Application Note

Optical Gas Analyzers in Modern Semiconductor Manufacturing

OVERVIEW

As the semiconductor technology process node advances into the sub 10nm (nanometer) range, semiconductor device and chip manufacturers require more sophisticated control of semiconductor processes for higher productivity and better chip yield results. One of the challenges chip manufacturers face is controlling the quality and consistency of the wafer film thickness. In order to control the quality of the thin films in situ or in-line, optical gas analyzers can be utilized as an effective solution. This application note discusses MKS' optical analysis solutions using a TFS™ analyzer, which involves a spectroscopy technique involving tunable filters, for several semiconductor manufacturing applications such as precursor concentration monitoring in a vapor phase delivery system, etch process, endpoint detection, chamber clean endpoint detection, and gas blending control. These solutions are applicable to ALD, CVD, PVD, ALE and MOCVD processes.

PROBLEM

In advanced semiconductor manufacturing, semiconductor chip manufacturers are challenged to achieve tighter control of wafer processing for chip fabrication to increase productivity and yield. To help achieve these requirements, real-time control systems are employed in some of the critical processes. By optimizing and controlling the process parameters, consistencies between chambers, wafers and runs can be achieved yielding predictable and repeatable results.

A one-of-a-kind gas sensing technology platform, the TFS analyzer from MKS offers monitoring solutions in several chip fabrication applications that meet both technical and economical requirements in high-volume chip manufacturing environments.

For example, in ALD application, it is desirable to monitor the quantity or partial pressure of pulsed precursor gases being delivered into the deposition chamber. TFS analyzers are considered to be a superior alternative to other optics-based sensors, providing high quantitative accuracy and fast response—two critical technical attributes required for this application. A TFS analyzer has also been commercially deployed in a CVD chamber clean monitoring application, where it offers higher endpoint detection reliability and repeatability than the traditional NDIR-based detector.

This application note describes the MKS TFS analyzer and its benefits and presents several applications in semiconductor chip manufacturing.

BACKGROUND

Gas Analysis Techniques:
Tunable Filter Spectroscopy Analyzers

Sensors based on non-dispersive infrared (NDIR) spectroscopy are widely used in the semiconductor processing and other industries. NDIR-based systems use optical filters to measure one or a few discrete wavelengths to measure the concentration of the sample gas through the absorption intensity and response at those wavelengths [1, 2]. Figure 1 shows the concept of an NDIR-based sensor. In some implementations, multiple filters are mounted on a filter wheel. The filter wheel rotates to put the different filters into the optical path allowing the system to collect readings for several wavelengths. While NDIR sensors provide an inexpensive solution for real-time process monitoring, their limitations mean they are not optimized for demanding applications such as those requiring multi-component analysis or highly selective measurements where the spectral response of multiple gases may overlap.

MKS TFS analyzers advance the traditional NDIR technology to enable high-performance applications while maintaining the simplicity of classical NDIR systems [3]. TFS analyzers use a tunable Fabry-Perot assembly that enables high-throughput and high-precision wavelength scanning in preselected region(s). Through a miniature rotating filter element, one or more wavelength bands are scanned in a continuous manner such that the true spectral features are obtained. This allows for wavelength scanning, capturing the spectra of the

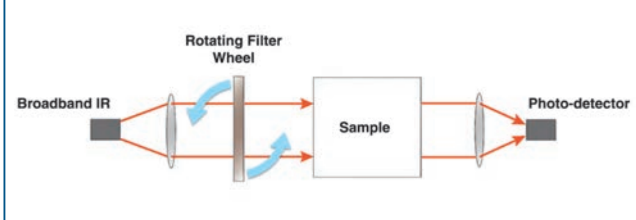

Figure 1 - Basic diagram of NDIR showing its major components

chemistries being monitored, as opposed to the single intensity response of an NDIR. Figure 2 shows the concept of spectrum generation using a tunable filter spectroscopy based system.

Another benefit of this platform is that multiple, independent spectral ranges can be scanned by including additional filter elements. For example, a TFS analyzer widely used in the natural gas processing and distribution industry uses two filters, one to scan the spectral range containing features due to hydrocarbon vibrations, and a second filter to capture a spectral range where CO_2 and H_2O peaks occur. In comparison to a full range NDIR or FTIR analyzer that scans over thousands of wavenumbers or nanometers, the TFS analyzer allows you to scan over discrete ranges, often 200-500 nm wide. Collecting a spectrum over these ranges, as opposed to a discrete point using traditional NDIR systems, allows you to apply advanced chemometric modeling techniques such as Partial Least Squares Regression techniques and spectral processing techniques such as derivatives to optimize the accuracy and repeatability of the critical analyses.

Figure 3 shows an example of how a TFS analyzer can be configured. In this example, the full infrared range spectra, collected using the MKS MultiGas™ 2030 analyzer, of gases present in the process are shown. The two regions highlighted show features for three gases of interest. A TFS analyzer can be configured to scan the two highlighted spectral ranges enabling measurement of three gas species. MKS TFS analyzers can be applied to various hardware configurations including in-line, at-line and open-path process monitoring configurations. To illustrate, Figure 4 shows an in-line configuration with KF-25 flanges.

SOLUTION

TFS™ Analyzer Application: Deposition Precursor Monitor

Due to its self-limiting characteristic, ALD is widely employed in thin film deposition applications for conformity of high aspect ratio. For both thermal and plasma-enhanced ALD processes, monitoring an accurate amount of the high-purity precursor concentration injected into the deposition chamber is highly desirable.

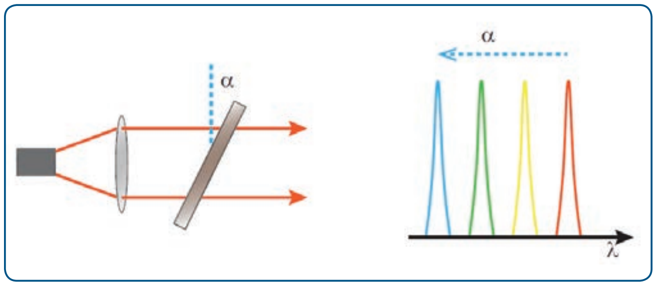

Figure 2 - Concept of using a tunable filter in spectroscopy. Rotation of the filter produces changes in the incident angle (left) which produces a varying wavelength transmission (right)

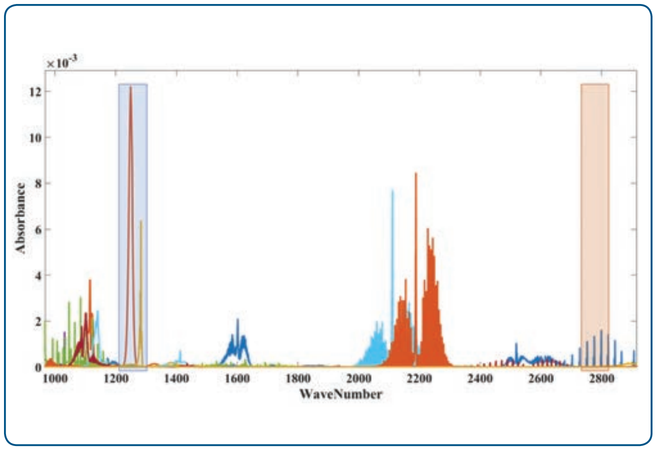

Figure 3 - Example of a dedicated TFS analyzer configuration. In this case, full range infrared spectra collected using an FTIR analyzer are shown. A TFS analyzer can be configured using 2 filters (highlighted ranges) to measure three independent gases.

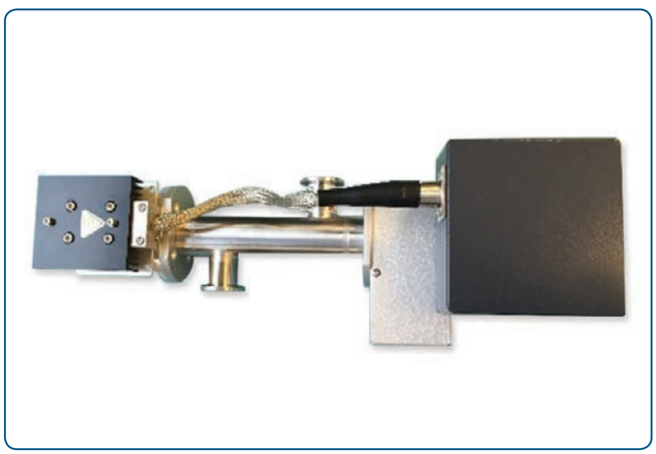

Figure 4 - In-line configuration with KF-25 flanges

In the past, it has been difficult for both semiconductor equipment manufacturers and chip manufacturers to implement a solution that meets the analytical, packaging, and commercial requirements. The existing high-end analytical techniques such as FTIR are too costly and bulky outside the R&D environment. On the other hand, low-cost sensors such as NDIR-based sensors do not have the capabilities to meet the demanding analytical requirements such as sensitivity and speed. Today, TFS analyzers are being considered as a solution in high-volume manufacturing environments as a tool that can be mounted at the precursor supply line close to the precursor ampoule in the source cabinet area.

One of the advantages of TFS analyzers is that they have gas speciation capabilities similar to FTIR and RGA which would enable measurement that is specific to the desired precursor gas, separating signals from any interferants such as those from the carrier gas and/or decomposed precursor elements that can occur over time due to thermal instability. The measurement signal can then be used by the tool makers or chip manufacturers as part of their real-time control system to optimize the ALD process for higher productivity and higher yield. Figure 5 shows an example of an ALD precursor monitor system configuration.

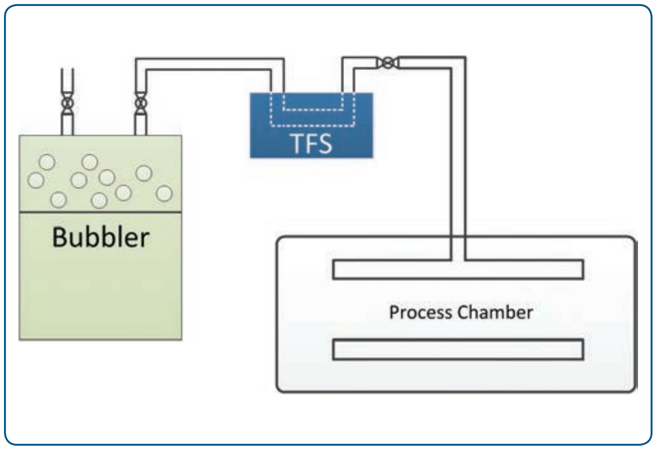

Figure 5 - Precursor monitor

TFS™ Analyzer Application: Cleaning Endpoint Monitor

Real-time chamber cleaning endpoint detection can be achieved by monitoring gas mixture trends during the cleaning process with the TFS analyzer for endpoint detection. Figure 6 shows a typical configuration of a TFS analyzer for cleaning endpoint detection.

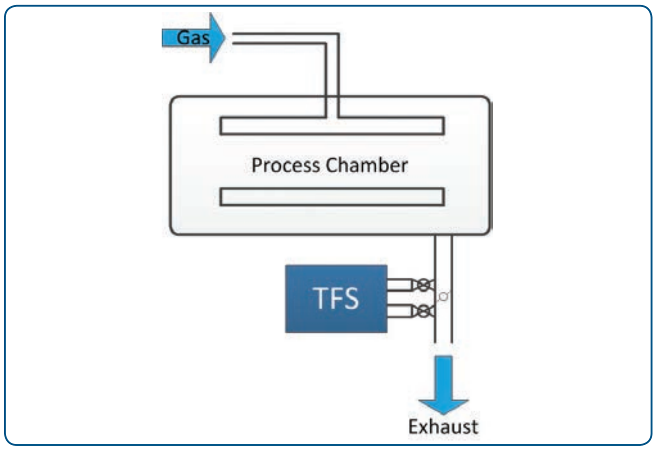

Figure 6 - Chamber clean endpoint detector

Traditional chamber cleaning is a time-based process. Due to the complexity of the chamber environment, a fixed duration cannot address all chamber cleaning requirements. In fact, an optimal duration of clean time for a given chamber is subject to change over time as etch rate variables may change or drift. Most time-based processes are designed to over-etch in order to ensure total removal of CVD film across multiple chambers and tools. Over-etching results in reduced wafer throughput, excess use of reactive gas, and possible damage to components of process kits inside process chambers and chamber walls. Conversely, under-etching results in deposition film buildup over time, leading to poor film deposition repeatability and particulates. This will ultimately result in lower product yield (Figure 7).

The MKS TFS analyzer monitors the chamber clean process in real-time. It is designed to mount on the foreline exhaust for measurement of upstream chamber silicon content. As the chamber is cleaned, the rate of SiF_4 creation decreases relative to the level at clean initiation. The endpoint is established by monitoring the decreasing SiF_4 concentration, and an embedded algorithm can signal when the rate of SiF_4 being created in the cleaning process has reached a minimum or has stopped. While chamber clean can vary based on complex environmental factors, the analyzer's adaptive measurement

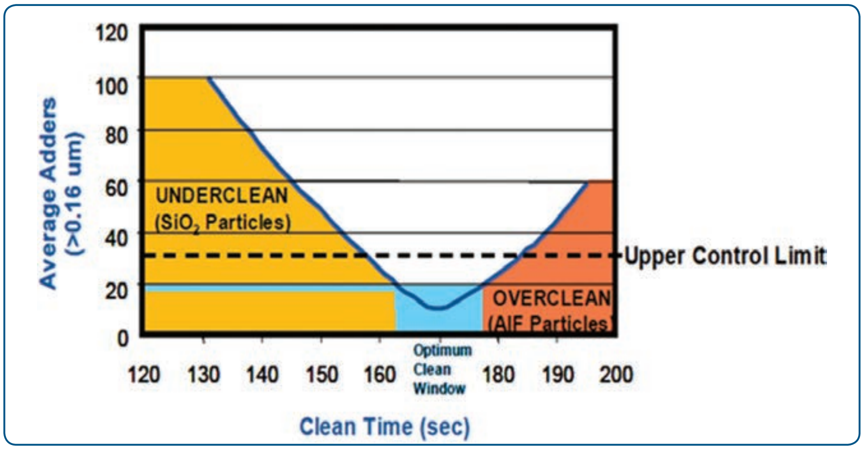

Figure 7 - Optimum clean window

approach accounts for all possible drift conditions in the chamber clean process ensuring optimal clean.

The MKS TFS analyzer can also be configured for multi-gas detection, such as SiF_4 and CO_2, SiF_4 and WF_6 and CO and CO_2 configurations, which may be relevant for multi-chemistry tools. It cannot only measure multiple gases, but each gas is measured with high selectivity without measurement biases due to presence of the background chemistry. For example, NDIR sensors may suffer from these interferences in carbon-based clean where both CO and CO_2 are present, creating measurement biases and thus inaccuracies. Due to the wavelength scanning nature of the TFS analyzers, it enables measurement of each individual compound accurately, eliminating the risk of erroneous endpoint decision due to measurement inaccuracies.

TFS™ Analyzer Application: Etch Process Endpoint Monitor

Controlling etching endpoint is critical in the etching processes. Over etching can cause serious issues such as lower yields, in addition to limiting the throughput. Optical emission spectroscopy (OES) technology is typically used for measuring etch endpoint. In tools where there is no plasma (i.e., remote plasma etching), OES cannot be used. In addition, the data analysis of OES signals is sometimes burdensome and a big challenge.

A TFS analyzer used for endpoint detection, instead directly measures the product of etching. For example, for polysilicon etching with fluorine, a TFS analyzer measures the etching product SiF_4. During etching at the foreline, SiF_4 can be detected until etching is completed. This is the etching endpoint. Similarly, different TFS analyzers that are sensitive to different gases can be selected for different etching process. These analyzers can work with both in chamber plasma etching or remote plasma etching.

A TFS analyzer can be used as an inline sensor and has a relatively high response rate, up to 5 Hz. Due to the fast speed, it provides transient information of the etching process. TFS analyzers are available in many configurations. Different configurations work for different partial pressure range. For example, a TFS analyzer can be installed behind the first stage vacuum pump, such that it can have a good signal to noise ratio, even if the process requires a very low pressure in the chamber as shown in Figure 8.

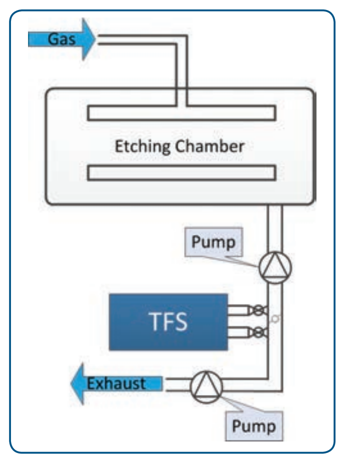

Figure 8 - One possible configuration for etching endpoint monitor with a TFS analyzer

TFS™ Analyzer Application: Gas Blending

TFS analyzers have been used to provide feedback control of gas dilution systems by several semiconductor fabs. The fabs had been purchasing cylinders of low concentration gases regularly. After implementing a gas mixing system with the TFS analyzer measuring the critical gas concentration, the fab was able to significantly decrease their cost for gas tanks and the labor required to change out tanks. The dilution system allowed them to blend gas from one tank of 100% active gas with a diluent to reach the required levels of tens to hundreds of ppm for the active gas required for their process. The analytical results of the TFS analyzer were used to validate the accuracy of the blended gas by providing feed-back control of the blending, eliminating errors based on inaccuracies in the concentration of the concentrated gas as well as errors due to inaccuracies in the gas flow controllers.

In addition to monitoring the concentration of the blended gas, systems have been developed and installed to measure the concentration of the pure gas as well as the concentration of the blended gas. TFS analyzers can be configured to measure the wide range of concentrations by either using different pathlengths (a smaller pathlength can be used for the more concentrated gas measurement system), or by configuring the TFS analyzer to measure the gas using different spectral ranges, for example using a strong mid-infrared band to measure the low concentration gas and using a weaker near-infrared overtone band to measure the higher concentration gas stream. Figure 9 shows an example of a gas dilution system with feedback control.

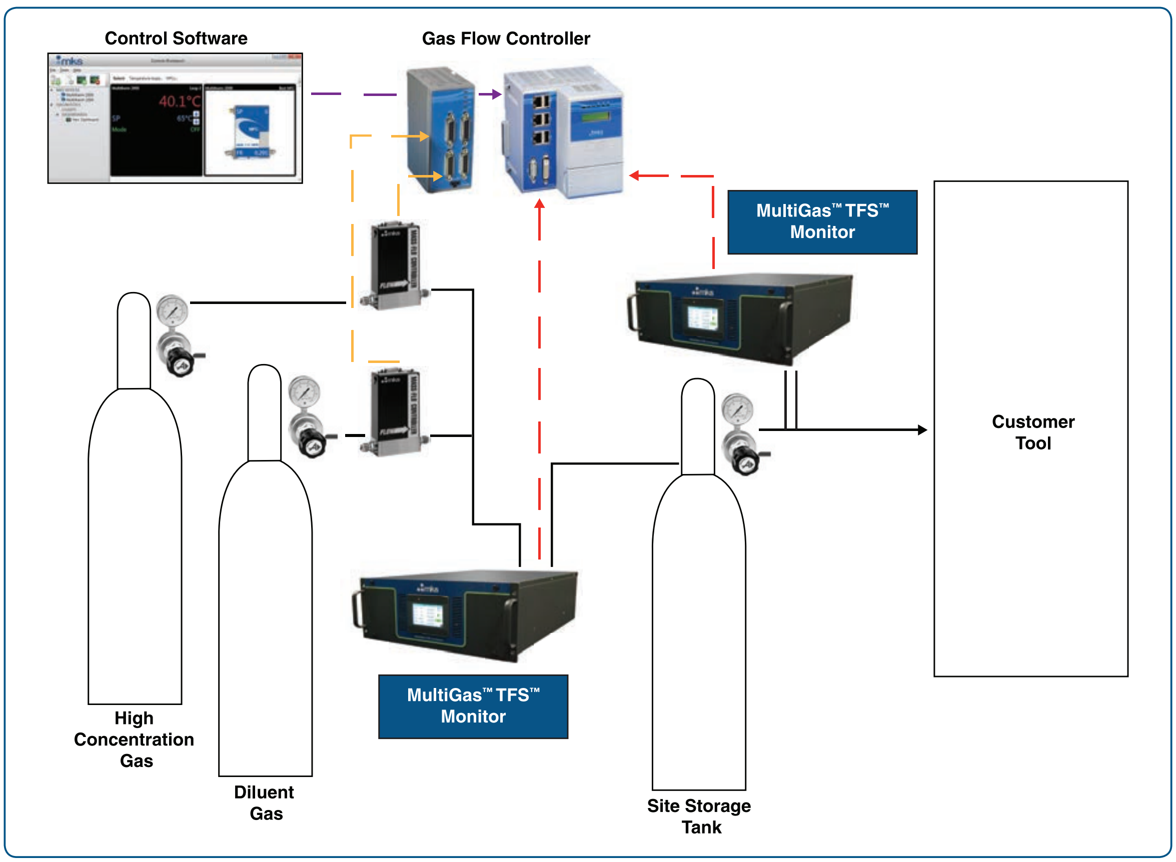

Figure 9 - Gas blending application of a TFS analyzer

CONCLUSION

Application-specific sensors based on MKS TFS analyzers offer semiconductor equipment and chip manufacturers cost effective, high-performance sensors and detectors capable of meeting the increasing challenges of real-time process control for sub 10 nm logic and 3D NAND memory chip processing. Sensors based on the TFS analyzer enable many applications including:

1. Precise control of precursor delivery into the deposition chamber
2. Monitoring and controlling the precise etching endpoint
3. Obtaining consistent and repeatable chamber clean endpoint
4. Taking control of process gas supply quality by utilizing on-site blending

These applications will help semiconductor chip manufacturers improve productivity, yields, and decrease overall cost of operation. The configuration flexibility of TFS analyzers allows the tool manufacturers to design and integrate real-time control systems that meet semiconductor device/chip manufacturer's process requirements.

REFERENCES

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[2] Jacob Y. Wong, Mike Schell, (2011) "Zero drift NDIR gas sensors", Sensor Review, Vol. 31 Issue: 1, pp.70-77

[3] Saptari, V. (2010), “Multiplex Tunable Filter Spectrometer,” US Patent No. US 8896839, Nov 2014

For further information, call your local MKS Sales Engineer or contact the MKS Applications Engineering Group at 800-227-8766.
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