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Diagnosis of Spatial Distribution of Electron Temperature and Electron Density of Argon Inductively Coupled Plasma by Tomographic Optical Emission Spectroscopic Measurement

Plasma process essential for large-scale integrated circuits to measure 3D spatial distribution of electron temperature and electron density

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Summary

- **We established a method to diagnose the three-dimensional spatial distributions of electron temperature and electron density in plasma using tomographic optical emission spectroscopic measurement and collisional-radiative model-based analysis.**

- **The correlation between the changes in pressure and power in the reaction chamber and the three-dimensional spatial distributions of electron temperature and electron density in the plasma process has not yet been quantified.**

- **Anomaly detection systems for plasma processes contribute to higher accuracy in plasma simulation.**

A research group led by Mr. Yuya Yamashita (Ph.D. student), Associate Professor Dr. Hiroshi Akatsuka, and colleagues at the Department of Electrical and Electronic Engineering, School of Engineering, Tokyo Institute of Technology, and ULVAC, Inc. successfully performed the world's first quantitative diagnosis of the three-dimensional spatial distributions of electron temperature and electron density in plasma processes using tomographic optical emission spectroscopic measurement and collisional radiation modeling. This study is expected to promote the development of plasma electronics in the future and process development, which will considerably contribute to the improvement of semiconductor processes in the industry.

Detail

Plasma process essential for semiconductor processing

Plasma (*1), also known as the fourth state of matter, is widely used in semiconductor manufacturing and fundamentally supports modern electronics. For example, the plasma process, which is a processing technology using plasma, is indispensable for the ultrafine processing of large-scale integrated circuits in semiconductor chips, which are the fundamental components of smartphones and PCs, and for synthesizing transparent conductive films, which are typically used in solar cells and LCD TVs.

This study contributed to the development of advanced and precise plasma processes. Plasma is widely used for etching (*2) and other processes in integrated circuits. It is necessary to control parameters, such as the power input and pressure in the plasma equipment, to determine the optimal processing conditions. However, the correlation between the amount of power and pressure required and the type of processing that can be achieved has not yet been clarified sufficiently. Therefore, optimizing the processing conditions in the semiconductor process is challenging.

In actual production, test processing is performed by changing the power and pressure of the plasma system in several ways, and the processing conditions are optimized by further evaluating the physical properties, which is an extremely expensive and time-consuming process.

Electrons play an important role in the progress of reactions in the plasma used in semiconductor processing. Electron temperature, which indicates the energy of the electrons, and electron density, which indicates the number of electrons per unit volume, are important indicators to control the plasma. In this study, we established a method for diagnosing the three-dimensional spatial distributions of electron temperature and electron density. We expect this method to optimize the conditions of plasma processing and contribute to yield improvements.

The world’s first diagnosis of the 3D spatial distributions of electron temperature and electron density in plasma

In this study, argon (Ar) plasma was generated using an inductively coupled plasma system, which is an experimental device that simulates a dry etching system. The generated plasma was observed simultaneously through 18 lenses installed in the device, and the spectral radiance (*3) of the optical emission spectrum (*4) was measured (Figure 1). A “spectral tomography calculation” was performed on the spectral radiance for each line-of-sight. From the line-of-sight dependence of the spectral radiance obtained in the experiment, the three-dimensional spatial distribution of the spectral emission coefficient (*5) was calculated based on the lens position relative to the plasma dimensions.

The spectral emission coefficients at each coordinate were analyzed based on the collisional-radiative model, which is a mathematical model of the atomic and molecular processes in plasma (*6). This method achieved the noncontact diagnosis of electron density and electron temperature, which are important indices for plasma control, without disturbing the plasma. Based on this diagnostic method, the relationship between the power and pressure applied to the plasma device and the electron temperature and electron density of the generated plasma (Figure 2) was clarified. This correlation was not apparent before, and we could quantify how the changes in power and pressure affected the electron temperature and electron density in the plasma device.

These results are expected to contribute to the elucidation of the mechanism of plasma processing.

Several previous studies have measured the optical emission spectra of plasma from a single perspective. However, in the current semiconductor process, silicon wafers (*7) are larger in diameter to increase the yield. The reactions occurring at the center and edge of the silicon wafer are different; therefore, an accurate diagnosis cannot be achieved by measurement from a single viewpoint. In addition, although previous studies have used tomography, a technique to calculate the three-dimensional spatial distribution of optical emission spectra and complex atomic and molecular processes has not been studied. Thus, no previous studies have considered atomic and molecular processes in detail or have realized the diagnosis of the 3D spatial distribution of plasma. Therefore, it was not possible to determine the electron temperature and density accurately, which are problems in the plasma process. “We have achieved more reliable diagnostics of electron temperature and electron density by analyzing the results of tomographic spectroscopy measurements based on our long-standing research results on plasma atomic and molecular processes,” said Associate Professor Akatsuka of Tokyo Institute of Technology.

Applications including anomaly detection systems and more accurate plasma simulations

“If this study can be applied as a measurement tool, we can consider an anomaly detection system for plasma processes: in other words, a tool that can detect abnormal reactions by observing during actual processing and eliminating the abnormalities before final processing," Yamashita said.

Furthermore, by conducting “plasma simulation” introducing electron temperature and electron density based on the power and pressure dependence obtained through this study, the company says that it can concretely contribute to cost reduction in the optimization of process conditions depending on conventional repetitive experiments. Dr. Kenta Doi of ULVAC, a joint research partner in this study, said, “The knowledge of electron temperature and electron density, which are direct factors in the optimization of process conditions and process results, will enable process development with more evidence.”

Dr. Doi added, “With regard to abnormality detection, it may become possible to detect signs of abnormality if the system is installed in actual equipment. If we can detect abnormalities, we will be able to operate the equipment more rationally.”

Annotation

*1 **Plasma**: An electrical discharge phenomenon that occurs in gas. When an electric discharge is generated in a gas, electrons are separated from atoms and molecules owing to the electrical energy. Consequently, three types of particles (electrons, positive ions, and atoms/molecules) coexist in the plasma. In an ordinary gas that is not plasma, only atoms and molecules exist.
*2 **Etching**: A semiconductor manufacturing process. In semiconductors, circuits are formed by transferring a circuit pattern onto a thin film of a substrate. Etching is used to remove thin films from unnecessary parts. Plasma has been used for dry etching.
*3 **Spectral radiance**: The dependence (spectrum) of the intensity and wavelength of the light emitted from a window is expressed as a physical quantity per window area and light spread angle. This value was obtained by adding the spectral emission coefficients of the plasma in the line of sight of the lens.
*4 **Optical emission spectrum**: The wavelength and intensity of light emitted when an atom or molecule transitions from a higher-energy state to a lower-energy state: The energy state of an atom or molecule can be quantitatively determined by analyzing its emission spectrum.
*5 **Spectral emission coefficient**: The intensity and wavelength dependence (spectrum) of light emitted by the plasma are expressed as a physical quantity per volume of plasma and light spread angle. As plasma has a three-dimensional spread, the spectral emission coefficient is position-dependent.
*6 **Atomic and molecular processes**: Reactions in which electrons, positive ions, atoms, and molecules collide. In the plasma, energy is exchanged through these collisions, leading to the reactions used in processing.
*7 **Silicon wafers**: Circular plate cut from high-purity silicon. It is also used as a substrate for semiconductors. Circuit patterns were formed on silicon wafers during the manufacturing process.

Figures

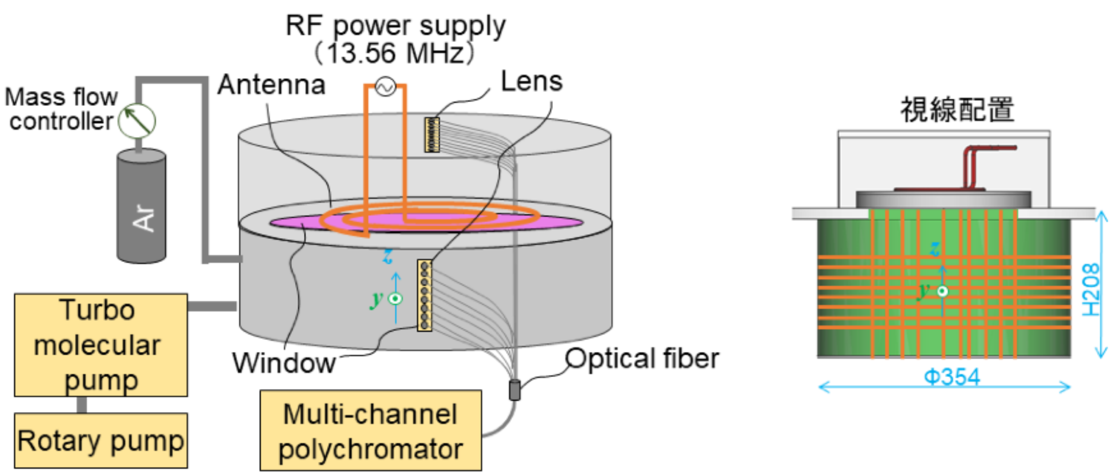

Figure 1 Plasma generated by an inductively coupled plasma system (left) observed using a “multichannel spectrograph” through 18 lenses (right) installed on the sides and top of the system. The line-of-sight dependence of the spectral radiance for each line of sight was measured.

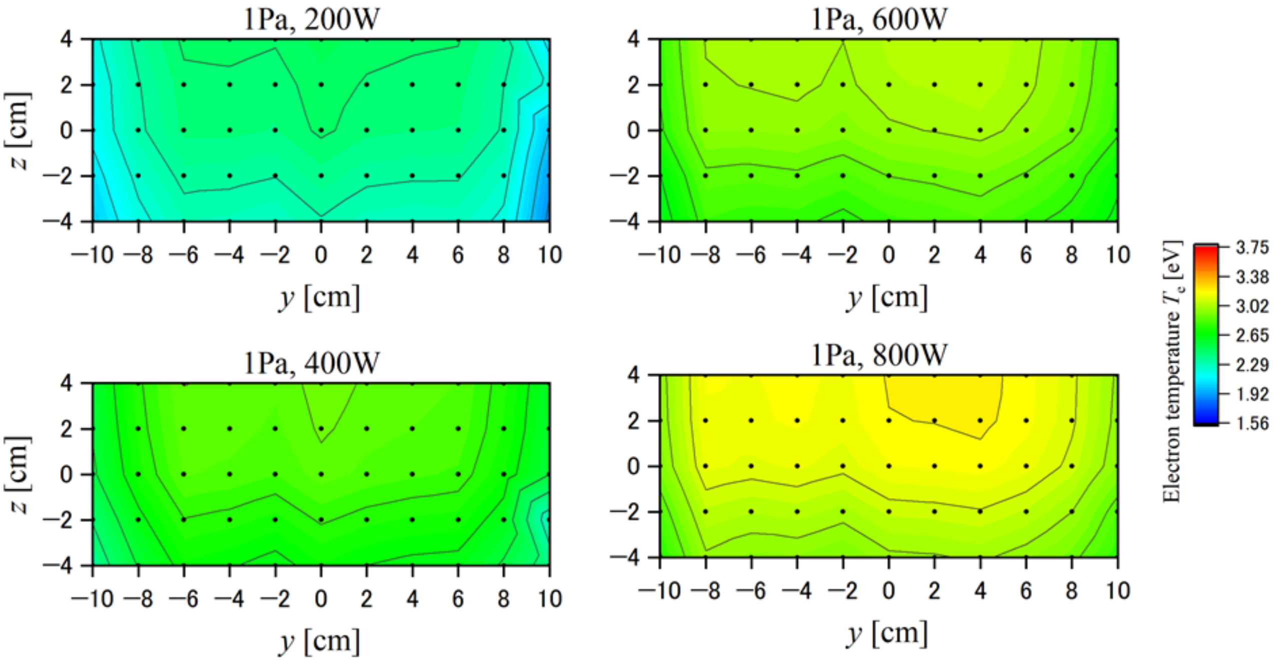

Figure 2 Diagnostic results of the power dependence of the spatial distribution of electron temperature. The electron temperature increased with increasing power. This may be due to the increase in drift velocity caused by the increase in induced electromagnetic field strength. In addition, the electron temperature showed an asymmetric distribution along the y-axis. This may be due to the antenna geometry.