

# In-Situ Plasma Chamber Monitoring for Feedforward Process Control

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This paper examines the effects of polymer buildup in plasma etching systems and describes a micromachined sensor for in-situ polymer thickness measurement. Using gas flows of 45sccm CHF<sub>3</sub> and 15sccm CF<sub>4</sub> at 50mTorr and 1000W, the oxide:polysilicon selectivity ranges from 2.6 to 8.5 as the polymer thickness on the tool walls varies from 0 to 240nm. The polymer sensor is based on an electrothermal oscillator that measures the thermal mass change as polymer builds up on a stress-compensated dielectric window. The change in the thermal mass of the window can be detected as a variation in the pulse width (cooling time) of the oscillation. The device operates with a typical cooling time of 2.7msec and has a measurement resolution of better than 1nm. The device is flush-mounted in the chamber wall with the exposed window area protected by a thin film of iridium against damage by the plasma.

## INTRODUCTION

In order to achieve the dry etching performance needed for next-generation ULSI wafer production, future etching equipment must employ sensor-driven adaptive control algorithms so that changes in the tool characteristics can be compensated for. In particular, the condition of the plasma etching chamber is important and today is rarely monitored as part of tool control. In the plasma etching process, the polymers used to enhance etch anisotropy and selectivity also deposit on the various parts of the chamber (1), changing the chemical and electrical properties of the discharge. The reactor surface, which serves as both a source and a sink for reactive gas species, not only strongly affects the concentration of reactants (eventually changing the etching characteristics) but also can produce particulates which lower yield. This paper reports the effects of chamber conditions on etching characteristics and describes a micromachined sensor for polymer buildup monitoring that is allowing new studies of etch chemistry and provides a means for improved run-to-run etch control in production reactors. While several approaches to polymer monitoring were considered, including infrared absorption spectroscopy (2), ultraviolet absorption spectroscopy (3), and the plasma emission spectrum (4), these techniques typically measure some radical (such as CF<sub>2</sub>) concentration in the plasma rather than the chamber condition. The correlation between radical concentration and polymer buildup is not well understood and must be readjusted whenever there is change in the etch recipe. Besides this, changes in the chamber condition produced by sputtered masking and substrate materials and the inability to extract the information needed to optimally schedule chamber cleans require the use of in-situ measurements for feedforward process control. Using MEMS (MicroElectroMechanical Systems) technology, a micromachined electrothermal oscillator was successfully designed, fabricated, and tested in an Applied Materials 8300 hexode type plasma etcher outfitted for both real-time and run-to-run control.

## ETCH CHARACTERISTIC VARIATIONS

Within the plasma etching process, a glow discharge is formed by exposing either fluorine-based (e.g., CF<sub>4</sub>, CHF<sub>3</sub>, SF<sub>6</sub>, NF<sub>3</sub>) or chlorine-based (Cl<sub>2</sub>) gaseous monomers at low pressure to an electric field. In the case of CF<sub>4</sub> or CHF<sub>3</sub> (primarily used in dielectric etching), radicals such as CF<sub>2</sub> created by electron-neutral dissociation in the plasma discharge not only coat the pattern sidewalls, producing anisotropy, but also adsorb on the various parts of chamber. In addition, there are also deposits formed on the chamber by sputtering of the photoresist masking material and the etched substrate material. The polymer buildup process is a strong function of processing parameters such as power, base pressure, and flow rate (5) and also shows a large dependence on the types of surface materials used, temperature, and the hydrogen/oxygen concentrations in the plasma discharge. These changes in the chamber condition due to polymerization affect the chemical and electrical properties of the discharge, which alters the concentration of reactants (eventually changing the etching characteristics). Etch rate and selectivity variations for certain oxide and nitride etching recipes have been explored in an Applied Materials 8300 hexode etcher. While the oxide recipe used 45sccm of polymer-producing CHF<sub>3</sub> and 15sccm of CF<sub>4</sub> to achieve high selectivity, the nitride recipe employed 42sccm of CF<sub>4</sub>, 15sccm of CHF<sub>3</sub> and 3sccm of polymer-suppressing O<sub>2</sub> at 50mTorr and 1000W. The chamber was wet cleaned first, and after each etching run, a 10min polymerization run producing about 50nm of polymer on the chamber wall surface was performed at 50sccm CHF<sub>3</sub>, 50mTorr, and 1000W without processing wafers. Each etching run included one oxide, one nitride, and one polysilicon wafer. As expected, due to the polymerization-suppressing capability of the oxide, the oxide etch rate remained constant ( $\pm$  1nm/min) as the polymer-producing CF<sub>x</sub> radical concentration increased due to changes in the chamber as 0 to 240nm of polymer built up on the tool walls.

## SENSOR DESIGN

Placing a micromachined sensor in the unfamiliar and rather hard-to-predict environment of a plasma chamber requires a careful examination of several important design requirements. Some of the important considerations are 1) protecting the device from the etching environment, 2) not disturbing the RIE operation with the sensor, 3) resolving polymer thickness to less than one nanometer, 4) maintaining stable device performance in spite of changes in other chamber characteristics such temperature and pressure, and 5) maintaining a known correlation between the amount of polymer deposited on the sensor and that deposited on the chamber wall. Several different approaches to meeting these requirements have been examined, including the use of an electrothermal oscillator, electrostatically-driven mechanical microbridge resonators, and acoustic wave devices (e.g., flexural-plate, surface acoustic and bulk crystal wave devices). Based on a detailed review of these sensors, a device based on an electrothermal oscillator was selected for its higher sensitivity, ease of fabrication, and reliable operation.

### Operation of the Device

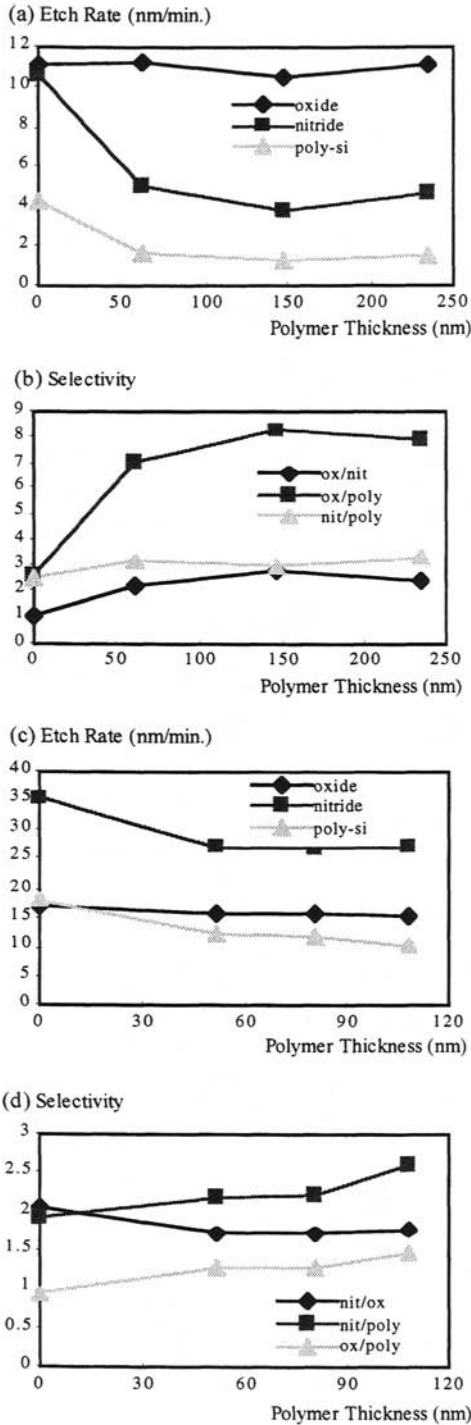
The electrothermal sensor can be operated by interfacing the heater and the temperature sensor to an amplifier, Schmitt trigger, and voltage-to-current converter as in Figure 2. During the first half cycle (heating), the Schmitt trigger is on and the V/I converter drives power to the heating resistor. As power is supplied, the window temperature rises and causes the temperature sensing film resistance to increase as well. The amplifier output voltage increases to reflect this change. When the amplifier output reaches the upper threshold of the Schmitt, the power from the heater is turned off and the sensing resistance starts to drop due to cooling of the window, resulting in a decreasing amplifier output voltage until it reaches the lower threshold of the Schmitt trigger. Then, the Schmitt turns on again, repeating the heating and cooling cycle. The electrothermal cooling time ( $t_c$ ) can be derived from

$$[P_e - A(T - T_f)]dt = MCdT \quad (1)$$

by integration and can be written as

$$t_c = \frac{MC}{A} \ln \left[ \frac{T_H - T_f}{T_L - T_f} \right] \quad (2)$$

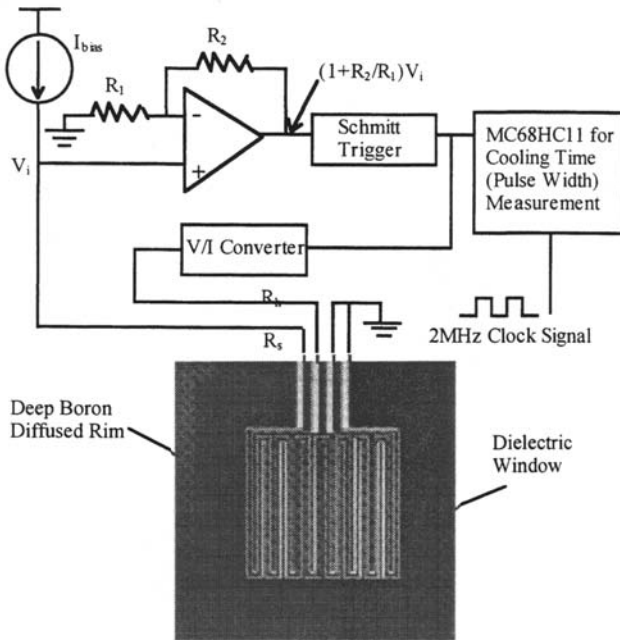
where the input power  $P_e = 0$  during the second half cycle ( $t_c$ ),  $A$  is the no-flow thermal conductance,  $T$  is the diaphragm temperature,  $T_f$  is the ambient temperature,  $M$  is the diaphragm mass, and  $C$  is the diaphragm specific heat,  $T_H$  and  $T_L$  are the high and low switching temperature levels corresponding to the upper and lower thresholds of the Schmitt trigger, respectively. The thermal mass of the windows can be written as



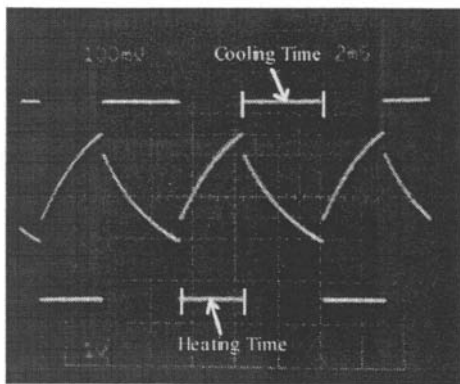
**FIGURE 1.** (a,c) Etch rate, and (b,d) Selectivity vs. Polymerization on the chamber wall. Experiment conditions for (a, b): 45sccm CHF<sub>3</sub>, 15sccm CF<sub>4</sub>, 50mTorr, 1000W, 15min etch each time. Experiment conditions for (c, d): 42sccm CF<sub>4</sub>, 15sccm CHF<sub>3</sub>, 3sccm O<sub>2</sub>, 50mTorr, 1000W, 5min etch each time. The decreases in etch rates of silicon nitride and poly-Si may be due to an increase in the CF<sub>x</sub> radical concentration in the plasma discharge which increases the polymerization on the wafers.

$$MC = \sum m_i c_i = m_{SiO_2} c_{SiO_2} + m_{SiN} c_{SiN} + m_{Ti} c_{Ti} + m_{Ir} c_{Ir} + m_{polymer} c_{polymer} \quad (3)$$

For these polymer buildup measurements, only the cooling time is monitored to allow simpler interpretation of the data. This cooling time changes with polymer deposition (i.e., with the thermal mass (MC) change) and has been monitored using the pulse width measuring function on a Motorola MC68HC11 evaluation board at an internal clock frequency of 2MHz. Figure 3 shows a typical output waveform from the sensor.



**FIGURE 2.** The electrothermal sensor measures changes in the electrothermal characteristics of a stress-compensated dielectric window ( $SiO_2/Si_3N_4/SiO_2$ ) containing interleaved heating and sensing resistors ( $R_h, R_s$ ). Polymer deposition on the window alters its mass and associated heat capacitance.



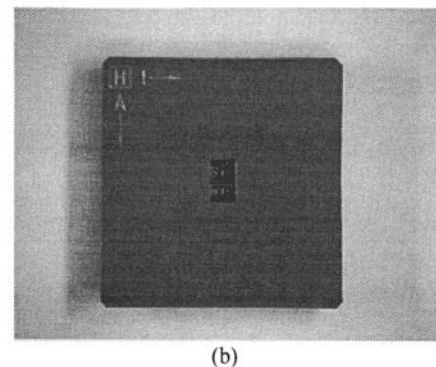
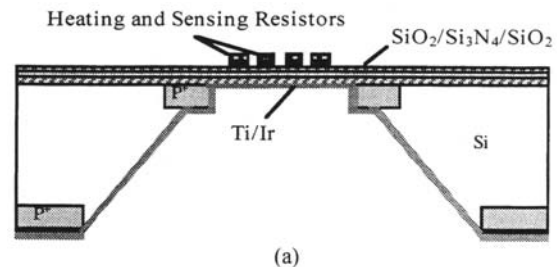
**FIGURE 3.** Output waveform of the electrothermal oscillator. The pulse width is a function of the polymer thickness.

## Device Structure, Packaging, and Placement

The cross-section of the batch-fabricated polymer sensor and a packaged device are shown in Figure 4. A cavity-down pin-grid-array (PGA) package has been adapted for this device due to the ease of wire bonding and durability of the ceramic package inside the vacuum chamber (lack of outgassing). First, to expose the backside of the device window to the inside of the chamber (plasma), a hole was cut ultrasonically in the package base. Then, the device was attached over the hole, followed by wire bonding and sealing of the bonding area by a metal lid having a tiny hole to ensure adequate pressure balance. A packaged device was placed in an Applied Materials 8300 hexode RIE using a specially prepared mounting structure. A 10-pin electrical feedthrough and spot-welded device mounting socket were used in place of one of the normal ports on the tool. Figure 5 shows the mounted device.

## TEST RESULTS

The sensor has been tested in an Applied Materials 8300 multiwafer RIE outfitted for both real-time and run-to-run control. The test results shown in Figure 7 represents twelve 10-minute etches using  $CHF_3$  and a final 20-minute  $O_2/Ar$  plasma clean-up etch to remove the polymer film from the chamber surface. The device functions as expected. These tests employed a 30sccm flow of  $CHF_3$ , a base pressure of 20mTorr, and 1000W for the etching runs and 10sccm of  $O_2$ , 10sccm of Ar, a base pressure of 15mTorr, and 1000W for clean-up.



**FIGURE 4.** (a) Device cross-section showing the stress compensated dielectric window, heating and sensing resistors, backside Si etching by EDP and Ti/Ir layer for protection; (b) Packaged device.

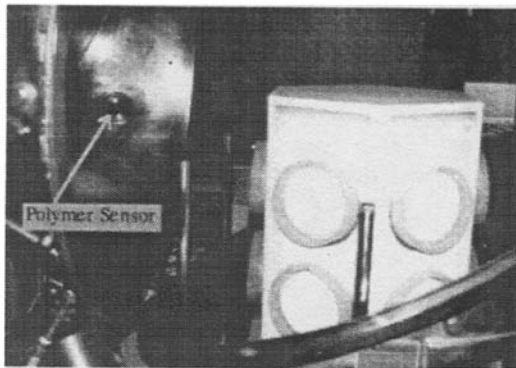


FIGURE 5. Picture showing the packaged polymer sensor mounted in the Applied 8300 hexode RIE chamber wall.

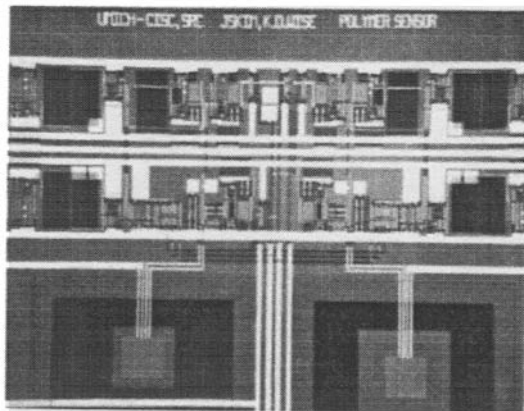


FIGURE 6. Picture of an active polymer sensor with on-chip temperature compensation and control circuitry.

The chamber was maintained at the cleanroom temperature of 23°C. The polymer film removal rate is more than 30 times greater when Ar is present during the cleanup cycle. The sensor response was verified by placing a silicon monitoring wafer on the chamber wall; after each 10-minute etch, the polymer thickness on this wafer was measured using an ellipsometer. About 3nm/minute of polymer is deposited by this particular etch. The sensor has a measurement resolution of <1nm. Each sensor employed four separate windows and the responses from these windows track closely. The cooling time increases with polymer thickness in agreement with electrothermal models and decreases during the cleanup etch to a level similar to the starting condition. This device is now being used for detailed studies of polymer buildup in RIE and as the basis for advanced control algorithms aimed at improving the precision achieved in advanced pattern transfer tools.

## CONCLUSIONS

A simple bulk-micromachined electrothermal oscillator with a dielectric window and metal film resistors has been designed and tested for the direct in-situ measurement of polymer buildup in plasma etching

systems. Its high sensitivity, ease of fabrication, reliable operation, and simple interface are advantages over other approaches to polymer measurement. Test results show increases in the device cooling time during etching runs as polymer is deposited and decreases during cleanup cycles as it is removed. The resolution in measuring polymer thickness is <1nm. After successful design and testing of the prototype polymer sensor, a new active device with on-chip temperature compensation and control circuitry has been designed and fabricated (Figure 6); this device is currently under test. These polymer monitoring sensors are allowing new studies of dry etch chemistry and provide a means for improved run-to-run etch control in production reactors in concert with advanced feedforward control algorithms.

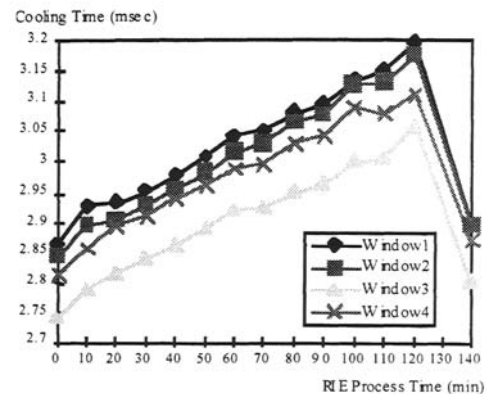


FIGURE 7. Test results showing increases in pulse width with polymer buildup and decreases with O<sub>2</sub>/Ar plasma cleaning.

## ACKNOWLEDGMENTS

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