Surface & Coatings Technology 206 (2012) 5042–5045

Contents lists available at SciVerse ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Plasma immersion ion implantation into cylindrical bore using internal inductively-coupled radio-frequency discharge

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ARTICLE INFO

Article history:
Received 1 March 2010
Accepted in revised form 23 August 2010
Available online 2 June 2012

Keywords:
Plasma immersion ion implantation
Cylindrical bore
Inductively-coupled radio-frequency discharge
Plasma uniformity

ABSTRACT

Plasma immersion ion implantation (PIII) is a potentially excellent interior surface treatment technique due to no line-of-sight restriction. However, some problems have been encountered due to the low ion energy and ion fluence non-uniformity especially for treatment of the interior wall of a thin tube. In this paper, a new method for inner surface PIII using internal inductively-coupled radio-frequency (RF) discharge is described. A cylindrical inductive coil inserted inside the tube serves as both the plasma source and grounded electrode to avoid overlapping of the plasma sheath fronts propagating from opposite sides. The effects of the gas species, gas pressure, RF power, and number of coil turns are investigated. Our results demonstrate the feasibility of this novel inner surface treatment method and the number of turns in the coil has a critical influence on the discharge behavior. If the number of turns is little, the plasma density is low and non-uniform inside the tube due to the relatively intense capacitively-coupled RF discharge at the two ends. In contrast, the plasma density and uniformity are evidently improved by using more turns in the coil.

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1. Introduction

Plasma immersion ion implantation (PIII) is superior to conventional beam-line ion implantation when dealing with specimens with an irregular shape [1]. The potential of implanting the interior surfaces of industrial components by PIII has aroused the interests of plasma scientists and engineers due to the difficulties by beam-line ion implantation. However, there are still problems associated with the generation and axial uniformity of the inner plasma together with overlapping of plasma sheath fronts [2], although there has been theoretical and experimental proof about the feasibility of implanting the inner surface of a hollow cylindrical bore [3–5]. Sun and Zeng independently utilized a coaxial grounded electrode positioned along the axis of the bore in order to improve the ion impact energy [6,7]. Malik et al. employed a grounded coaxial electrode to deposit TiN_x and diamond-like carbon thin films onto the interior surface of a hollow cylindrical sample [8]. Liu et al. investigated the ion fluence and energy uniformity on inner surfaces with and without a grounded electrode [9]. Their results show that the coaxial grounded electrode can indeed improve the ion impact energy, but the laterally non-uniformity of incident dose is still a practical problem. This non-uniformity arises because the plasma is generated in the vacuum chamber and diffuses into the interior of the tube. Liu et al. proposed an improved method by introducing an internal plasma source consisting of a capacitively-coupled radio-frequency (RF) antenna and coaxial grid electrode [10]. The hardware was demonstrated to work well yielding a more uniform plasma density. It should be noted that this technique is only suitable for large diameter tubes since diode discharge in the capacitively-coupled RF system requires large space. In order to implant tubes with small diameters, we propose a new PIII technique based on internal inductively-coupled RF discharge. In this paper, the feasibility of the novel technique and influence of important instrumental parameters on the RF discharge are described.

2. Experimental details

The principle of the experimental setup is shown schematically in Fig. 1. The RF coil and tube to be treated are coaxially arranged in the vacuum chamber. The plasma is produced by applying RF power to the cylindrical coil. One end of the cylindrical coil is connected to the chamber wall and the tube is negatively biased by an external high-voltage modulator. Hence, an accelerating field for positive ions can be established between the grounded cylindrical coil and inner surface of the tube. The biggest advantage of this hardware is to mitigate the impactness of the radial dimension on the RF discharge. The inductively-coupled RF discharge is produced axially so that ignition of the glow discharge in a small-diameter tube is possible.

The uniformity of the plasma density was investigated in this work using the measurement system shown schematically in Fig. 2. The inductive coil was made of aluminum 20 mm in diameter and

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doi:10.1016/j.surfcoat.2012.05.118

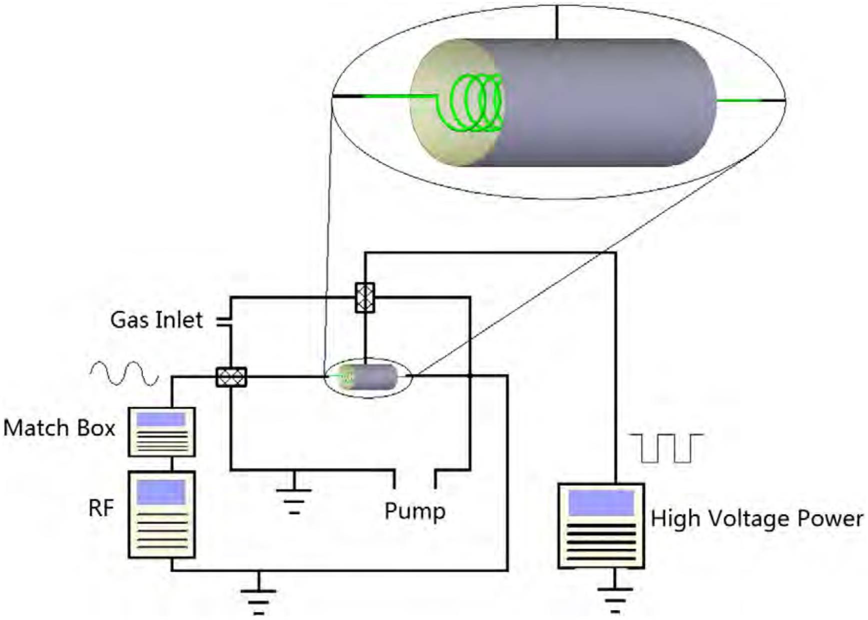

Fig. 1. Schematic of the plasma immersion ion implantation setup for tubes employing internal inductively-coupled RF discharge.

260 mm long, and the tube 48 mm in diameter and 200 mm long was cut into five parts (marked as A, B, C, D, and E respectively in Fig. 2) insulated from each other using Teflon pads. Each part was connected to a negative DC bias source via independent resistors. The inductive coil was placed coaxially inside the tube and cylindrical coils with 25 turns and 35 turns were used. One end of the cylindrical coil was grounded and the other end was connected to the output of a 13.56 MHz RF power supply, as shown in Fig. 1. A multi-meter was employed to monitor the voltages on each resistor of 100 Ω to evaluate the axial distribution of the plasma density. The ion current was obtained by dividing the voltage by the resistance of resistor. Then the ion current density was calculated by dividing the detected current by the surface area of the cylindrical parts. During the discharge experiments, argon, nitrogen or oxygen was used as the work gas.

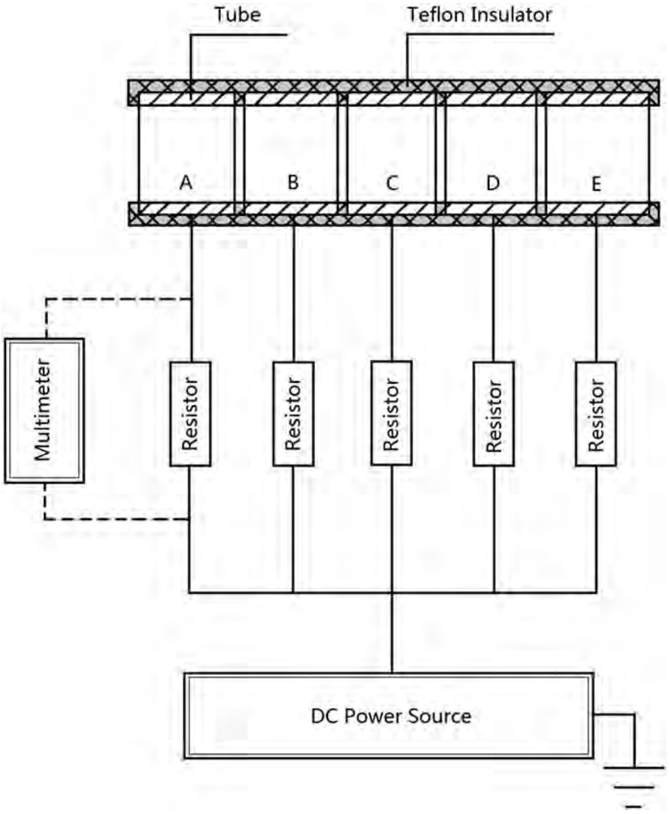

Fig. 2. Schematic diagram of the measurement system to evaluate the uniformity of the plasma density.

3. Results and discussion

Fig. 3 shows the glow discharge generated by the inductive coil inside the stainless steel tube. The plasma can be produced with pure argon or nitrogen at a pressure of 0.7 Pa. A −20 kV high voltage with a pulse width of 20 μs is applied to the tube to evaluate the feasibility of this novel technique to implant ions into the internal wall. The interior of the tube is filled with the plasma even during the pulse-on period. This means that the glow discharge can be effectively sustained due to the shielding effect of the grounded coil structure and a high plasma density can be produced by the inductively-coupled RF discharge.

Fig. 4 displays the distribution of the work density produced with different plasma gases. The plasma is generated by a 25-turn cylindrical coil at a pressure of 1 Pa and RF power of 250 W. The plasma density is not uniform along the tube axis and the minimum plasma density is observed in the middle. It may be attributed to the inherent characteristics of the inductively-coupled discharge [11]. It has been

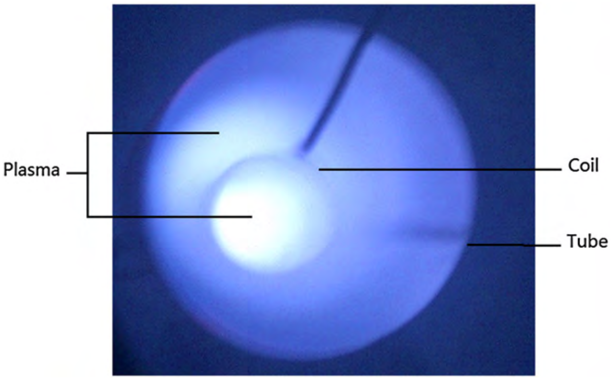

Fig. 3. Glow discharge generated in the tube.

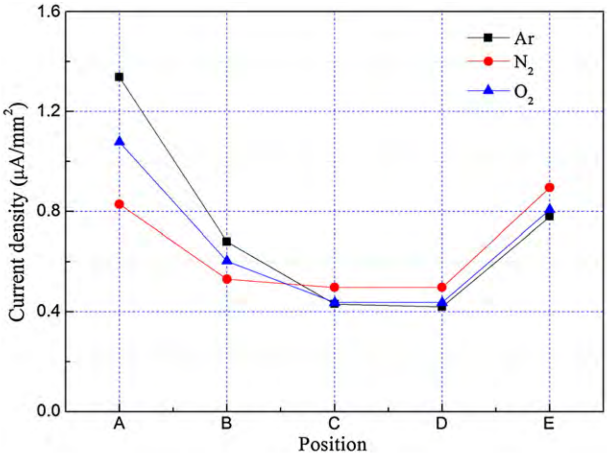

Fig. 4. Effect of the gas species on the current density with RF power of 250 W, gas pressure of 1 Pa, and a coil of 25 turns.

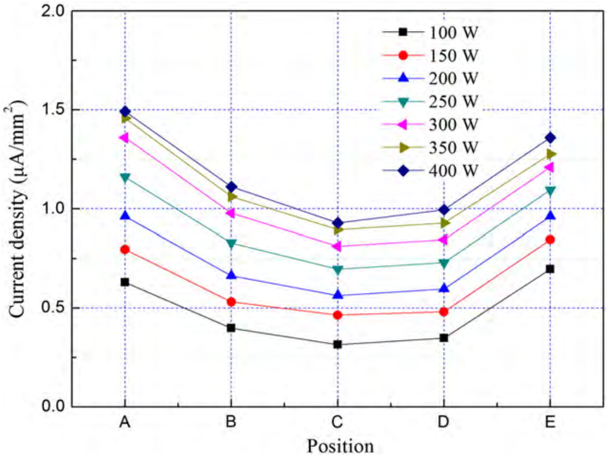

Fig. 6. Effect of the RF power on the current density with N_2 gas pressure of 1 Pa and a coil of 25 turns.

reported that a capacitive-coupled discharge has to be established before the inductively-coupled discharge works [12,13]. The capacitively-coupled discharge still exists and continues to exert influence on plasma density even during the inductively-coupled discharge since a voltage is applied to the coil to drive the RF current through it [14]. This capacitive discharge is ignited more easily especially at the ends of the cylindrical coil due to the large space between the tube end and chamber wall. The additional discharge occurs outside the tube and the generated plasmas can diffuse into the interior of the tube leading to the axial non-uniformity in the plasma density.

Fig. 5 shows the influence of the gas pressure on the plasma density distribution. The plasma is generated by a 25-turn cylindrical coil at RF power of 250 W at different nitrogen gas pressure. The gas pressure has a critical influence on the plasma density and discharge behavior. When the pressure is higher than 2.0 Pa, the parasitic capacitance discharge at the ends of the coil is more evident leading to a very non-uniform plasma density. It may be related to the decrease in the electron mean free path resulting from the additional capacitive discharge at the ends at high gas pressure. This increases the probability of collisions between electrons and neutrals subsequently promoting ionization. More plasma diffuses into the tube from the two ends and a larger ion flux can be clearly observed.

Fig. 6 depicts the influence of RF power on the axial current density distribution inside the tube. The nitrogen plasma is produced by a 25-turn cylindrical coil at pressure of 1 Pa. The reflected RF power which is relatively low due to effective matching can be neglected. As shown in Fig. 6, the current density profile hardly depends on the RF power for a given coil. An increase of the current density can be observed at different measurement sites for a higher RF power. This may be attributed to the high ionization rate of nitrogen as a result of the higher coupled RF power.

According to the experimental results, the axial plasma uniformity is hardly affected by the gas pressure and RF power at low pressure suitable for PIII. It may be mainly attributed to the parasitic capacitance discharge in addition to inductive discharge at two ends. To obtain good axial plasma uniformity, a different coil is needed. Fig. 7 shows that the number of turns in the coil has significant influence on the discharge performance. Compared to the glow discharge produced by a 25-turn coil, a 35-turn coil gives rise to a higher plasma density and more importantly, better plasma uniformity. The increased plasma density may be attributed to the high ionization rate of N_2 gas at high RF power coupled to the plasma. According to equation $P_{abs} \approx \frac{\pi N^2 R |\tilde{I}_{rf}|^2}{\sigma_{eff} l \delta_p}$ [15],the RF power coupled to the plasma P_{abs} increases with larger N, where N is the number of turns in the coil, $\tilde{I}_{rf}$ is the RF source current, R is the radius of the coil, l is the length of the coil, σ_{eff} is the effective conductivity of the plasma, and δ_p is the skin thickness. Hence, the plasma density generated by a 35-turn coil is higher than that by a 25-turn coil because more power is absorbed by the plasma.

Fig. 8 exhibits the axial distribution of the plasma density for various RF power using a 35-turn coil and N_2 gas pressure of 1 Pa. At the

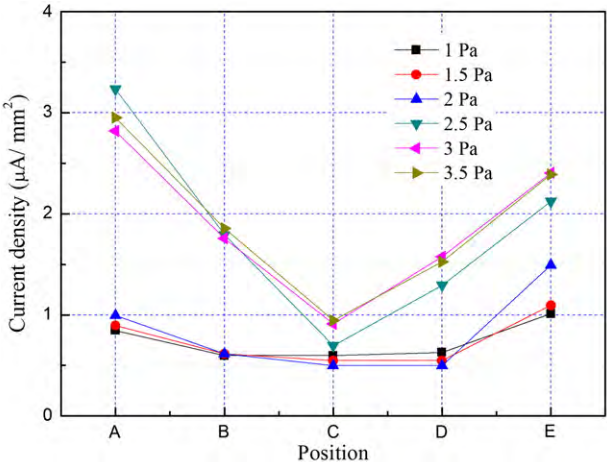

Fig. 5. Influence of the N_2 gas pressure on the current density with RF power of 250 W and a coil of 25 turns.

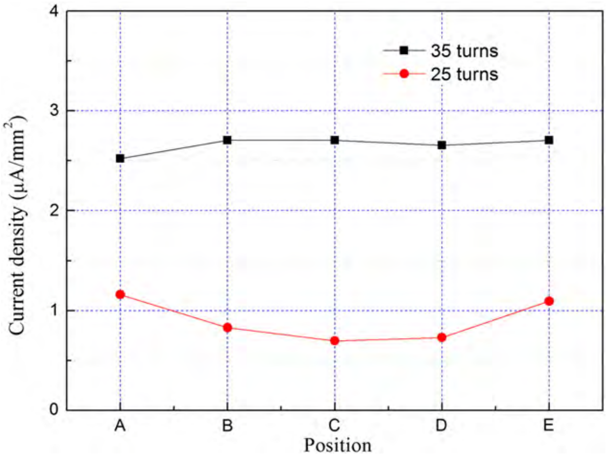

Fig. 7. Influence of the number of turns in the coil on the plasma density with RF power of 250 W and N2 gas pressure of 1 Pa.

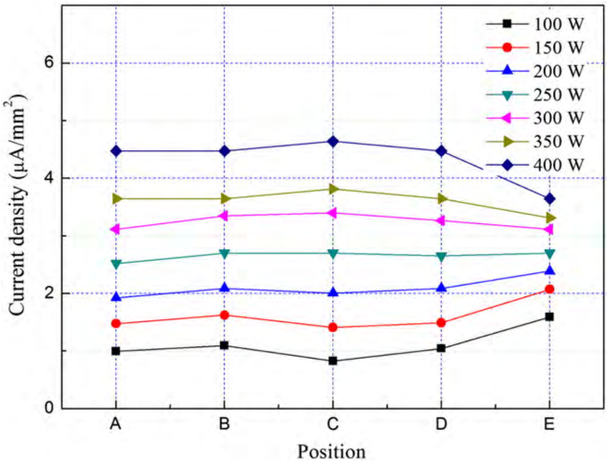

Fig. 8. Dependence of the current density on RF power using N_2 gas pressure of 1 Pa and a coil with 35 turns.

lowest RF power, the effect of capacitive discharge is still relatively large leading to a non-uniform plasma density. As the RF power is increased, the inductive discharge effect inside the tube becomes more substantial consequently increasing effectively the density and uniformity of the internal plasma. If the RF power is increased further, the glow discharge in the middle section is more intense leading again to a non-uniformity plasma density. Therefore, there is an optimal setting that gives the best results.

4. Conclusion

A novel method employing inductively-coupled discharge in plasma immersion ion implantation of a small tube is described. The RF discharge is established even during the high-voltage pulse-on period inside the tube by introducing a coaxial cylindrical inductive coil. Our experimental results demonstrate the efficacy of this technique for internal surface PIII into tubes even with a small diameter of 3 cm. The number of turns in the coil affects the RF discharge significantly. For a coil with fewer turns, the plasma density is not uniform due to the relatively substantial capacitive discharge at the two ends. A coil with more turns may increase the coupling effect leading to a more intense inductively-coupled plasma leading to a more uniform plasma density suitable for PIII into the inner surface of a cylindrical bore.

Acknowledgments

This work was financially supported by the Natural Science Foundation of China (no. 10775036, no. 50773015), Program for New Century Excellent Talents in University in China, and Hong Kong Research Grants Council (RGC) Special Equipment grant no. SEG CityU05.

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