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Development of a Plasma Distribution Diagnostic System Based on VPPC(Variable Position Pinhole Camera)

Sang-Je Lee [a], Geunwoo Go [a], Kyoung-Jae Chung [a*]
[a] *Department of Nuclear Engineering, Seoul National University, Seoul, Korea*
[*]*Corresponding author: jkjlsh1@snu.ac.kr*

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1. Introduction

The quality and uniformity of plasma etching processes are critically determined by the spatial distribution of ions and reactive species within the plasma. Conventional optical emission spectroscopy (OES), however, provides only line-integrated light intensity along a given line-of-sight (LoS), which makes it difficult to directly obtain the local emissivity distribution inside the chamber. Simulation studies have confirmed that tomographic reconstruction of emissivity profiles is feasible when sufficient LoS data are acquired from multiple viewing angles. In practical semiconductor manufacturing systems, however, the number of available observation ports is typically limited to two, which imposes severe restrictions on the number of measurable LoS. To overcome this limitation, we have designed and constructed a novel diagnostic system, termed the Variable Position Pinhole Camera (VPPC), which enables the acquisition of multiple LoS data despite the limited number of chamber ports.

2. Methods and Results

2.1 Structure and Operation of the VPPC

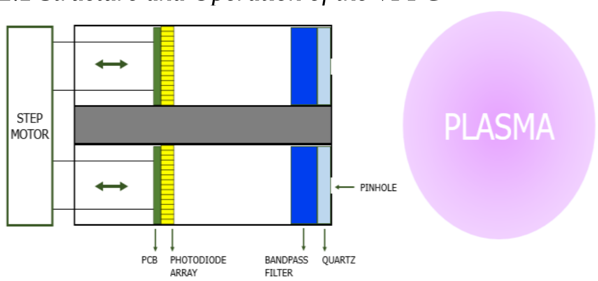

Fig. 1. Schematic of the VPPC structure and its components.

The VPPC system consists of two 16-element photodiode arrays, a bandpass filter, a 1-mm quartz window, and the body structure. The light emitted from the plasma inside the chamber sequentially passes through these components. As shown in Fig. 1, the VPPC body is divided into two parts: one part contains two circular channels that allow the photodiode arrays to move back and forth, and the other part has a pinhole of 0.5 mm diameter to restrict the collected light to a specific direction. These two body parts were bonded using vacuum-compatible adhesive. A 1-mm-thick transparent quartz plate was then attached to the pinhole side to maintain vacuum integrity while transmitting plasma emission. A bandpass filter was installed to select only the desired wavelength; in this study, a 750 nm filter was chosen due to its strong correlation with electron density in Ar plasma. Finally, a 16-element photodiode array was mounted to convert the transmitted optical signals into electrical current.

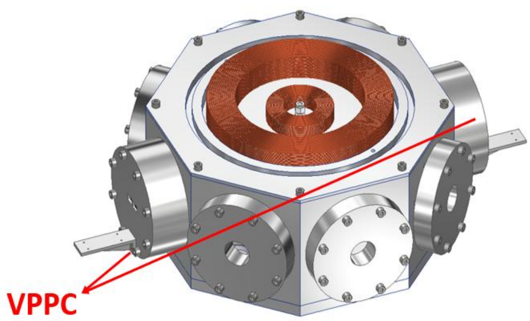

Fig. 2. VPPC mounted on the plasma chamber.

As shown in Fig. 2, the VPPCs are mounted on both sides of the chamber, and by moving the photodiode arrays along their tracks, multiple line-of-sight (LoS) measurements at varying angles can be obtained, enabling spatially resolved plasma diagnostics.

2.2 Measurement Principle

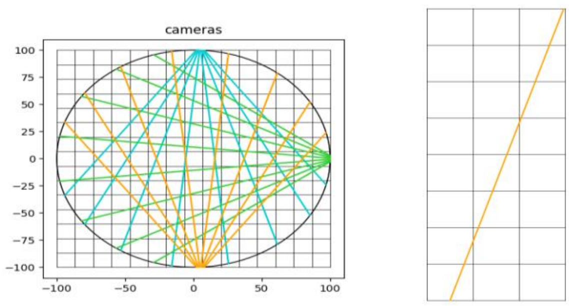

Fig. 3. Measured signals expressed as linear combinations of pixel emissivities.

The use of a sub-millimeter pinhole ensures that light from distinct directions, corresponding to different positions within the plasma, can be selectively collected. Each photodiode in the array captures the line-integrated emission intensity along its own LoS.

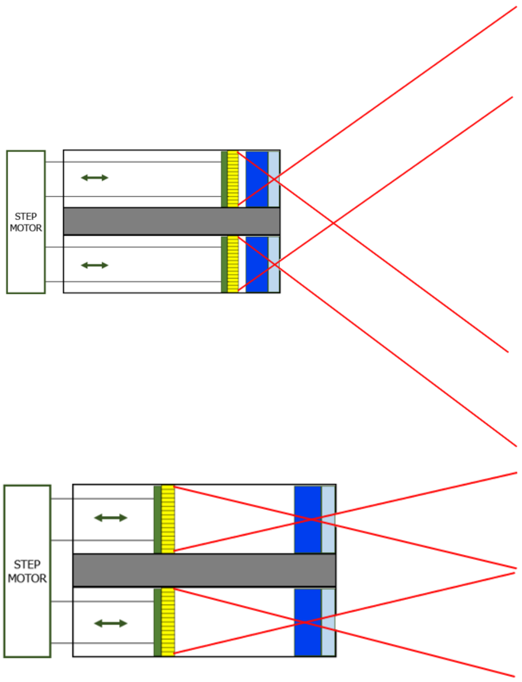

Fig. 4. Illustration of VPPC scanning positions: (1) forward position and (2) backward position.

By mechanically scanning the VPPC position, the number of available LoS measurements increases, thereby enhancing the resolution of tomographic reconstruction, as illustrated in Fig. 4. The figure shows (1) the forward position and (2) the backward position of the VPPC. The measured signals can be formulated as linear combinations of the emissivity values from all pixels along each path.

To solve this inverse problem, we employed a Phillips–Tikhonov regularization approach, which stabilizes the reconstruction by suppressing noise amplification while preserving spatial smoothness. [1] Using this method, the two-dimensional emissivity distribution was estimated on a 31 × 31 pixel grid from 76 LoS signals. Simulation results showed a root-mean-square (RMS) deviation of 10.96% from the ground truth. To further improve accuracy, additional 2D Laplacian and axisymmetric Laplacian constraints were applied, leveraging the inherent axisymmetric geometry of the etch system.

2.3 Simulation Results

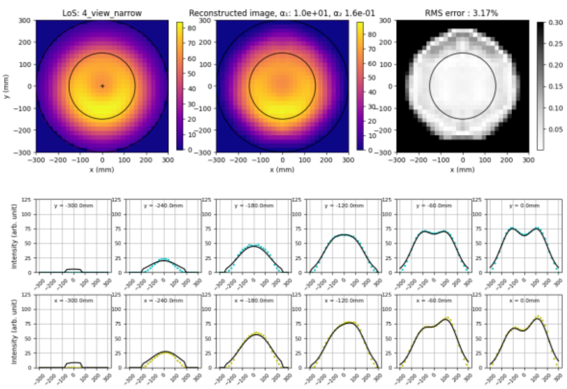

Fig. 4. Phantom test results demonstrating system performance.

A forward simulation was conducted using four viewing angles to emulate the designed VPPC geometry. The first panel presents the synthetic LoS intensity data, while the second shows the reconstructed emissivity distribution obtained with regularization parameters α_1 = 10.0 and α_2 = 0.16. The assumed plasma emission was hollow-shaped, with reduced intensity at the center and stronger emission near the periphery. The third panel illustrates the pixel-wise RMS error, which yielded an overall RMS of 3.17%, indicating high fidelity of the reconstruction. Cross-sectional profiles along the x and y axes further confirmed the accuracy of the method: the reconstructed profiles (dotted lines) were in close agreement with the ground truth (solid lines), validating the VPPC's capability to capture the underlying plasma emissivity distribution with minimal error.

3. Conclusions

In this work, we developed and validated the Variable Position Pinhole Camera (VPPC) as a novel diagnostic tool for tomographic optical emission spectroscopy in plasma etching systems. The proposed method successfully reconstructed two-dimensional emissivity distributions from limited lines-of-sight, achieving an RMS error as low as 3.17% in simulation. These results demonstrate that the VPPC approach can overcome the intrinsic limitations of conventional OES and provide spatially resolved plasma diagnostics with high fidelity. This diagnostic concept offers significant potential for real-time monitoring and control of industrial plasma processes, where chamber ports are highly restricted. A prototype VPPC is currently being fabricated and will be experimentally tested on SEMES Michelan_O5 equipment to further validate its applicability under manufacturing conditions. Future work will focus on optimizing the reconstruction algorithm for real-time operation and extending the technique to multi-wavelength diagnostics for simultaneous monitoring of multiple plasma species.

Acknowledgments

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