Application of CW-CRDS to Monitor and Control
Chemical Vapor Deposition

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ABSTRACT

Continuous wave excitation cavity ring-down spectroscopy (CW-CRDS) is being developed for real time chemical sensing of volatile CVD byproducts (e.g. HF, H₂O) and as a quantitative and robust metrology tool for advanced process control methodologies.

SUMMARY

Real-time metrology providing information on reactant depletion and product generation for process control during semiconductor manufacturing is needed to enhance productivity and reduce costs [1]. While there are many methods to characterize thin films, it can be difficult to characterize processes because no standardized measurement methods exist to quantify the effects of gas phase changes on film properties. We believe that continuous wave cavity ring-down spectroscopy (CW-CRDS) [2] holds potential in wafer state metrology for advanced process control, yield management, and quality assurance.

Optical sensors exploiting advances in diode lasers, coatings, and photonics can provide compact, rugged and reliable devices for in situ spectroscopic sensing. Absorption spectroscopy is attractive as a metrology method because it is species specific and quantitative. Process control becomes viable when gas phase observations are captured in real time and combined with a model incorporating the effect of process parameters.

Advantages of CRDS over conventional laser absorption spectroscopy include lower detection limits, and insensitivity to absorption by ambient species and to fluctuations in laser intensity and phase. Also, the sample volume in CRD systems can be made relatively small, thus providing good spatial resolution in the transverse direction and facilitating integration into process tools. Finally, CRD signals can be modeled with a relatively simple yet rigorous and accurate theory.

We are investigating the quantitative capabilities of CW-CRDS by targeting hydrogen fluoride, HF, and water vapor, H₂O. The former is a major byproduct occurring when excess fluorine (in the chamber and on surfaces) reacts with hydrogen-containing precursors. H₂O is important in fluorine process environments since it is the most common reactive impurity involved in gas phase and surface reactions leading to the formation of HF and other compounds. The capability to monitor the real-time evolution of HF in a process chamber will provide critical feedback used for system control. As a specific example, this has the potential to provide wafer state reaction information that is the basis for film thickness metrology in CVD systems.

In the first stage of this work, we are developing a bench-top CW-CRDS sensing platform to provide a prototype system that is compatible with semiconductor manufacturing applications. This prototype will be integrated with a commercial thermal CVD chamber that runs tungsten hexafluoride (WF₆) chemistries to deposit blanket tungsten films. The CRDS measurements will be used to characterize the limitations of quadrupole mass spectrometry measurements of HF and to provide wafer state reaction information that is the basis for film thickness metrology [3]. We anticipate that this effort will help drive the development of several aspects of CW-CRDS technology toward a reliable field-deployable system.

Unlike many other applications of CRDS emphasizing detection sensitivity, this study is not aimed at trace species for fault detection or contamination control but aims to monitor fluctuations in the concentration of
majority reaction byproducts of the CVD process for real-time control. Operating conditions in the commercial CVD chamber are typically 67 Pa pressure and 400 °C temperature. Feed gas consists of less than 10% WF₆ by volume and chemical conversion rates of 2% are typical. A mechanistic model for W-film growth specifies the stoichiometry of HF generated for each WF₆ consumed. Quantitative analysis of HF concentration can then be correlated to film thickness [3].

The test platform being developed incorporates a compact (nominally 25 cm) high finesse linear cavity encased in a stainless steel or anodized aluminum housing with O-ring seals and gas inlet and pump ports. Temperature control, upstream flow control, and downstream pressure control are being implemented. High quality dielectric-coated mirrors and custom mirrors with corrosion-resistant coatings are being examined. Pairs of high-reflectivity (99.995%) mirrors coated at 670 nm and 685 nm are selected for HF spectroscopy. Commercially available CW tunable diode lasers with nominal powers less than 30 mW and time averaged bandwidth of about 20 MHz are being used as the light sources to pump the ring-down cavity. An optical isolator is used to prevent feedback into the diode source. A spatial filter and a modematching lens are used to couple into a single mode of the ring-down cavity. In one embodiment, an acousto-optic modulator in conjunction with a gate and delay generator and a low noise fast photodiode receiver (monitoring the ring-down signal) are used to detect light build-up within the cavity and fast switching to induce the transient decay of light. The signals are digitized and processed on a personal computer.

![Figure 1. Estimated Fractional Optical Loss Per Pass for HF absorption at 670 nm in a 25 cm cavity at 298K.](image)

CW-CRDS can be used to probe numerous absorption transitions of HF and water vapor. The spectroscopic parameters of HF are known and the rotational structure is simplistic. The line strengths at room temperature for the strongest rotational features of the HF (0-4) vibrational band are estimated to be $-1.2 \times 10^{-26}$ cm$^3$ cm/molecule at 298K using the data of Rimpel [4]. Calculated per pass losses in a 25 cm cavity are illustrated in Fig. 1. As indicated by this figure, for HF partial pressures greater than 1 Pa -10 Pa, optical losses of $\sim 10^{-5} - 10^{-4}$ per pass are expected and should be readily observable. Number densities will be extracted from the ring-down signals and used as input parameters to numerical simulations of W deposition.

CRDS studies will be part of a larger view toward the impact of optical sensing in semiconductor manufacturing processes. We will use lessons learned from the CRDS experience as a stimulus for identifying and assessing the viability of different sensor-based approaches to wafer state metrology for control. We expect that the application itself will initiate new ideas in CRDS and more generally in optical absorption methods.

REFERENCES