Development of a Laser Gas Analyzer for Semiconductor Etching Process using IRLAM Technology

SAKAGUCHI Yuhei
HADA Miyako

In the semiconductor manufacturing process, dry etching technology is utilized for making nm-order microstructures. Sensing technologies for real-time process monitoring is important for precise process control in advanced etching processes. HORIBA has developed an infrared laser absorption modulation (IRLAM) using a quantum cascade laser (QCL). Taking advantage of IRLAM's high sensitivity and fast response performance, we have developed a gas analyzer which optimized for etching processes. In this paper, we introduce the configuration of the analyzer and evaluation results of actual etching process.

Key words
Infrared absorption spectroscopy, Quantum cascade laser, Semiconductor etching process, gas analysis

Introduction

Semiconductor devices have become highly integrated and complexed microstructures in the past few years[1]. There has also been an increase in the level of dimensional accuracy that must be under control. Dry etching technology is used for the formation of nm-order microstructures in transistor gate electrodes and contact holes[2].

To control the etching process in real-time, optical emission spectroscopy (OES) has been used at plasma etching tool. It is widely utilized in various stages from research and development to mass production[3]. However, there are some cases in advanced etching processes where it is difficult to control by OES technology because sufficient signals cannot be obtained due to small open area and high aspect ratio. In addition, OES cannot apply to chemical dry etching processes because they do not use plasma. There is demand for new sensing technology that can be applied to such advanced processes.

Infrared spectroscopy is one of analytical technologies which HORIBA has applied in various industrial fields including automotive, scientific, environmental, and semiconductor industries for long time. Fourier transform infrared spectroscopy (FTIR) is the techniques which can obtain wide range infrared spectrum. Infrared light from high-temperature light source passes through an interferometer and an interferogram is generated. The interferogram is converted to the spectrum by Fourier transform.

Another technique, called nondispersive infrared spectroscopy (NDIR), uses an optical filter to extract a portion of the wavelength of light from the light source[4]. This technique is simpler than FTIR and it enables to make a compact analyzer with simpler configuration.

Gas analyzers based on FTIR and NDIR have long history of more than half a century and are well established for process monitoring and control, however, technical challenges against limit of sensitivity and response time are needed in semiconductor process applications.

The infrared laser absorption modulation method (IRLAM), a newly developed gas analysis technique by HORIBA, enables high-speed measurement with high sensitivity. We have used this IRLAM technology to develop a gas analyzer optimized for semiconductor etching process applications. The basic principle of IRLAM and the details of the developed analyzer for semiconductor applications are described. Then the effectiveness of this analyzer is shown from the evaluation in real etching processes.

IRLAM Principle and Configuration

Each gas molecule has a specific energy level depending on its structure. When gas molecules interact with light, they absorb light in specific wavelength. The relationship between the intensity of incident light I_0 and transmitted light I through the material is called Beer-Lambert Law.

$$A = -\log\frac{I}{I_0} = \varepsilon Cl$$

The absorbance A is proportional to the concentration C and the absorbance coefficient ε of the material and the sample thickness l. Quantification by absorption spectroscopy such as NDIR, FTIR and IRLAM utilizes on this principle.

IRLAM uses a quantum cascade laser (QCL) as a light source that emits light in the mid-infrared region. HORIBA has established the technology to design and manufacture QCLs in-house and can prepare the optimum QCL for each gas to be measured.

The laser beam emitted from the QCL enters the gas cell and is multiply reflected between two mirrors installed in the gas cell, thereby obtaining long optical path length. Longer pathlength enables higher sensitivity as indicated by Beer-Lambert Law.

IRLAM uses a gas cell with two concave mirrors, the configuration is known as a Herriot cell. Narrow and thin original mirrors are specially designed. This design simultaneously achieves long path length and small cell volumes. This has resulted in improved sensitivity and response time, as well as smaller analyzer size.

IRLAM applies a unique calculation algorithm to extract "features" from the measured gas absorption signal. The details are explained in another paper[5]. This method makes it possible to correct for the effects of interfering gases, QCL oscillation wavelength drift, and spectral broadening caused by pressure and coexisting gases. The calculations can be performed by an embedded microprocessor, which contributes for a compact device configuration.

IRLAM Product for Semiconductors

Figure 1 shows the appearance of the LG-100 series which is newly developed laser gas analyzer. The sensor unit size is 440(W)x170(D)x150(H) mm, and the communication converter box is 80(W)x92(D)x87(H) mm. The measurement gas is SiF_4 that is a major byproduct of the semiconductor etching process.

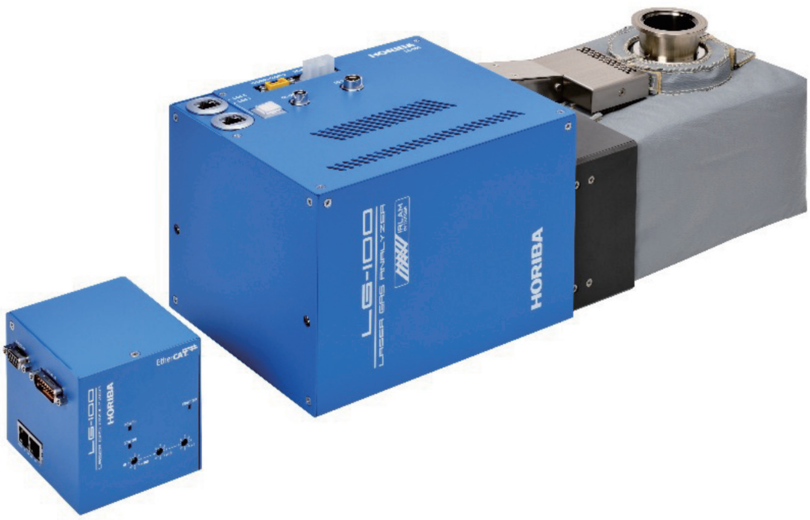

Figure 1 Photograph of the laser gas analyzer, LG-100.

The schematic diagram of the analyzer and the overview of the optical system are shown in **Figure 2**. The sensor unit has NW40 flanges of the gas inlet and outlet for easy installation to the piping of semiconductor etching tool. The gas cell can be heated up to 180ºC, and the built-in heaters are optimally positioned to ensure uniform temperature distribution, preventing the formation of cold spots. The optical system between the laser source, gas cell, and detector is arranged in compact size.

In gas measurement, the total pressure in the gas cell is also an important information. Capacitance diaphragm vacuum gauges are widely used for pressure measurement in semiconductor manufacturing equipment. HORIBA has developed own capacitance diaphragm vacuum gauges[6]. Pressure range of HORIBA's vacuum gauges (VG series) are from 1 Torr to 1,000 Torr and it can be used up to 200°C. For the etching process, the chamber pressure is typically several mTorr, and the exhaust line pressure is less than 1 Torr. The analyzer has vacuum gauge designed to be built into the gas cell taking advantage of in-house technology.

Regarding communications, EtherCAT® has been increasingly adopted in recent semiconductor manufacturing equipment due to its real-time communication performance, so the analyzer support EtherCAT® communication. The communication converter box has EtherCAT® and analog input/output interfaces for easy integration into the equipment.

Performance

Table 1 shows the main specifications of the analyzer. The output of the analyzer is the partial pressure value of SiF$_4$ and its full scale is 10 mTorr. Repeatability, linearity and zero noise (3σ) are less than ±1% F.S..

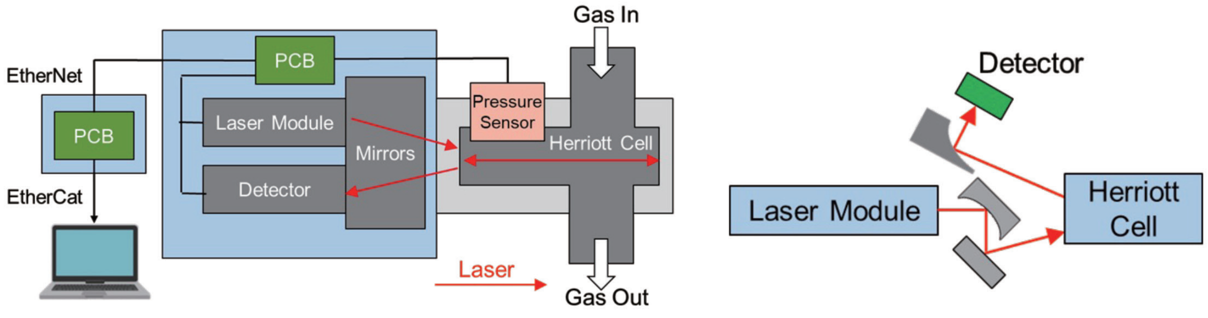

Figure 2 Schematic diagram of the Laser gas analyzer (left) and optical system (right).

Table 1 Typical specifications of LG-100.

Principle	Infrared laser absorption modulation
Cell temperature control temperature	180°C
Measured gas and full scale	Measurement gas: SiF$_4$ Full scale: 10 mTorr
Repetitiveness	±1%F.S.
Linearity	±1%F.S.
Zero noise	Less than 1%F.S. (3σ)
Zero drift	±1%F.S./8 h
Ambient temperature range	20 to 50°C
Pressure sensor measuring range	1 Torr
Pressure sensor accuracy	±1%F.S.
Warm-up time	More than 120 min.
Leak rate	1 x 10^{-6} Pa-m^3 /s (He)
Pressure-resistant	200 kPa(A)

Figure 3 shows SiF_4 gas measurement result. Partial pressure was changed from 0%F.S. to 100% F.S.by dilution known concentration SiF_4 gas with N_2. **Figure 4** shows the measurement result of noise at zero and its stability over 8 hours. The repeatability and linearity were within ±1%F.S., and the noise was approximately 0.2%F.S., indicating a good signal-to-noise ratio.

Example of Application to Etching Application

The analyzer was installed in semiconductor etching tool which is inductively coupled plasma type and evaluated in etching process. **Figure 5** shows the experimental configuration. The analyzer was installed in the foreline between the turbo molecular pump and the dry pump.

The sample wafers were a SiO_2 deposited on a 4-inch Si wafer. The change of partial pressure of SiF_4 generated in etching was measured with the analyzer.

Three samples were prepared with different open area ratios and patterned mask as shown in **Figure 6**. Sample (a) is an unmasked sample with an open area ratio of 100%. Samples (b) and (c) are masked with an open area ratio of 5%. Sample (b) and (c) have the same open area ratio but different mask patterns, (b) has a square shape and (c) has a rectangular along to the diameter. The typical etching conditions for these experiments were as follows: chamber pressure 1.0 Pa, C_4F_8 30 sccm*, O_2 20 sccm*, the ICP power was 500 W, and the bias was 30 W.

*sccm: standard cubic centimeter per minute

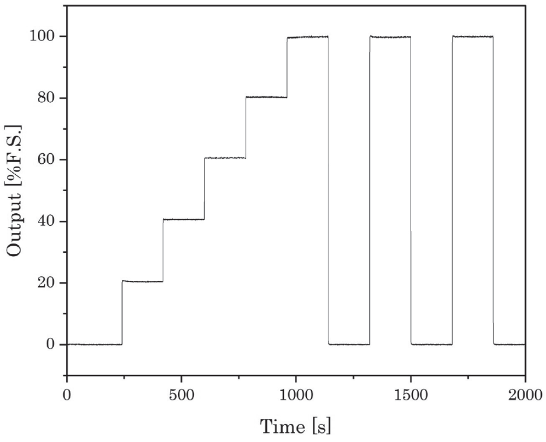

Figure 3 Measurement result of SiF_4 gas.

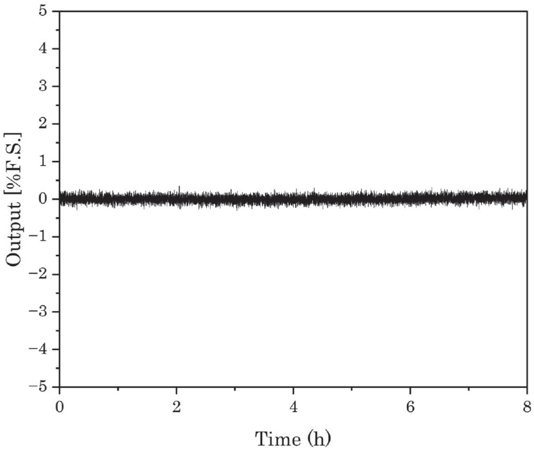

Figure 4 Zero noise and stability.

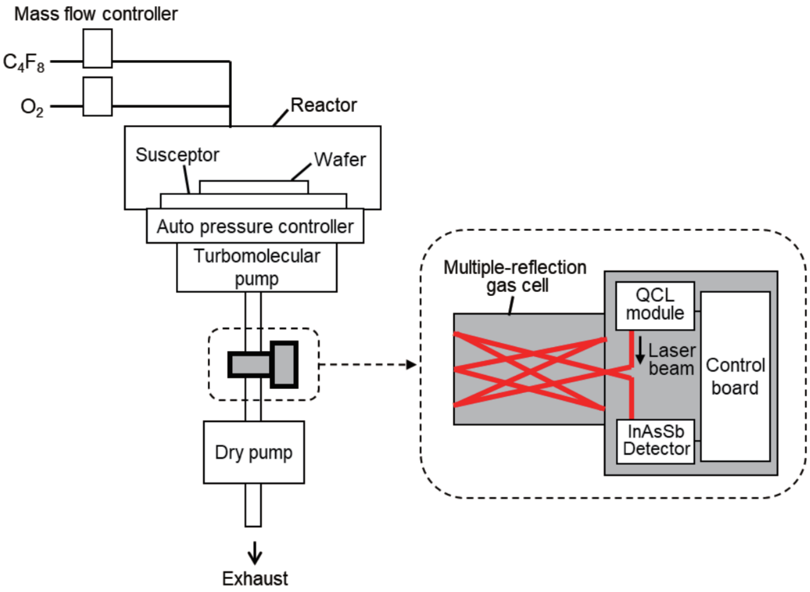

Figure 5 Schematic diagram of the etching tool with the laser gas analyzer.

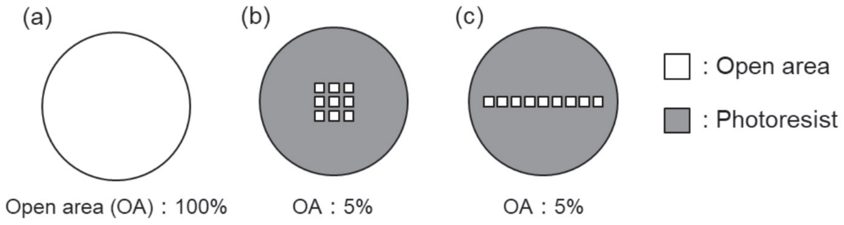

Figure 6 Schematic diagram of SiO_2 samples. Each open area ratio is 100% (a), 5% (b)/(c). There are two types of samples of 5% open area with different open area arguments, square type (b) and rectangular type (c).

Figure 7 shows the measurement results from 1min etching of unmasked sample using bias power in the range of 30 -180 W. It was observed that the partial pressure of SiF_4 increased as the bias power increased. This is a reasonable result because the higher the bias power, the higher the incident energy of plasma ions and the etching amount. When the plasma stopped, the partial pressure of SiF_4 also decreased at the same time, and it was confirmed that there was not significant delay even if the measurement location was foreline. **Figure 7(b)** shows the relationship between the etch rate of SiO_2 and the partial pressure of SiF_4 at each bias power. This plot demonstrates highly linear correlation with a determination coefficient (R^2) of 0.999. This result suggests that the SiO_2 etch rate can be estimated in real time by measuring the partial pressure of SiF_4 .

Figure 8 shows the results of etching the samples shown in **Figure 6(b) and (c)** under the standard condition of 30 W bias power. After the etching process started, the partial pressure of SiF_4 started to change at 222 and 231 s respectively, and the change converged at 242 and 297 s. This is caused by the higher etch rate of Si than that of SiO_2, and the convergence of the partial pressure change indicates the point of complete switchover to Si and the end point of etching. In addition, differences in the behavior of SiF_4 were observed depending on the mask pattern. The differences include variations due to chamber conditions, but the main factor is thought to be caused by differences in the shape of the mask pattern. From these results, it was found that not only the etching endpoint can be detected by measuring the SiF_4 partial pressure change, but also the difference in SiF_4 partial pressure behavior due to the difference in mask patterns can be observed.

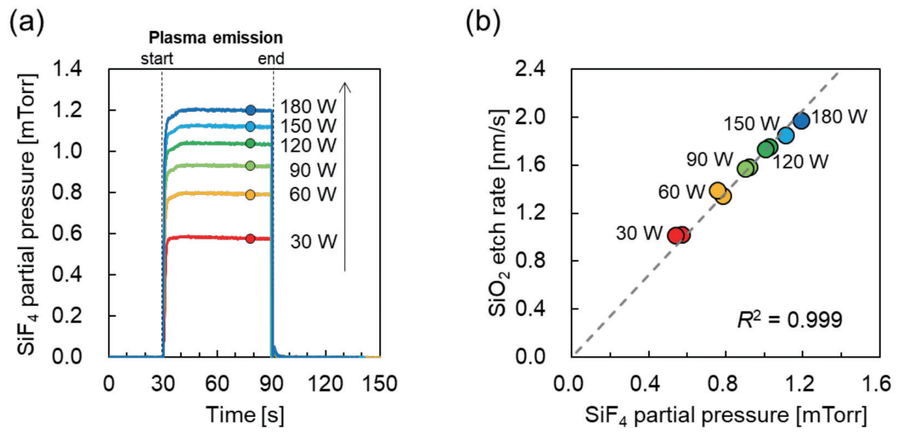

Figure 7 Measurement of SiO_2 etching with bias power in the range of 30–180 W for 1 min using the sample of 100% open area: trend of SiF_4 partial pressure (a). Correlation between SiF_4 partial pressure and SiO_2 etch rate (b).

Conclusion

The gas analyzer based on IRLAM technology for semiconductor application is newly developed. This analyzer (LG-100) has high sensitivity and can detect partial pressure change of the byproduct in the foreline of the etching tool. This information is useful to understand the state of the process.

In recent years, AI technology and machine learning are developing and progressing, and semiconductor manufacturing equipment is also being researched toward autonomous control by utilizing these technologies.

To control complex processes, many data are collected and try to find meaning of these data through multivariate analysis, etc. If the essential data that is directly related to the process state can be obtained, the more precise control is expected. We expect that the measurement data using this analyzer will provide new information that can be used for real-time monitoring and control of the process, and it will contribute to improving the efficiency and yield of the semiconductor manufacturing process.

* Editorial note: This content is based on HORIBA's investigation at the year of issue unless otherwise stated.

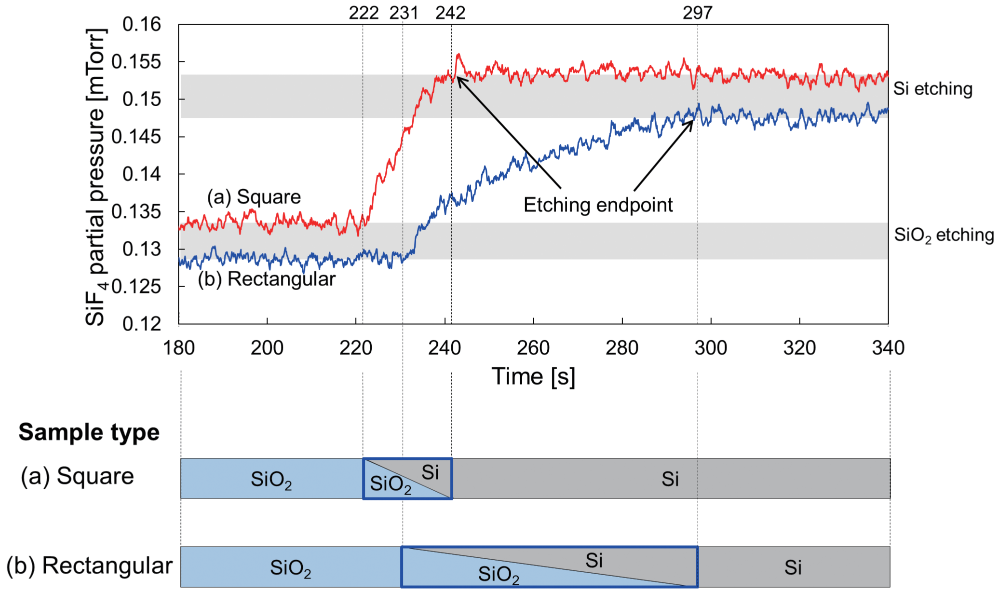

Figure 8 Trend of SiF_4 partial pressure and schematic diagram of etched layer transition during etching with the samples of 5% open area: square type (a) and rectangular type (b).

References

[1] Xiaoyue Wang et al.: Three-dimensional transistors and integration based on low-dimensional materials for the post-Moore’s law era, *Materials Today*, Vol 63, 170 (2023)

[2] Tetsuya Tatsumi: Plasma control technology in semiconductor device processing, Applied Physics, Vol. 85, No. 9, 761 (2016)

[3] Yutaka Iida: Practical Example of Plasmas Emission Analysis Endpoint Detection Monitor EV140C in Semiconductor Manufacturing Process, Readout, vol.35, 62 (2009)

[4] Kozo Ishida: Development of Infrared Gas Analyzer, Readout, vol.32, 65 (2006)

[5] Kyoji Shibuya: Development of gas analysis technology "IRLAM" using quantum cascade lasers and an original concentration calculation method, Readout, vol.57, 55 (2023)

[6] Sotaro Kishida: Development of VG-500 Series Capacitive Diaphragm Vacuum Gauges for High Temperature, e-Readout-004-2 (2021)

SAKAGUCHI Yuhei

Manager
Development Dept.3,
Research & Development Division,
HORIBA STEC,CO., Ltd.

HADA Miyako

Assistant section leader,
Gas Analysis team1, Development Dept.3,
Research & Development Division,
HORIBA STEC,CO., Ltd.