Interactions between plasma and ionization gauge in plasma immersion ion implantation

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Abstract

During plasma processes such as plasma immersion ion implantation-deposition (PIII-D), proper monitoring of the working gas pressure is essential as the pressure has a large influence on the discharge behavior and plasma parameters (for example, plasma density, ion distribution, electron temperature, etc.), and consequently the surface properties of the treated samples. The pressure is generally monitored using thermal gauges at low vacuum and ionization gauges at high vacuum. An ionization gauge detects the pressure by measuring the collected ion current that can be affected by the presence of an externally sustained plasma in the vacuum chamber. Its existence can introduce errors in the ion current measured by the ion gauge leading to an erroneous pressure reading. This is also true for PIII experiments conducted using high-voltage glow discharge, that is, with plasma created by biasing the samples with a high negative voltage. The plasma in the ion gauge can work as a seed plasma to help ignite the glow-discharge plasma with a relatively small time delay. At a nitrogen pressure of 2.5 mtorr and voltage of $\sim$20 kV, the ionization gauge can expedite the formation of the glow discharge plasma by 10s of $\mu$s. These discrepancies must be understood and accounted for in practical applications, as a different gas pressure impacts the plasma chemistry, ion mean free path, and so on.

Keywords: Plasma processing and deposition; Ion implantation; Glow discharge; Vacuum measurement

1. Introduction

The surface properties of samples or components treated by plasma immersion ion implantation-deposition (PIII-D) [1] are determined by processing parameters, such as the implantation voltage, sample temperature, processing time and pulse frequency/width [2–5]. In particular, the vacuum affects the plasma behavior, partial pressure of residual gas species, mean free path of the charged particles, and ultimately the surface properties of the samples. Previous experimental results have shown that the plasma composition and electron temperature are impacted by the gas pressure, in addition to the power of the plasma source [6–8]. For instance, at a higher pressure, the ratio $N_2^+/N^+$ increases while the electron temperature decreases [7]. Baldwin et al. found that at 0.3 Pa, the excited neutral density reached a maximum, and subsequently higher nitriding efficiency could be achieved [9]. In our recent experiments on elevated-temperature PIII, a lower nitrogen retained dose was observed in a lower working pressure due to surface oxidation and impeded nitrogen diffusion [10].

In PIII, the samples are typically immersed in a plasma generated by an external plasma source or high-voltage glow discharge. The plasma spreads throughout the vacuum chamber by diffusion and may affect vacuum sensors, such as an ionization gauge, that detect the pressure by collecting the ion current generated by its own source. However, the gauge cannot distinguish ions generated by an external plasma drifting to the ion gauge, and the ionization gauge readout may be different from the real gas pressure. Compared to conventional plasma nitriding, the plasma in PIII can more easily reach the gauge due to the low pressure and large mean free path. Moreover, the plasma may sometimes be generated near the chamber wall, e.g. during hot filament glow discharge, and it is unlike the case of conventional plasma nitriding in which the plasma is produced near the samples. Thus, plasma produced near the chamber...
wall in PIII has a closer path to the ionization gauge. It is also conceivable that the plasma generated in the ion gauge may diffuse out and affect the plasma implantation processes. In this work, interactions between the external plasma and ionization gauge during PIII processes were experimentally investigated.

2. Experimental

The experiments were conducted in our multi-purpose plasma immersion ion implanter [11,12]. The ion gauge was installed on the side of the chamber beneath the hot filaments. The sample was a stainless steel rod, 50 mm in diameter and 400 mm long. An argon plasma was ignited employing radio frequency (RF) or hot filament discharge. In another experiment, high voltage was applied to the sample to generate high-voltage glow discharge. The implantation voltage varied from \(10\) to \(30\) kV and the pulse duration from 100 to 1000 \(\mu\)s. A Granville-Phillips Series 274 ionization gauge was used in our experiments.

3. Results

Experimental results indicate that the free electrons emitted from the hot filaments have no effect on the readings of the gauge. However, when hot filaments are used to ignite the plasma, the pressure readout changes. As shown in Figs. 1–3, the pressure reading increases with plasma in the vacuum chamber. The variations depend primarily on the bias current (plasma density) and gas pressure. The discrepancy increases with higher plasma density, as shown in Fig. 1. It increases exponentially with the bias current at high pressure. The difference between the real and measured pressure is also related to the gas pressure. It generally increases with higher pressure, but there is a critical pressure near \(0.5\) mtorr, as shown in Fig. 2. The existence of external plasma has a small effect on the measured value when the pressure is below \(0.5\) mtorr, but the variation may reach 60% when the pressure is higher than \(0.5\) mtorr. When the plasma is ignited by a capacitively coupled RF source, the readout of the gauge is also higher than that without the plasma, as shown in Fig. 3. This is consistent with results acquired using hot filament glow discharge, but a critical pressure is not observed in the latter case.

The implantation voltage pulse has no appreciable effect on the readout of the ion gauge with external plasma. In contrast, in pulsed high-voltage glow discharge, the readout of the ion gauge decreases. Fig. 4 shows the experimental results at different voltages. Between \(2.0\) and \(3.5\) mtorr, the pressure remains constant when \(-10\) kV is applied to the sample, followed by a drop at higher voltages. After a critical voltage, the readout increases again. At a pressure higher than \(3.5\) mtorr, the readout firstly reaches a minimum at \(-10\)
Fig. 4. Influence of high-voltage glow discharge on the gauge readout.

kV and then increases with higher voltage. In high-voltage glow discharge PIII, the readout is always below the original value (without pulsed plasma implantation).

The ion gauge also affects pulsed high-voltage glow discharge plasma implantation [13]. As shown in Figs. 5 and 6, a time delay is observed between the discharge current and implantation voltage. The ionization gauge can effectively diminish the glow discharge delay time, and the influence is more evident at lower pressure or lower voltage. At higher pressure, ionization is easier, and consequently the influence of the ion gauge on the delay time is less visible. Figs. 5 and 6 also illustrate that the ion gauge cannot improve the ionization efficiency, despite the smaller delay time.

4. Discussion

Our results demonstrate that improper readings may result in the presence of plasma in PIII. The readout also varies with the power applied to the plasma source. This phenomenon may sometimes be confused with outgassing of the chamber wall. For example, a hot filament heats the chamber wall, and electrons bombard ing the wall may also lead to pressure readout increases. Therefore, it seems reasonable to adjust the pressure when the plasma source is switched off. In our experiments, this factor has been properly taken into account.

The ion gauge readout becomes larger than the actual pressure in the presence of an external plasma, whereas the readout becomes smaller during pulsed glow-discharge plasma implantation. This can be attributed to the measurement mechanism of the ionization gauge. The gauge is composed of a filament, anode grid and ion collector. Electrons emitted from the filament are attracted to the anode, ionizing gas molecules in their paths; the number of positive ions produced is proportional to the pressure [14]. Ionization gauge controllers measure the positive ion current in amperes and convert the values to pressure:

$$P_{\text{read}} = k_0 i_p$$  \hspace{1cm} (1)

where $P_{\text{read}}$ is the readout pressure, $i_p$ is the ion current collected and $k_0$ is the equivalent sensitivity of the gauge. Considering a system composed of a vacuum chamber and ion gauge, two plasmas exist and two ion currents appear:

$$i_p = i_{p1} + i_{p2}$$  \hspace{1cm} (2)

where $i_{p1}$ originates from the external plasma and

$$i_{p2} = k_i P_{\text{real}}$$  \hspace{1cm} (3)

Fig. 5. Influence of ion gauge on the high-voltage glow discharge at different applied voltages (gas pressure $P_{\text{gas}} = 2.5$ mTorr).
where $i_{p2}$ is the ion current produced by electrons originating from the gauge, $k$ is the sensitivity of the gauge and $i_e$ is the current required to ionize the gas in the gauge, composed of the electron current in the gauge ($i_{e1}$) and that in the external plasma ($i_{e2}$).

Plasma in the chamber can diffuse into the ionization gauge and can be detected by the gauge, while electrons from the external plasma may also assist in ionization of the gas molecules in the gauge. Consequently, the combined effects increase the total collected ion current, $i_p$, thereby producing anomalously high pressure readings, as shown in Figs. 1–3. A higher plasma source power leads to a higher plasma density (more ions and electrons) and a higher effective collected ion current $i_p$. Our results disclose a critical pressure in hot-filament glow discharge, as shown in Fig. 4. Our empirical observation of a greater error in the pressure readout when the working pressure is higher than 0.5 mtorr is useful when designing experimental protocols. In pulsed high-voltage glow discharge plasma implantation, there is no plasma in the chamber before each high-voltage pulse. In this respect, a reverse trend can occur in which the plasma in the ionization gauge can out-diffuse. When a high-voltage pulse is applied between the target and anode (chamber wall), the electric field builds up and the plasma in the proximity of the gauge outlet or even within the gauge will be exhausted by this electric field. Thus, the effective number of particles (ions and electrons) decreases, giving rise to a smaller ion current collected and reading on the gauge, as shown in Fig. 4.

Owing to the limited plasma in the ionization gauge, its contribution to the external plasma is not significant. The plasma sheath shielding makes the applied voltage (electric field) invisible to the chamber wall and plasma in the gauge [15]. In contrast, the influence of the gauge on high-voltage glow discharge plasma implantation is inevitable, as indicated in Figs. 5 and 6. Although the exact mechanism is unknown, seed plasma is very effective in building up the plasma. A suitable electron density or a small, preexisting RF plasma may decrease the delay time to zero [13]. These experiments demonstrate that the plasma in the ionization gauge can act as the seed plasma in high-voltage glow discharge plasma implantation. As shown in Fig. 5, the gauge plasma has a similar influence on the delay time as a 5-kV voltage increase.

### 5. Conclusion

Interactions between the external plasma and ion gauge during plasma ion implantation were experimentally investigated. The external plasma may increase the gauge readout. The higher the plasma density, the greater is the difference between the detected and actual pressure. The plasma in the gauge also affects high-voltage glow discharge plasma implantation, as it introduces a seed plasma. This detection artifact must be taken into account in designing PIII experiments.

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### References