Development of substrate temperature monitoring system for high-accuracy plasma process

高精度半導体プラズマプロセスのための基板温度計測システムの開発

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Atomic scale deposition and etching processes are necessary technologies for the fabrication of nanoscale devices because atomic layer etching and atomic layer deposition are expected to allow the continuous improvement of manufacturing processes, since these result in a more precise process. To achieve the atomic level plasma process, the wafer temperature is considered to be one of the most important disturbances. However, there is no useful method to monitor the wafer temperature during plasma process. We developed a noncontact wafer temperature measurement technique using optical interferometry. The robustness of performance against disturbances has been markedly improved. In particular, the measurement technique has a large tolerance to disturbances due to dispersion and changes in the polarization of the signal light. This technique is a robust and practically useful tool.

原子層堆積，原子層エッチングの研究の盛り上がりは，半導体デバイス製造プロセスに求められる加工精度が原子スケールに到達したことが背景にある。原子スケールの加工精度にはプラズマプロセス中のモニタリング技術は必要不可欠である。しかし，プラズマプロセス中の基板温度を高精度にモニタリングする有効な手法はなかった。我々は高精度かつ高速で振動に強い耐性を持つ基板温度計測システムの開発に成功した。将来，製造現場では歩留り向上のため機械学習の導入はさらに進み，その発展を支えるモニタリン技術の一つとして本計測システムの活躍が期待できる。

Introduction

Semiconductor devices such as Ultra Large Scale Integration have continued the integration and miniaturization. The plasma process accuracy for manufacture has reached atomic scale. This background is one of the factors for studies related to atomic layer deposition and atomic layer etching to be carried out vigorously. This makes many researchers and companies attracted to atomic layer deposition and etching process. The control of atomic-scale etched profiles in plasma process is required to understand chemical reaction between atomics in plasma and surface. For plasma etching process, as shown in Figure 1, the organic film used as low-k material induced the bowing change of 1 nm by temperature change of 0.6°C during plasma etching process.[1] The temperature dependence of etched profile is because the surface temperature strongly influences the reaction rate between plasma and

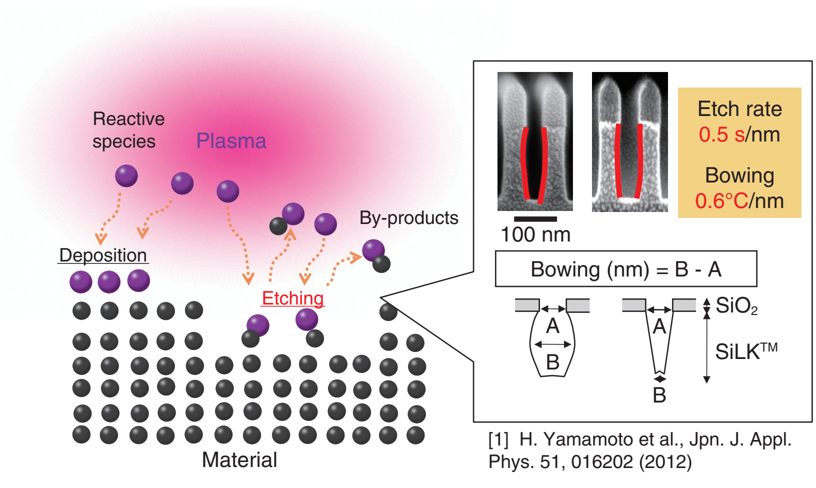

Figure 1 process time and wafer temperature accuracies required for atomic-scale process control.

surface, the sticking coefficient of by-products on surface. In according to this temperature dependence of etched profiles, we need to achieve reproducibility of wafer temperature within 1°C during plasma process. However, the parts inside a process chamber such as the electrode, focus ring, susceptor of reactor are exhausted. The exhausted parts are why the heat balance at the wafer vary slightly. Even if the heat flux from the plasma keep constant, changing in the coolant coefficient of the wafer disturb reproducibility of wafer temperature during the process. Moreover, improvement of temperature uniformity over the wafer is one of key factors to increase the production yield. The temperature monitoring system is required to develop the process characteristics.

Several Techniques for Wafer Temperature Monitoring

Although the temperature is known to be an important factor for plasma etching processes, many complications make it difficult to monitor the wafer temperature during plasma processes with high accuracy. Table 1 shows issues of several temperature monitoring techniques for application for plasma etching process. Conventionally, the thermocouples and fluorescence thermometer with contact-type temperature sensors need to come in contact with the specimen, e.g., the wafer surface at the bottom of the substrate. The thermal conductance between the wafer and the probe tends to affect measurements. Particularly at low pressures, poor contact often results in erroneous measurements, that is, it is difficult to measure substrate temperature with high accuracy.[2] Noncontact methods enable a more accurate substrate temperature measurement. The use of a pyrometer makes it difficult to measure the temperature of semiconductor substrates such as silicon, because the thermal radiation depends on temperature and its variation is too small to detect especially at temperatures below 600°C.[3] Many methods of measuring substrate temperature during plasma processing have been proposed. Other noncontact methods using an optical interferometer with an infrared laser were proposed.[4-6] These noncontact optical techniques determine temperature changes from the thermal expansion and refractive index changes of a transparent substrate of known thickness. However, there remain difficulties such as their poor tolerance to mechanical disturbances, resulting in limited resolution and temperature ranges when monitoring silicon wafers. Our research

Table 1 Issues of several temperature monitoring systems for application to plasma etching process

Method	Issue
Thermocouples (Contact-type)	· Erroneous and low response measurement due to poor thermal conductance.[2] · Electrical noise by electromagnetic wave supplied. · Dielectric breakdown.
Fluorescence thermometer (Contact-type)	· Erroneous and low response measurement due to poor thermal conductance.[2] · Dielectric breakdown.
Infrared radiation thermometer (Noncontact-type)	· Infrared radiation from plasma. · limited temperature range.[3]

group worked on development of monitoring system with high accuracy and response during plasma etching process.

Development of Temperature Monitoring System by Conventional Optical Interferometer

At the beginning of the research, we consider application of the conventional optical interferometer shown in bottom left of Figure 2. The measurement system is based on a Michelson interferometer, which consists of a super luminescent diode (SLD), a reference mirror scanner, a fiber collimator, an optical fiber and so on. The SLD light is divided into two beams by the fiber coupler. The signal light irradiates the substrate. The reference light goes to a scanning reference mirror. In the substrate, the SLD light is reflected on the substrate backside and surface. In the reference mirror scanner side, the reference-optical-path length is changed because the mirror is moved. The lights reflected at the substrate go back to the fiber coupler through the fiber collimator, and then interfered with the light reflected at the scanning reference mirror within the range of coherence length. The position of interferogram was changed by the thermal expansion and the change of refractive index with increasing the substrate temperature. The change of temperature was

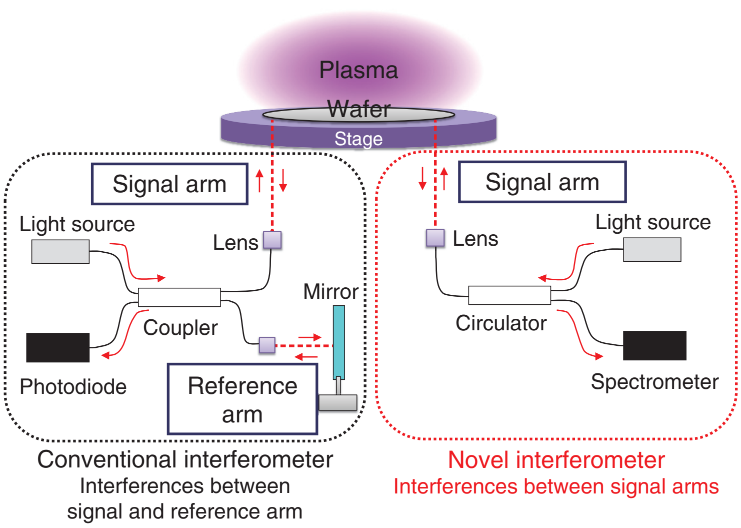

Figure 2 Optical interferometer for wafer temperature monitoring system

measured by the shift of the peak position of interferogram. By using this measurement system, we can measure the substrate temperature in the real time.[7] The system resolved issues of size, working temperature range. The time resolution was, however, limited to the second time scale because the system uses a mechanically scanned mirror to obtain an interferogram for the substrate temperature. The use of a dual path interferometer has low robustness against fiber-induced dispersion, polarization mismatch, and polarization changes due to mechanical vibration. Therefore, vibrational noise during scanning affects optical stability, leading to low accuracy of temperature measurement. Rapid measurement compared with typical vibrational periods is required in building a robust system and improving the accuracy for applications for semiconductor materials.

Development of Novel Temperature Monitoring System

For actual plasma etching process, the previous method has two issues,

i) low robustness against mechanical vibration because of dual path interferometer,

ii) measurement speed of a few seconds due to scanning.

We focus on characteristics of semiconductor wafer to solve these issues. For novel method, a temperature monitoring system using a frequency-domain optical interferometer without a reference mirror has been developed. The method can potentially measure substrate temperatures in a few milliseconds. For previous method, interferograms are generated in the time-domain from interferences between the reflections from the front and back surfaces of the substrate and the reference mirror when light from light source irradiates a wafer. If the interference signal is collected using a spectrometer, the interference is acquired in the frequency-domain. Since Fourier detection measures all of the lights reflected on the top and bottom surface of the wafer simultaneously, an inverse Fourier transform of the spectral interferogram determines all of the time-domain interferograms. The time interval between interferograms is used to derive the optical path length of the sample. As process accuracy reach atomic scale, both side of the wafer, are performed mirror polishing, have high degree of parallelism. In according to the characteristics, we attempt to make the wafer surface play the role of mirror. Therefore, the high parallelism of the semiconductor wafer enables the removal of a reference mirror from the interferometer and measure wafer temperature with a common path interferometer. The standard deviation of temperature measurement was less than 0.04 °C. The performance has been improved. Moreover, we have confirmed that the novel method can successfully reduce noise arising from mechanical vibrations, fiber-induced dispersion, and polarization mismatch.[8, 9] This technique is a robust and practically useful tool for measuring wafer temperature during plasma etching process.

Apllication of Novel Temperature Monitoring System

Here, we briefly introduce several examples of applications. Using the high-precision and rapid-response temperature monitoring system, the heat balance in the wafer for an industrially applied chamber can be modeled on the basis of the measured temporal change in wafer temperature. In according to the model built by analyzing the temporal wafer temperature during plasma etching processes, the actual temporal changes were found to be affected by the heat influx from the outer focus ring surrounding the Si wafer because the focus ring become higher temperature than the wafer. From the results, we expected that the heat flux from the focus ring FR to the wafer temperature would be negligibly small within a few seconds after plasma exposure. However, the effect of higher temperature of the focus ring on the radial distribution of wafer temperature increases with process time. To realize uniform process characteristics over the wafer, the temperature difference between the Focus ring and the wafer should be considered.[10] It is found that this method is effective for evaluating uniformity of temperature distribution along radial direction, and it is useful system for reducing time and cost in process development and device manufacturing.

Process engineers are faced with many complicated phenomena occurring during plasma processes. One is that wafer temperature is not dynamically controlled by stage temperature because the wafer temperature rises rapidly from the initial temperature after plasma exposure begins. (Figure 3) In plasma processes, the wafer and wall temperature rise modifies the radical densities of gaseous chemical species. The recombination rates of the positive ions and atoms at the surface depend on temperature. To achieve a precise control in plasma processes, the wafer temperature must be controlled on the basis of accurate measurements. We developed a feedback control system based on actual temperature monitoring in real time by dynamical changes in plasma discharge on-off intervals to suppress variation of wafer temperature during process within a few degree C. When applied a water temperature feedback control system to low-k organic film etching, it was found that etched trench width increased by 2.5 Å/K. The results indicated that the feedback control system can potentially control etched profiles on atomic-scale.[11, 12] The wafer temperature strongly influences etched features due to the temperature dependence of sticking probability

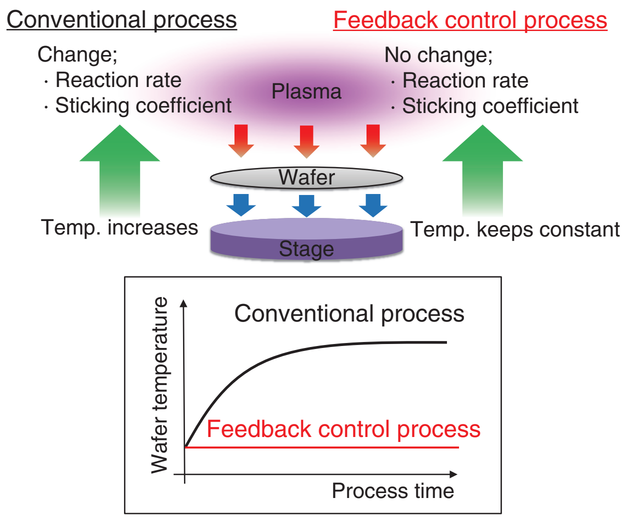

Figure 3 Schematic illustration of plasma process with feedback temperature control.

of the etched products. Therefore, keeping the wafer temperature constant is effective for clarifying interactions between the plasma, material surface, and the etched feature formation mechanisms.

Conclusion

Etched profiles control with high accuracy can be achieved by controlling the wafer temperature dynamically. Moreover, our monitoring system can be applied not only to the plasma etching process but also to many semiconductor device manufacturing processes such as a rapid thermal annealing process and chemical vapor deposition. Recently, AI technology has applied to the semiconductor device manufacturing site to improve productivity. In order to improve the accuracy of machine learning, real-time monitoring techniques would play an important role. We can expect that our monitoring system active in various fields in the near future.

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