Investigation of plasma potential and pulsed discharge characteristics in enhanced glow discharge plasma immersion ion implantation and deposition

Liuhe Li\textsuperscript{a,b,*}, Qiuyuan Lu\textsuperscript{a,b}, Ricky K.Y. Fu\textsuperscript{b}, Paul K. Chu\textsuperscript{b,*}

\textsuperscript{a}Department 702, School of Mechanical and Automation Engineering, Beijing University of Aeronautics and Astronautics, Beijing, China
\textsuperscript{b}Department of Physics and Materials Science, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong

\textbf{A R T I C L E  I N F O}

Article history:
Available online 30 January 2009

\textbf{PACS:}
52.65.-y
52.65.Rz
52.77.Dq
52.40.Kh

Keywords:
Plasma immersion ion implantation
Glow discharge

\textbf{A B S T R A C T}

Enhanced glow discharge plasma immersion ion implantation and deposition (EGD-PIII&D) does not require external plasma sources. In this technique, the plasma is produced by self-glow discharge when a high negative voltage is applied to the sample. The small-area, pointed-shape hollow anode and large area tabular cathode form an electron-focused electric field. Using a special electric field design, the electrons from either the plasma or target (secondary electrons) are focused to a special hollow anode. As a result of the special electron-focusing field, the self-glow discharge process can be enhanced to achieve effective ion implantation into the substrate. In this work, the plasma potential distribution is investigated in details and the possible pulse discharge mechanism is discussed. The unique characteristics of the pulsed plasma and plasma extinction are studied.

\textcopyright 2009 Elsevier B.V. All rights reserved.

1. Introduction

Plasma immersion ion implantation (PIII) is used in modification of materials such as metals, plastics, and ceramics to improve surface mechanical properties including wear, corrosion, fatigue and friction [1]. In typical PIII processes, the samples are immersed in a plasma and pulse-biased to a high negative voltage to perform ion implantation [2]. The process usually requires external plasmas ignited by radio frequency (RF), microwave, vacuum arc, hot filaments. An alternative plasma source ion implantation and deposition method, enhanced glow discharge plasma immersion ion implantation and deposition (EGD-PIII&D), which does not require external plasma sources has been recently proposed [3–5]. In this technique, the plasma is produced spontaneously via glow discharge due to the high negative voltage applied to the samples. We have investigated the process in which a small, pointed hollow anode and large area tabular cathode form an electron-focused electric field [6]. By using a special electric field design, the electrons from either the plasma or target (secondary electrons) are focused to a special hollow anode. Thus, the self-glow discharge process can be enhanced to achieve more effective ion implantation into the substrate. The hollow anode is used so that the gas or vapor to be implanted can be fed through and transmitted through the electron-focused area. Our results show that by using this technique, self-glow discharge is enhanced and a higher ion density can be attained for more efficient ion implantation [4]. The effects of different distances between the anode and cathode on the glow discharge characteristics and the influence of the plasma electron density have been evaluated [5]. The results disclose that the electron density is quite uniform in the vicinity of the negatively biased substrate when the implantation chamber is large.

In EGD-PIII&D, glow discharge is utilized to produce the required plasma. In order to offer more precise control of the implantation and deposition process, the characteristics of the glow discharge as well as bulk plasma require further investigation. In this work, the pulsed glow discharge characteristics are examined in details. The plasma potential distributions for different implantation pulse durations are determined and the pulse discharge mechanism is discussed. In addition, a long tail at the trailing edge of the implantation pulse lasting for 10 ms or so is observed. To investigate this phenomenon, anodes with different sizes are used and the possible reason is discussed. The unique characteristics of the pulsed plasma and plasma extinction are also studied.

2. Experimental details

The enhanced glow discharge plasma immersion ion implantation experiments were performed in an apparatus shown in Fig. 1. The equipment comprises three main components: (1) implantation system, (2) pumping system and (3) high voltage power sys-
tem. All of them are placed in a 1.2 m tall PIII instrument with a diameter of 1 m. The latter two parts are not shown in Fig. 1. The implantation system consists of an electrically conducting rod, sample holder, implantation chamber, and exit of the feeding conduit. The implantation chamber is made of electrically insulating materials. The sample holder is located at the end of a conductive rod that extends through the wall of the vacuum chamber and is connected to the negative electrode of a high voltage power supply. The exit of the feeding conduit is grounded and serves as the hollow anode. The surface area of the exit of the feeding conduit is much smaller than that of the sample holder. Hence, electrons in the plasma as well as secondary electrons emitted from the sample holder all fly to the exit. As a result, an electron-focusing electric field is formed between the exit and sample holder. The distances between the tip and the substrate were preset to 10, 30, 90, 150 and 180 mm, respectively. The probe is grounded via a large resistor \( (R = 10 \times 10^6 \text{\Omega}) \). The potential of the plasma bulk is monitored by an oscilloscope by a 10M HP probe and the resulting traces are saved in the oscilloscope. Experiments were performed with and without the auxiliary disk. Stainless steel auxiliary disks with diameters of 10, 20 and 60 mm welded to a hollow tube were used to investigate the plasma extinction phenomenon. Argon was bled into the chamber at a flow rate of 5 SCCM (standard cubic centimeter per minute) and the substrate was pulse-biased to \(-10 \text{ kV}\). The pulse repetition rate was 50 Hz. The voltage rise time was about 0.5 \( \mu \text{s}\).

A hard tube (TM702) was used in the modulator as a switch to directly provide the target with a negative high voltage. The voltage was adjusted by the screen and control grids. The bias voltage of the screen grid was fixed at 2 kV. The voltage on the control grid determined the dynamic behavior of the output voltage.

3. Results and discussion

Fig. 2 shows the potentials measured without the auxiliary disk in EGD-PIII&D at different distances from the substrate. The pulse widths are: (a) 50 \( \mu \text{s}\), (b) 75 \( \mu \text{s}\), (c) 100 \( \mu \text{s}\), (d) 125 \( \mu \text{s}\) and (e) 150 \( \mu \text{s}\). The end of the gas inlet tube with a size of \( \phi 6 \text{ mm} \times 1 \text{ mm} \) is used as the anode. In this situation, the electric field produced by the point shape anode and large substrate holder plate constitutes
an electron-focusing field that can enhance the glow discharge. The
high voltage sheath can be described by Child’s law [4]:
\[
S = \frac{\sqrt{2}}{3} \lambda_{De} \left( \frac{2V_0}{T_e} \right)^{3/4},
\]
where \( S \) is sheath thickness, \( \lambda_{De} \) is the electron Debye length, \( V_0 \) is potential at the plasma – sheath edge, and \( T_e \) is electron temperature. The Child’s law sheath is on the order of 100 Debye lengths (~10 mm) in a typical discharge [5]. Hence, at a distance of 10 mm from the substrate holder, the probe may be at the edge of the sheath or the presheath and the potential \( \phi \) at a distance \( x \) from the sheath edge as a function of position can be described by the following relationship [5]:
\[
\phi = -V_0 \left( \frac{x}{S} \right)^{4/3}.
\]
The potential \( \phi \) increases by a power of 4/3 with distance from the sheath edge. This may be the reason why the potential at 10 mm resembles a saw-tooth wave but those measured at 30, 90 and 180 mm from the substrate holder resemble a square wave (Fig. 2) similar to the pulsed negative high voltage. At a distance of 10 mm, the sheath or presheath edge has expanded to there be-

Fig. 3. Long tails observed in EGD-PIII&D for pulse widths of: (a) 50 \( \mu \)s, (b) 75 \( \mu \)s, (c) 100 \( \mu \)s, (d) 125 \( \mu \)s and (e) 150 \( \mu \)s.

Fig. 4. Potentials at distances of: (a) 10 mm, (b) 30 mm, (c) 90 mm and (d) 180 mm from the substrate for different auxiliary size.
cause the negative potential increases linearly with time. Hence, a saw-tooth waveform is observed in Fig. 2. According to Fig. 2(e), it can be concluded that even at the end of the 150 μs pulse, the sheath is still expanding because the potential pulse at the 10 mm point also has a saw-tooth shape. Furthermore, the thickness of the high voltage sheath is less than 30 mm, because the waveform at a distance of 30 mm from the substrate exhibits a square shape.

Fig. 2 also reveals that a leading edge overshoot at the beginning of the potential pulse except at a distance of 10 mm. This overshoot width is nearly the same at 50 μs regardless of whether the implantation pulse width is 50, 75, 100, 125 or 150 μs, as shown in Fig. 2(a)-(e). This shows that there is a plasma balance arising from the electron-focusing enhanced glow discharge. The more negative potential at the beginning is due to inadequate electrons and ions, sheath expansion, and insufficient interactions between the electrons with neutral particles.

An unexpected phenomenon, a long tail, is observed at the trailing edge of the negative potential pulse. In order to investigate it further, a longer sampling time is used and the results are displayed in Fig. 3. It can be observed that the long tail can be observed regardless of pulse width. There are two possible reasons. One is the extinction mechanism of the plasma produced in the glass implantation chamber. The other is the circuit of the implantation power supply. Auxiliary disks with diameters of 10, 20 and 60 mm are used as the anode to study this phenomenon and the results are shown in Figs. 4 and 5. Fig. 5 shows the potentials at a large time scale. It should be noted that with increasing auxiliary disk size, the brightness of the glow discharge decreases, implying that increasing the anode size weakens the glow discharge effect. In fact, when the auxiliary disk is increased to 60 mm, the discharge becomes unstable.

Fig. 4(a) reveals that at a distance of 10 mm from the substrate, the potential pulse has a saw-tooth shape. This illustrates that the high voltage sheath has expanded to this point regardless of anode size. At a larger distance from the substrate holder, only the setup with a 60 mm diameter auxiliary disk shows a saw-tooth waveform. This indicates that in this case, the sheath expands to a much larger distance. Because a 60 mm diameter auxiliary disk is used as the anode, the electron-focusing effect is weakened. As a result, the electron temperature $T_e$ and the plasma density diminish and according to Eq. (1), the sheath thickness increases.

During implantation, the long tails at the trailing edge are observed for all anode size (Figs. 3 and 5), but the positive side is affected by the anode size. Without the auxiliary anode disk, the positive peak in the tail is larger but the positive peak is smallest for the largest anode size anode (Fig. 5). Because the glow discharge plasma is produced in a glass implantation chamber, the ions and electrons can only disappear by recombination and diffusion to the anode, substrate holder, or chamber wall. In the high voltage pulse supply, vacuum tubes are used to modulate high negative voltage and so when the charges come to the substrate holder or the insulating wall, they are impeded. Only when the charges reach the grounded anode can they disappear immediately. At the beginning, the positive charges are nearly equal to negative charges and the plasma is nearly neutral. Consequently, the potential in the implantation chamber is nearly zero after the negative pulse. However, since electrons have higher velocity than ions, they are more prone to hitting the grounded anode and disappear. After several milliseconds, more and more positive charges accumulate in the implantation chamber and consequently, the positive potential peak appears in the tail. If the anode is larger, the possibility of the charges to hit the anode is higher. Hence, the positive potential peak is smaller for smaller anode size.

4. Conclusion

The potential distributions for different implantation pulses in enhanced glow discharge plasma immersion ion implantation and deposition (EGD-PIII&D) are investigated. At a distance of 10 mm from the substrate, the potential exhibits a saw-tooth waveform. When the distance from the substrate is over 30 mm, the potential pulse has a square shape similar to the implantation pulse. It can be concluded that the thickness of the sheath or pre-sheath extends to more than 10 mm but less than 30 mm, and at the end of 150 μs, the sheath continues to expand. In EGD-PIII&D process, it takes 50 μs to build up the electron-focusing enhanced
glow discharge plasma. Increasing the size of the anode weakens the enhanced glow discharge effect and the sheath thickness increases. A long tail is observed at the trailing edge of the negative high voltage pulse. When the auxiliary disk is large, the possibility of the charges to reach the anode increases and consequently, the positive potential peak at the tail is smaller for a smaller anode.

Acknowledgments

The work was jointly supported by Hong Kong Research Grants Council (RGC) Central Allocation Equipment Grant No. CityU 1/06C, National Science Foundation of China No. 10775103 and Aeronautics Science Foundation of China 2007ZF51072.

References