Spatially resolvable optical emission spectrometer for analyzing density uniformity of semiconductor process plasma

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We proposed a spatially resolved optical emission spectrometer (SROES) for analyzing the uniformity of plasma density for semiconductor processes. To enhance the spatial resolution of the SROES, we constructed a SROES system using a series of lenses, apertures, and pinholes. We calculated the spatial resolution of the SROES for the variation of pinhole size, and our calculated results were in good agreement with the measured spatial variation of the constructed SROES. The performance of the SROES was also verified by detecting the correlation between the distribution of a fluorine radical in inductively coupled plasma etch process and the etch rate of a SiO2 film on a silicon wafer. © 2010 American Institute of Physics. [doi:10.1063/1.3488104]

I. INTRODUCTION

Plasma processes are widely used in microelectronic device fabrication for deposition, etching, and ashing of thin films. The uniformity of plasma density in the semiconductor manufacturing process is critical to enhancing yield as pattern widths shrink and wafer size increases. Various studies have been undertaken to clarify the correlation between the yield of a plasma process and the spatial distribution of a plasma parameter, such as the radical densities, ion densities, electron temperature, potentials, etc. It has been shown that there is a strong correlation between the radial variation of radical concentration and the yield of a plasma process.

Measurements of the relative spatial distributions of radical densities have been constructed using various optical measurement techniques, such as laser induced fluorescence, optical emission spectroscopy (OES), and absorption spectroscopy. OES, which measures the optical emission of species in the plasma, is the most popular semiconductor plasma process diagnostic technique because of its simplicity, high sensitivity, and wide applicability. In general, however, OES cannot record the spatially resolved measurements by itself, since OES detects the integrated signal along the line-of-sight. Assuming axial symmetry in the plasma density, one often attempts to obtain the spatial distribution of species concentration from the OES signal by taking the Abel inversion. Otherwise, a movable electro-optical probe is inserted into the plasma to directly detect spatial variations in species concentration by collecting the emission of the molecules in front of the probe.

In the present work, we designed an OES that is capable of detecting spatial variations in plasma density, and we constructed this OES with a series of lenses, apertures, and a pinhole as a spatial filter to enhance the spatial resolution. We theoretically verified the spatial resolution capability of the OES, and the results of the calculation were compared with experiments.

II. SPATIALLY RESOLVABLE OPTICAL EMISSION SPECTROMETER

The optical layout of the spatially resolvable optical emission spectrometer (SROES) constructed in the present work is depicted in Fig. 1. The SROES is equipped with three lenses (L1: 40 mm in diameter, and 160 mm focal length, L2, and L3: 12.7 mm in diameter and 20 mm focal length) to image the target plasma that can be assumed to be a volume source, three aperture stops (A1, A2, and A3) to block stray light originating from other sources than the object plane under test, and one pinhole, 50 μm in diameter. The object plane of the SROES can be adjusted by changing the distance between lens L1 and the pinhole. Aperture A1 reduces the stray light of the volume source incident on the pinhole. Aperture A2 adjusts a solid angle of incident beams to maintain a constant emission collection efficiency from the object plane. It calibrates the change of the incident intensity by varying the solid angle with respect to the distance from the light source. A pinhole was installed at the imaging plane to limit the detection area. After the collected light passes through the pinhole, it is delivered to an optical fiber 600 μm in diameter) with image relay optics consisting of two delivering lenses (L2 and L3) and an aperture A3. The aperture A3 is located between the two delivering lenses, limiting any stray light that passes through the pinhole. A spectrometer (Ocean Optics, USB4000) was used to analyze the spectrum of the light that passed through the optical fiber.
III. ANALYSIS OF SPATIAL RESOLUTION OF AN OPTICAL EMISSION SPECTROMETER

A. Calculation of spatial response function of SROES

The spatial resolution of an SROES can be separated into two parts based on the direction of the measurement; the spatial resolution in a lateral direction (x, y-direction in Fig. 1) and that in an axial direction (z-direction in Fig. 1). Process plasma used in semiconductor production equipment can be assumed to be volume sources consisting of multiple atomic radiators. The spatial resolution in a lateral direction can separate the light coming from off of the optical axis of the SROES. Studies for measuring the lateral distribution of certain radical emissions have been performed by some groups to evaluate the plasma density distribution between a cathode and anode within a plasma chamber.\textsuperscript{16}

Since it is well known that OES has the capacity for line of sight detection in a volume source, it is admitted that conventional OES does not have a spatial resolution in axial direction. In the present work, we designed a SROES to provide spatial resolution in the axial direction. When the target position of the SROES is \((x_0, y_0, z_0)\) in the plasma volume source shown in Fig. 1, we can write the spectral distribution of the signal detected by the SROES as

\[
I_S(x_0, y_0, z_0, \lambda) = \frac{c }{2} \int_V \left[ E(x, y, z, \lambda) \right]^2 T(x, y, z, \lambda) S(\lambda) dV,
\]

where \(c\) is the speed of light, \(e_0\) is the vacuum permittivity, and \(V\) is the volume of the plasma. \(E(x, y, z, \lambda)\) is the electric field distribution of the emitted light at the wavelength \(\lambda\) in the volume source, and \(T(x, y, z, \lambda)\) is the optical transfer function determined by the optical system of the SROES. \(S(\lambda)\) is the spectral sensitivity of the detector installed in the SROES.

When we calculated the spatial resolution of the SROES, we assumed that the emission from the plasma source was homogeneous within the volume \(V\). Also, we fixed the wavelength at 632.8 nm to compare the calculated spectral resolution with the experimentally determined spectral resolution of the SROES. We calculated the optical transfer function \(T(x, y, z, \lambda)\) using a commercial ray tracing program (\textsc{code v}, Optical Research Associates, Pasadena). We set all optical design parameters of the SROES to obtain the optical transfer function at each point. After that, we calculated the integrated signal using Eq. (1). The difference of the signal with respect to the distance between a light source and lens L1 could be offset by fixing the solid angle of aperture A2. To evaluate the spatial resolution of the SROES, we calculated the signal generated in an x-y plane at a certain distance from the target position by integrating the signal in the plane.

Figure 2 shows the normalized signal calculated as a function of the axial displacement from the target position. The axial displacement is the distance from the target position. The normalized signal decreases with the absolute value of the axial displacement, reaching a maximum at the target position. The spatial resolution of the SROES in the axial direction can be defined by taking the full width half maximum of the profile of the normalized signal, which was approximately 18 mm.

To verify the calculations, we performed an experiment using a simulated light source, which consisted of a He–Ne laser (632.8 nm), a focusing lens (30 mm of focal length), and a diffuser glass. An He–Ne laser beam was focused by a lens onto the surface of the diffuser glass, generating a Lambertian point source. By placing the diffuser glass at a constant position, we detected signals with the SROES by moving the position of the SROES in an x-y plane and integrating the signals measured in the plane. We obtained the normalized signals integrated in the x-y plane for various axial displacements, which are plotted as the filled squares in Fig. 2. The experimental results were in very good agreement with the calculation. Note that the SROES constructed in this work clearly demonstrated the capability to measure an emission signal from a volume source with spatial resolution in the axial direction (Fig. 2).

Similarly, we evaluated the spatial resolution of the SROES in the vertical direction of the optical axis. Assuming the axial symmetry, we integrated the signal calculated along the vertical direction of the optical axis. We plotted the normalized signal as a function of the lateral displacement from the optical axis in Fig. 3. From the results of the calculation shown in Fig. 3, we got the spatial resolution of the SROES in lateral direction about 140 \(\mu\)m. Note that the calculated spatial resolution matches to size of the pinhole multiplied by the optical magnification of the SROES.

We can easily expect that the pinhole installed in the SROES in Fig. 1 limits the area of plasma source to be detected so that the size of the pinhole may play the most important role in determining the spatial resolution of the SROES. To explore the relationship between the pinhole size and the spatial resolution of the SROES, we calculated the
spatial resolution of the SROES in axial direction (solid line) as a function of the diameter of the pinhole. Figure 4 shows that the spatial resolution of the SROES monotonically increases with the diameter of the pinhole as is expected. We also measured the spatial resolution of the SROES by installing different size pinhole and plotted the results of experiments (filled square) in Fig. 4. The comparison between the results of the calculation and the experiment shows a good agreement. Note that designing rules of pinhole size are considered by taking into account the trade-off between the spatial resolution and the signal of the SROES, since the signal of the SROES depends on the square of the pinhole size.

B. Calculation of calibration factor for the plasma source geometry

Evaluating the spatial response function of the SROES, we confirmed the spatial resolution of the SROES not only theoretically but also experimentally (Fig. 3). However, we have concerns about any systematic error in the SROES due to the geometry of the plasma source under test. In the calculations, we assumed that the density of the plasma was uniform and the geometry of the plasma source was cylindrical, which is popular in semiconductor production. Assuming that the plasma source was 30 cm in diameter and 4 cm thick, we calculate the variation of the signal from the SROES across the center of the plasma source. The normalized signal of the SROES calculated as a function of the displacement from the center of the plasma is plotted in Fig. 5. The difference in the signals of the SROES at the center and the edge of the plasma was \( \sim 15\% \).

To accurately measure the emission intensity from the plasma source, the signal of the SROES needs to be calibrated with the curve in Fig. 5, which shows the normalized signal at various plasma source measurement positions. Moreover, since the curve depends on the geometry of the plasma source, we should calculate this SROES signal calibration curve for a given plasma source geometry. However, we could easily compensate for the systematic error by using an actinometry method17–21 when we detected the optical emission from the radicals in the plasma.

IV. PERFORMANCE TEST OF SROES FOR MEASURING THE INDUCTIVELY COUPLED PLASMA ETCH PROCESS

To evaluate the spatial resolution of the SROES constructed in the present work, we tested its performance by measuring the radial distribution of fluorine radicals in a semiconductor process plasma. The fluorine radical generated by dissociation of \( \text{C}_4\text{F}_8 \) is known as an active radical molecule in the plasma process. An experiment was performed in the processing of an inductively coupled plasma (ICP) etching of a SiO\(_2\) thin film on a 6 inch silicon wafer. The chemical reaction for the SiO\(_2\) thin film etch in the process plasma was described by

\[
\text{C}_4\text{F}_8(\text{g}) + \text{SiO}_2(\text{g}) + \text{O}_2(\text{g}) + \text{Ar} \rightarrow \text{SiF}_4 + 2\text{CO}_2 + 2\text{CF}_2 + \text{Ar}.
\]

In the experiment, we fed \( \text{C}_4\text{F}_8, \text{O}_2, \) and \( \text{Ar} \) gases at flow rates of 45, 5, and 10 (SCCM) (SCCM denotes standard cubic centimeters per minute at STP), respectively. We added \( \text{Ar} \) gas with the reaction gases for an actinometry measurement of the fluorine radical \( \text{F} \), since \( \text{F} \) and \( \text{Ar} \) have similar excitation thresholds with the spectral emission lines of 703.7 and 750.4 nm, respectively. The pressure of the reaction chamber was maintained at 0.8 Pa, and 2000 W of rf power was applied to the plasma source.

The signal from the SROES detecting the emission from a radical \( \text{X} \) under test is written by

\[
\text{X} + \text{Ar} \rightarrow \text{Y} + \text{Ar}.
\]
of the SROES in the direction of the optical axis was in the range of 18–27 mm for pinhole sizes from 15 to 100 μm. We experimentally determined the spatial resolution of the SROES in the direction of the optical axis using a simulated volume source. The results of the measurements were in good agreement with the calculations. Also, the performance of the SROES was verified by detecting the correlation between the distribution of a fluorine radical in an ICP etch process and the etch rate of a SiO$_2$ film on a silicon wafer. The SROES can resolve the small variations in the emission intensity of the radical in the radial direction of the Si-wafer to within ~4%, which is in good agreement with the variation in the etch rate of SiO$_2$ film.

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1. The latest edition of the ITRS can be found at http://public.itrs.net/.

\[ I_r(r) = k_r(T_e)n_e(r)[X(r)], \]  

where \( r \) is the radial coordinate, \( k_r(T_e) \) is the excitation rate of a molecule \( X \) by an electron whose temperature is \( T_e \), \( n_e \) is the electron density, and \([X]\) is the number density of radical \( X \). The density of the fluorine radical is a primary influence on the etch rate in the ICP etching of SiO$_2$ films. By applying the actinometry method, we qualitatively determined the radial distribution of fluorine radicals in the process plasma by taking the ratio \( I_r/I_{Ar} \).

Using the SROES, we measured the densities of the fluorine radicals in the process plasma at several points in the radial direction, and the results are plotted with open squares (□) in Fig. 6. After the plasma process was complete, we detected the etch rate of SiO$_2$ film using an optical ellipsometer, and the results are indicated with open triangles (△) in Fig. 6. Although the variation in the radial direction was only ~4%, we found that the results obtained with two different measurement techniques were in very good agreement.

**V. CONCLUSION**

We constructed an SROES using a series of lenses, apertures, and pinholes to measure the density uniformity of a semiconductor process plasma. We analyzed the spatial resolution of the SROES with a CODE V program not only in the direction of the optical axis but also in the direction perpendicular to the optical axis. The calculated spatial resolution...