, in 1985, 1988, and 1995, respectively.

In 1997, he did postdoctoral research work in plasma physics at the Institute of Low Energy Nuclear Physics, Beijing Normal University, China. He currently is a Research Assistant in the Plasma Laboratory of the City University of Hong Kong. His research focuses on metal plasma immersion ion implantation and its application to advanced material.

Baoyin Tang graduated from the Department of Engineering Physics, Harbin Institute of Technology, in 1960.

He is a Professor and Director of the Surface Modification of Materials Group in the Advanced Welding and Production Technology National Key Lab of the Harbin Institute of Technology. He was engaged in teaching works on electrical physics and research works on accelerators, ion sources, and ion implantation before 1990. He worked with Prof. J. R. Conrad in the Plasma Source Ion Implantation Group, University of Wisconsin-Madison, to study plasma-based ion implantation and surface modification of advanced materials from April 1990 to December 1992. He has been working with Prof. P. K. Chu in the Department of Physics and Materials Science, City University of Hong Kong, since 1995. His research work includes development of multipurpose PIII equipment, improvement of PIII techniques, and industrial applications. In recent years, he has published more than 40 scientific and technical papers in international academic conferences and journals.



Zhaoming Zeng received the B.S. and M.S. degrees in materials science and engineering from Harbin Institute of Technology, China, in 1990 and 1993, respectively. He is currently pursuing the Ph.D. degree at the Harbin Institute of Technology.

Since 1998, he has been a Research Staff Member of the Plasma Laboratory in the City University of Hong Kong. His research interests include metal and material surface modification, plasma processes, and plasma immersion ion implantation equipment.

Qingchuan Chen, for a photograph and biography, see p. 238 of the February 1999 issue of this TRANSACTIONS.

Paul K. Chu (M'97), for a photograph and biography, see p. 238 of the February 1999 issue of this TRANSACTIONS.

Ian G. Brown (SM'83–F'96), for a photograph and biography, see p. 198 of the February 1999 issue of this TRANSACTIONS.