Improved hydrogen ionization rate in enhanced glow discharge plasma immersion ion implantation by enlarging the interaction path using an insulating tube

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A small pointed hollow anode and large tabular cathode are used in enhanced glow discharge plasma immersion ion implantation (EGD-PIII). Electrons are repelled from the substrate by the electric field formed by the negative voltage pulses and concentrate in the vicinity of the anode to enhance the self-glow discharge process. To extend the application of EGD-PIII to plasma gases with low ionization rates, an insulating tube is used to increase the interaction path for electrons and neutrals in order to enhance the discharge near the anode. Results obtained from numerical simulation based on the particle-in-cell code, finite element method, and experiments show that this configuration enhances the ionization rate and subsequent ion implant fluence. The process is especially suitable for gases that have low ionization rates such as hydrogen and helium. © 2011 American Institute of Physics. [doi:10.1063/1.3544022]

I. INTRODUCTION

Enhanced glow discharge plasma immersion ion implantation (EGD-PIII) is conducted using a special hardware configuration composed of a small pointed hollow anode and large tabular cathode.1 This technique is similar to the hollow-anode discharge (HAD) proposed by Miljevic2–5 and further researched by Anders and co-workers.6–8 In both methods, the glow discharge is produced by a small anode and large cathode. The glow discharge is enhanced by the electrons focused to the small anode9 and the plasma ball which plays an important role in the glow discharge can be observed.7,10 In spite of some similarities, there are many differences between these two techniques. For instance, the location of the plasma ball is different. In EGD-PIII, the plasma ball is in the downstream direction, whereas in the hollow-anode discharge configuration described by Anders, the plasma ball is in the upstream direction. Consequently, the plasma ball becomes larger in EGD-PIII as the gas flow is increased. In HAD, the glow discharge current decreases with increasing gas flow, but in EGD-PIII, the opposite is true. Hence, in EGD-PIII, the ion density increases with the gas flow rate but in HAD, the total currents of atomic and molecular ions diminish with increasing gas pressure (gas flow).8 The difference may stem from the difference in the plasma ball. As the gas flow is increased, the volume of the plasma ball in HAD decreases but that in EGD-PIII increases.

In EGD-PIII, the ion current is higher than that in conventional plasma immersion ion implantation (PII) methods using similar implantation parameter11 and at the same ion implantation current, the fluence is higher than that in traditional PIII. Furthermore, based on theoretical simulation and experimental data, the distribution of the implanted fluence is more uniform over a large area.11–13 Hence, EGD-PIII is a potential alternative in commercial applications such as the production of silicon-on-insulator substrates. However, we have discovered from our experiments that the discharge and implantation effects when using hydrogen and helium plasmas are not as good as those observed from nitrogen and argon plasmas. Therefore, in order to increase the attractiveness of this technique, the ionization rate of hydrogen must be further improved. There may be two reasons for the difference between nitrogen and hydrogen. One reason is that the cross section of electron–neutral collisions for hydrogen is smaller than that of larger species.14,15 The other one is that the energy needed to ionize hydrogen or helium is higher than that for oxygen or argon, implying that it is very difficult to obtain the same number of ions at the same voltage.14 In this work, we report a means to improve the implantation efficacy by increasing the interaction path for electrons and neutral particles and verify the enhancement by theoretical simulation and experiments.

II. APPARATUS AND EXPERIMENTAL DETAILS

Figures 1(a) and 1(b) depict two different EGD-PIII configurations. In the original EGD-PIII experiments, the substrate is pulsed biased to a high negative pulsed and the dielectric chamber and grounded gas inlet at the center of the chamber top constitute the main functional components,16 as shown in Fig. 1(b). In the new redesigned configuration illustrated in Fig. 1(a), an insulating tube is placed between the chamber and gas inlet to increase the interaction path for
electrons and neutrals. The length of the insulating tube is 100 mm and the outer and inner diameters are 6.5 and 2.6 mm, respectively. The size of the implantation chamber is 210 mm × φ180 mm. In our experiments, hydrogen was the plasma gas and the negative high voltage was varied between 12 and 14 kV. The pulse width was varied from 50 to 100 μs, whereas the frequency was fixed at 100 Hz. The gas glow rate was adjusted between 20 and 100 sccm, and the resulting hydrogen pressure in the chamber was 1.8 × 10⁻² and 1.0 × 10⁻¹ Pa, respectively.

Numerical simulation based on the particle-in-cell algorithm was conducted to determine the potential distributions during implantation.⁵,¹⁷,¹⁸ According to the axial symmetry, the simulation region was set as the r-z plane with an area of 390 × 150 mm². Plasma generation and secondary electron emission are not considered to simplify the simulation model. The plasma with a density of 1.0 × 10¹⁶ m⁻³ was distributed within the dielectric cage and insulating tube. A negative voltage pulse of 10 kV was applied to the sample stage and rod, and the high voltage pulse had a duration of 40 μs and rise time of 1 μs.

In order to reveal the hydrogen density gradient between the implantation chamber and insulating tube, the pressure distribution was investigated by the finite element method. The bottom pressure, set as the exit of the model, was 7.2 × 10⁻² Pa, and hydrogen was bled in the vertical direction at a rate of 80 sccm. The hydrogen density and coefficient of dynamic viscosity at standard temperature and pressure are 0.08988 kg/m³ and 1.3540 × 10⁻⁵ Pa·s, respectively.¹⁹

III. RESULTS AND DISCUSSION

The left photo in Fig. 1(a) shows the hydrogen discharge under conditions of 13 kV, 100 Hz, 50 μs, flow rate of 60 sccm, pressure of 5.4 × 10⁻² Pa, and average implantation current of 3.9 mA. There are electron–neutral collisions, as indicated by the glare in the insulating glass tube. Compared to the traditional discharge shown in Fig. 1(b), the tube is the brightest part and the entire implantation chamber is lit up due to strong collision and ionization inside. Electrons from the plasma near the substrate and secondary electrons resulting from ion bombardment fly toward the grounded anode passing through a narrow channel where the density of neutrals is much higher than that in the chamber. A region with a high ion density is thus formed as a result of increased collisions between electrons and neutral particles.

The electron mean free path is introduced to investigate the different collision frequencies in the implantation chamber and insulating tube. The electron mean free path can be defined by the following equation:¹⁴

\[ \lambda = \frac{1}{n_n \sigma}. \]  

(1)

Here, \( n_n \) is the density of neutral molecule and \( \sigma \) is the collisional cross section of neutral molecules. The neutral density can be calculated by Eq. (2) based on Clapeyron equation and cross section of electron-neutral collision by Eq. (3),

\[ p = n \kappa T, \]  

(2)

\[ \sigma = \pi r^2. \]  

(3)

where \( p, \kappa, \) and \( T \) in Eq. (2) are gas pressure, Boltzmann constant, and temperature in vacuum chamber, respectively. The temperature is set at 300 K in our experiment. In Eq. (3), the collision radius \( r \), defined as the molecular radius in particle collision, is 1.37 × 10⁻¹⁰ m for hydrogen and 1.89 × 10⁻¹⁰ m for nitrogen.¹⁴ Substituting Eqs. (2) and (3) into Eq. (1), we obtain the relationship between the electron mean free path and gas pressure,

\[ \lambda = \frac{\kappa T}{p \sigma}. \]  

(4)

The numerical expression of the electron mean free path in the hydrogen and nitrogen experiments can be inferred using Eqs. (5) and (6), respectively,

\[ \lambda_{H_2}[m] = \frac{0.0702}{p_{H_2}}[Pa], \]  

(5)

\[ \lambda_{N_2}[m] = \frac{0.0369}{p_{N_2}}[Pa]. \]  

(6)

Comparing Eqs. (5) and (6), electrons will collide with nitrogen molecules more frequently than hydrogen at the same working pressure since the mean free path in nitrogen is shorter. This helps to explain the weaker hydrogen discharge observed experimentally.

Figure 2 shows the distribution of the hydrogen pressure gradient in the implantation chamber with the insulating tube
obtained by the finite element method. Although the pressure in the chamber is between 0.06 and 0.08 Pa, the pressure in tube varies with the location and the maximum reaches 1.634 Pa at the entrance of hydrogen where the anode is located. The mean free paths in the chamber and insulating tube calculated by Eq. (5) are about 1.1 and 0.081 m, respectively. The difference between the electron free paths in the chamber and tube induces the discharge phenomenon in Fig. 1(a). In the implantation chamber, the electron mean free path is larger than the dimension of the chamber and as a result, the electron-neutral collision frequency is low. On the other hand, inside the insulating tube, the mean free path has the same scale as the tube size in the vertical direction, and electron collisions occur more frequently under the influence of the electric field.

Figure 3(a) displays the potential configuration in the whole region at the end of the pulse, and Fig. 3(b) shows the enlarged view of the potential contours in the insulating tube. The equipotential lines are dense and horizontal near the stage and become sparser and more oblique with vertical distances. It means that the potential drop is mainly concentrated near the negatively biased substrate and the ion energy and fluence will be quite uniform except at the edge of the stage due to the influence of the dielectric chamber. The variation in the equipotential lines is similar to that without the insulated tube. The dimensions of the tube are 270–330 mm in the z direction and 0–5 mm in the r direction. The horizontal equipotential lines in the tube, which means that the direction of the electric field is parallel to the sidewall, will benefit ion and electron motion. Although the potential difference exerted on the insulating tube is about 150 V which is very small compared to the 10 kV applied to the substrate, it is large enough to supply ionization energy to electrons and bring electrons to the anode and ions to the implantation chamber.

In order to verify the discharge effect in a plasma gas with a low ionization rate, hydrogen is implanted using the system and the instantaneous implantation currents are recorded by a digital oscilloscope (Tektronix TDS 3014C) to obtain the average current. The hydrogen flux varies from 20 to 100 sccm. Unlike other gases with higher ionization efficiency, obvious differences can be observed from the hydrogen implantation experiments. At a fixed bias voltage, the target current does not change obviously when the gas flow rate is smaller than a certain value. It may be because when the flow rate is relatively small, collisions and ionization are not high enough to enhance the current, although electrons and secondary electrons are indeed focused into the exit of the gas inlet. Consequently, the threshold gas flow rate above which enhanced ionization can be observed near the tube is investigated. The effects of the voltage pulse width and biases are monitored, and Fig. 4 shows the average target current distribution with and without the insulating tube at different gas flow rates under the following experimental conditions: (a) 12 kV, 100 Hz, and 50 μs, (b) 12 kV, 100 Hz, and 100 μs, and (c) 14 kV, 100 Hz, and 100 μs. The lines marked “1” are current curves measured with the insulating tube, whereas the lines marked “2” represent those recorded without the tube. Comparing the two current curves, the threshold flow rate value declines by about 13 sccm and helps the implantation efficiency. The main reason is that the insulating tube concentrates the electrons into a slender channel and the electron flux needed for ionization is reduced. When the flow rate exceeds the threshold value, the ionization effect near the tube begins.
to play a more important role and the target current starts to increase. Meanwhile, the glass tube becomes brighter as a result of the higher ionization rate inside. Comparing the threshold values of the curves in Figs. 4(a) and 4(b) obtained at 30 sccm, prolonging the pulse does not affect the threshold appreciably. However, the value is reduced to 27 sccm, as shown in Fig. 4(c), implying that an increased biased voltage works. This can be explained by the fact that at a certain bias, the electron density and energy are almost the same at any time during the pulse no matter how long the pulse is. Increasing the bias thus improves both the amount and energy and as a result, the flow rate threshold decreases. A better implantation efficiency can be obtained by reducing the flow rate threshold and increasing the target current in the presence of the insulating tube near the hollow anode.

Another interesting phenomenon observed from our experiments is that the increment in the average target currents is not constant or changes linearly with the flow rates. There is a certain flow rate at which the current curve in the presence of the insulating tube is similar to the one without the tube. The flow rates are inflexions of the implanted current increments at 70, 60, and 50 sccm, as shown in Figs. 4(a), 4(b), and 4(c), respectively. When the flow rate is lower than the inflexion point, most of the ions in the tube are transferred to the substrate. When the electron flux generated by ionization reaches a certain value, the electron velocity is much higher than that of ions, many electrons accumulate at the inner wall of the insulating tube due to the small tube diameter forming local electric fields pointing to the inner wall. The effects of this local field and ion–electron recombination probably play a big role, leading to a smaller increment in the target current at the inflexion flow rate. With increased hydrogen supply, the effect of ionization dominates again and the increment in the target current increases, as illustrated by the tendency observed from the curves. The curves also show that increases in the pulse width and bias voltage reduce the inflexion flow rate, and the current increment reaches a maximum at a flow rate of 100 sccm.

Figure 5 displays the target current waveforms under the following conditions: (a) 12 kV, 100 Hz, and 50 μs, (b) 12 kV, 100 Hz, and 100 μs, and (c) 14 kV, 100 Hz, and 100 μs. The black lines marked “1” are current waveforms measured with the insulating tube, whereas the red lines marked “2” represent those recorded without the tube at a gas flow rate of 100 sccm. The current peaks immediately when the pulse begins and returns to a steady state in the case without the insulating tube. It is because of the buildup of the ion sheath near the cathode which causes more ions to be implanted into the substrate. When the electrons accumulate at the exit of the inlet, ionization is effective and the current increases steadily. The current waveforms obtained with the insulating tube are almost the same as those without tube before 10 μs. When many ions are generated in the tube and transported to the substrate, the current increases again. Moreover, since the potential between the tube and cathode is almost the bias voltage, ions from the insulating tube are implanted into the substrate at a higher energy than those generated near the cathode, thus increasing the ion implantation depths and fluences. Comparison of the current waveforms acquired with the insulating tube at different pulse widths shows that in spite of slight fluctuations between the two curves, the current amplitude is fixed at nearly 1.2 A. It is consistent with our aforementioned results showing that prolonging the pulse width does not reduce the threshold value of the flow rate. The fine features
FIG. 4. (Color online) Hydrogen average target currents distribution with and without the insulating tube with increasing gas flow rate under different experimental voltages: (a) 12 kV, 100 Hz, and 50 μs; (b) 12 kV, 100 Hz, and 100 μs; and (c) 14 kV, 100 Hz, and 100 μs.

FIG. 5. (Color online) Hydrogen current waveforms with or without the insulating tube under different experimental conditions: (a) 12 kV, 100 Hz, and 50 μs, (b) 12 kV, 100 Hz, and 100 μs, and (c) 14 kV, 100 Hz, and 100 μs. The hydrogen flow rate is 100 sccm.
in the curves may be caused by the output characteristics of the high voltage power modulator when the pulse widths are changed or different ion fluxes being delayed in the implantation chamber after the pulse as a special discharge characteristic of EGD-PIII discussed by Lu et al.\textsuperscript{16} When the bias voltage is changed from 12 to 14 kV, the target current increment is greater, reaching about 30% under conditions of 14 kV, 100 μs, and 100 sccm. It can be explained by the higher secondary electron yield as the ion impact energy is increased.\textsuperscript{21}

IV. CONCLUSION

The interaction path for electrons and neutrals is increased by adding an insulating tube to the conventional EGD-PIII setup. Our theoretical and experimental studies reveal enhanced ionization of the plasma gas with low ionization efficiency such as hydrogen. On account of the shorter electron mean free path in the insulating tube and uniformly distributed equipotential lines, ionization and ion transport are enhanced. The threshold value of the gas flow rate decreases, and more ions with higher energy are implanted by using the insulating tube. Our results show that EGD-PIII employing an insulating tube offers many benefits, especially when the plasma gas has a low ionization rate.

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