Plasma distribution in the slender bore excited by coaxial rf electrode

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Abstract

A metal coaxial radio-frequency (rf) electrode has been utilized to produce plasma and deposit the coating onto the inner wall of the tubes. The inner electrode acts both as a plasma source and as a sputtering target to achieve plasma-based IBAD. The non-uniformity of thickness of deposited films and plasma density in the bore has been investigated for tubes with different lengths and inner diameters. The experimental results demonstrate that plasma density is higher at two ends of the tube and lower in the middle section of the tube. The uniformity of plasma density may increase with the inner diameter of tubes increasing, but will decrease with the length of tubes increasing. Copper films have been deposited using this technique and the variation of film thickness agrees with the distribution of plasma density along the bore axis. It is also observed that the uniformity of plasma density is higher than that of film thickness due to diffusion behavior of plasmas.

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1. Introduction

To protect the surfaces of components from wear and corrosion, many plasma surface modification techniques have been developed. The external surface is easier to be treated, however it is difficult to treat the internal surface, particularly for tubes and for deep hole with high length to diameter (l/d) ratio. To deposit the inner wall of tubes is, in fact, to solve the problem of generating and sustaining stable uniform plasma inside the tube.

Tubes are widely utilized in many fields, e.g., aerospace [1,2], biomaterials [3,4], etc. Some techniques have been attempted to treat the inner surface of tubes. Bardos et al. deposited TiN of about 1 μm thick inside the tube of 8 mm in diameter utilizing the advantage of hollow cathode discharge [5]. Ensinger et al. used a method of ion beam sputtering to treat the tube with φ100 × 1000 [6]. A cone-shaped sputtering target was inserted into a tube. By applying a high-energy ion beam to bombard the target, carbon films with the thickness of tens of nanometers were deposited. Moreover, a copper film was also deposited into the tube with φ16 × 170 using this approach [7]. Liu et al. presented a grid enhanced plasma source ion implantation system, with which TiN film could be obtained on the inner wall of tube with φ100 × 210 [8]. Furthermore Lee et al. reported a triode sputtering system and their results showed that the thickness of deposited tantalum film reached about 50 μm in the steel tube with φ20 × 92.4 [9].
In this work, we utilized a radio-frequency (rf) discharge sputtering approach. A metal coaxial rf electrode was introduced into the tube, through which plasma was generated and sputtering deposition was also induced due to self-bias effect of rf discharge. The influence of length and inner diameter of tubes on coating thickness and distribution of plasma density has been investigated in detail.

2. Experimental

A schematic diagram of the experimental apparatus is shown in Fig. 1. The samples are stainless steel tubes with different inner diameters and lengths. Sputtering target is a copper rod with the diameter of 1.78 mm and length of 240 mm. The base pressure in the chamber was about $9.0 \times 10^{-3}$ Pa. The tube and copper electrode were ultrasonically cleaned in acetone before being loaded into the chamber. The copper electrode was connected to rf power and the tube was connected to the pulsed negative bias. In order to monitor the distribution of plasma density in the tube, a circuit system was set up as shown in Fig. 2. Five probes were inserted in the tube, which were insulated by ceramic tube. The probes were electrically biased at the pulse voltage of $+50$ V. The waveforms of voltage across the resistors were recorded by a digital oscilloscope (Tektronix TDS340A) to provide the information of the distribution of plasma density. During measurement, the gas pressure was 36 Pa and rf power was 600 W. Before copper films were fabricated, the copper electrode and tube were sputtered and cleaned using argon plasma with rf power of 200 W. Afterwards the copper films were deposited under argon pressure of 36 Pa, rf power of 600 W and treatment time of 60 min. The pulse bias to the tube was $-100$ V with pulse duration of 20 μs and repetition rate of 14 kHz.

Different tubes were utilized in the experiments. The inner diameters of the tubes ranged from 12 mm to 17 mm and their lengths ranged from 60 mm to 200 mm. After deposition, treated tubes were uniformly divided into several parts. After mounting and grounding, the cross-sections of the samples were observed by optical microscope to evaluate the thickness of the films.

3. Results and discussion

Typical waveforms of voltage across the resistors are shown in Fig. 3. It shows that the plasma density along the tube axis is higher at two ends of the tube and lower in the middle section of the tube. It may result in the non-uniformity of thickness of fabricated films. The influence of tube length and inner diameter of tube on distribution of plasma density is shown in Fig. 4a and b. A large diameter leads to a larger plasma density and a better uniformity along the axis. There exists an optimal tube length to achieve higher plasma density. It may be attributed to different coupling of rf power. The bright copper films with the thickness of several micrometers have been obtained after sputtering–deposition. Fig. 5 is a cross-sectional optical photograph of copper film on the tube 15 mm in diameter and 200 mm in length. Fig. 6 demonstrates the thickness of deposited copper films. The variation of film thickness along the axis is evident and the films are much thicker at two ends than at the middle section. The thickness of the films deposited at the middle section is slightly dependent on the tube diameter and length. Generally the distribution of film thickness is consistent with that of plasma density.
The discharge inside the tube obeys the Paschen formula \[ U = \frac{Bpd}{\ln(pd) + \ln A - \ln(A + \frac{1}{\gamma})} \] derived from the Townsend breakdown theory:

where \( p \) is the pressure, \( d \) is the electrode gap width, \( \gamma \) is the coefficient of secondary electron emission, \( A \) and \( B \) are the constants determined by gas and electron temperature. The values of \( B \) in the rf field are lower than that in DC glow discharge [10], therefore the rf discharge is easier to ignite compared to DC case in the tube. As a result the discharge may be generated and maintained by applying only moderate voltages under low pressure conditions. A stable glow discharge inside the tube was observed when 300 W rf power was applied. With an rf power of 600 W, more intense glow discharge with green color was observed.

It is clearly observed that glow discharge appears firstly near two ends of the tube when the rf power is applied, and then diffuses into the tube when the rf power increased. The Paschen’s law may be responsible for the non-uniformity of rf discharge. The discharge is easier to ignite near the ends of the tube due to the larger space and resultant large \( pd \). In contrast, the value of \( pd \) is much smaller in the middle part of the tube due to the effect of small inner diameter. Consequently the discharge in the middle of tube is quite difficult to initiate. The plasma can be generated only as the applied rf power or working pressure increases to a given high level. So it is not strange that

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**Fig. 4.** Influence of inner diameter and length of tube on non-uniformity of plasma density: (a) different inner diameter with length of 200 mm, (b) different tube length with inner diameter of 15 mm.

**Fig. 5.** Cross-section optical image of copper film.

**Fig. 6.** Influence of inner diameter and length of tube on non-uniformity of film thickness: (a) different inner diameter with length of 200 mm, (b) different tube length with inner diameter of 15 mm.
the plasma density is higher near the ends of the tube and lower in the middle part. As a result the sputtering rate is different in the tube and the variation of film thickness is observed. The plasma density is higher with the increasing inner diameter of treated tubes due to easier discharge according to Paschen’s law as shown in Fig. 4a. The influence of tube length on the discharge is complicated as shown in Fig. 4b. For a given inner diameter, a proper tube length gives rise to a higher plasma density in the middle part of the tube. For a short tube it is difficult to couple well the rf power into the tube and consequently the plasma density is lower. The reflection power of rf system is larger and more discharge is observed outside the tube. In contrast, the discharge becomes weak for a long tube and meanwhile the middle section receives less plasma generated at two ends of the tube, consequently the plasma density is also lower. Only for tubes with a certain length that the plasma density at the middle section is higher due to more intense discharge and more diffusion of plasma produced at two openings of the tube. The variation of thickness of deposited copper films is consistent with the distribution of plasma density in the tube. Interestingly the variation of plasma density is smaller than that of the thickness of deposited films. It may be due to the easier movement of plasma than sputtered particles.

4. Conclusion

The coaxial rf discharge behavior has been investigated for a thin tube. The copper films of several micrometers thick have been deposited onto the inner wall of a stainless steel tube. The discharge is not uniform in the tube. More intensive discharge may be observed at two ends of the tube while the discharge is weak in the middle section of the tube. The discharge behavior and deposition rate is much dependent on the inner diameter and length of treated tubes. It is easier to ignite for a larger inner diameter and a higher deposition rate is also achieved. There exists a proper tube length to produce a higher plasma density due to different rf coupling effect and plasma diffusion.

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