Sensor systems for real-time feedback control of reactive ion etching

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Previous efforts from our group have shown encouraging initial results in stabilizing etch rates versus time during a run by using real-time, multivariable feedback control (RTC) in an Applied 8300 reactive ion etcher. That work indicated the need for improvements in our sensor systems, both the sensors currently used in feedback control and those monitoring the effects of the control on the wafers being etched. In this article we report on our efforts in the development and improvement of two such sensor systems. The first is an optical emission spectroscopy system which simultaneously measures two emission line intensities for use in actinometry. The second sensor system uses spectral reflectometry data to determine the *in situ* film thickness, from which we calculate the etch rate. We show examples of RTC using the actinometry sensor system during fluorine-based polycrystalline silicon etching. The results of using these sensors for RTC are presented by comparing open loop signals with those from real-time closed loop etch runs. *In situ* etch rate accuracies, estimated using our reflectometry system, are discussed. Film thicknesses calculated from *in situ* measurements are compared with those calculated by *ex situ* spectroscopic ellipsometry. © *1996 American Vacuum Society.*

I. INTRODUCTION

The lack of feedback control and *in situ* sensors in etch and other process equipment has been identified as one of the major problems facing the semiconductor industry.[1,2] It is generally accepted that the main etch parameters which need to be controlled for reduction of process drift are the etch rate (or etch depth), anisotropy, selectivity, and uniformity across a wafer, typically from center to edge. In previous articles our group[3–6] and others[7–9] have discussed the use of sensor-based real-time feedback control (RTC) as a method to reduce the process variations and increase the robustness of reactive-ion etch (RIE) processes.

Real-time feedback control depends critically on noninvasive sensors for process parameters.[3,7–9] We are conducting our etch sensor and control experiments in an Applied Materials 8300 hexode reactive ion etcher, a multiwafer, low-pressure etch tool, without a load lock. We are using CF_4/O_2 chemistry for etching of polycrystalline silicon, with approximately 5% Ar for actinometry. We chose CF_4 because it is the best understood chemistry for silicon etching. Even so, a number of factors have been strongly correlated with the etch rate.[5,9–12] Among these, the fluorine concentration influences the chemical contribution to the silicon etch, whereas the formation of polymers inhibits the etching. Ion bombardment both removes the polymers by sputtering and enhances the surface reaction rate by reduction of surface binding energy. Wafer temperature can also affect the etch rate by in-

fluencing polymer sticking efficiency and redeposition. The interaction of these effects makes the modeling of the etch phenomena in terms of the process parameters (rf power, pressure, flow, etc.) a complex task. Therefore, our control strategy is to measure the internal plasma parameters and stabilize them through feedback adjustment of process parameters. In our previous work,[3,4] we have attempted to control fluorine concentration and ion energy to achieve a more constant etch rate. An actinometry system was used to estimate fluorine concentrations, and the dc bias (V_{bias}) measured at the matching network was used as an indicator for ion energy. [The dc bias is acquired from an RF Services 8300RL impedance matching network, which has (among other features) a rf choke to block 13.56 MHz and a 1.3 kHz low-pass filter.]

In this article we discuss two sensor systems which we have designed and improved. To assist in the control of the fluorine concentration, we have designed an actinometry sensor system which uses optical emission spectroscopy (OES) to monitor the fluorine and argon emission intensities. A spectral reflectometry sensor system is also currently being used as a real-time monitor of sample reflectance for determining the film thickness and etch rate. We present results showing the use of these sensor systems in the real-time control and monitoring of plasma parameters and etch rate, respectively. While our emphasis is on the use of sensor systems for multivariable RTC, we wish to point out that the sensor systems described in this article can also be used with other methods of control, e.g., run-to-run control,[13] end point detection, etch characterization, or etch process diagnostics.

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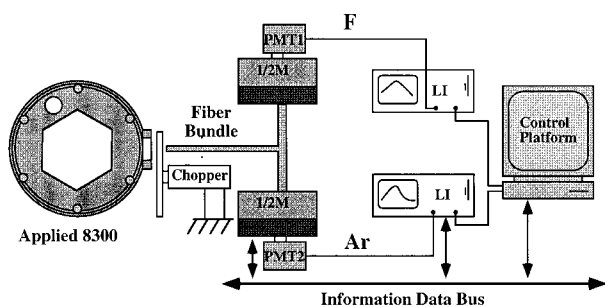[b] Author to whom correspondence should be addressed.

FIG. 1. Schematic of fluorine actinometry using optical emission spectroscopy.

II. ACTINOMETRY SENSOR SYSTEM

The concentration of a chemical specie in a plasma is proportional to the intensity of the optical emission of that specie. Actinometry is a technique which takes the ratio of emission intensity of the specie of interest to that of an inert specie. If electron impact with the specie of interest at the ground state is the primary excitation mechanism leading to the emission line, actinometry can provide an accurate estimate of the specie concentration. The validity of this method for fluorine concentration measurement in CF_4/O_2 plasmas with Ar as the actinometer has been demonstrated.[14] Furthermore, for process control applications, actinometry has the advantages of reducing the effects of window transmission changes and electron energy distribution function variations on the concentration measurement.

Using OES (see Fig. 1), we measure the intensity of the fluorine 703.7 nm emission line (I_F) and the intensity of the argon 750.4 nm emission line (I_{Ar}). Using actinometry, we estimate the fluorine concentration as $[F]_{act} = K(I_F/I_{Ar})P$, where P is the pressure and K is a proportionality constant.[3] (The pressure was measured using an MKS Type 127A Baratron Capacitance Manometer sensitive to pressure between 1 and 100 mTorr.) We are continuing efforts to improve this model to account for Ar dilution effects.[15]

Light from the plasma glow is modulated to 1 kHz using a mechanical chopper and is passed via UV-grade bifurcated quartz fibers, through 475 nm cutoff order-sorting filters into a pair of SPEX 500M $\frac{1}{2}$ m monochromators with 1200 grooves/mm, 750 nm blaze gratings. The entrance slit of each monochromater is set to 0.1 mm, and the exit slit is set to 0.2 mm, yielding a wavelength resolution of roughly 0.8 nm. The asymmetric slit settings are chosen to flatten the tops of the measured lines in order to reduce sensitivity to minor grating misalignment or drift. The light is converted into electrical signals by a pair of thermoelectrically cooled Hamamatsu R928 photomultiplier tubes. We suggest using low-noise transimpedance amplifiers immediately after the photomultiplier tubes to eliminate the necessity of transmission of low-current signals through long cables. The electrical signals are then demodulated with SRS 850 lock-in amplifiers and passed into our controller. The time constants on the lock-in amplifiers are set to 100 ms.

To achieve adequate signal-to-noise ratio (SNR) for the

fluorine estimator at sampling rates which would not limit the RTC system bandwidth, it was critical to obtain high SNRs for the I_F and I_{Ar} signals. The Ar signal in particular strongly affects $[F]_{act}$ since it appears in the denominator of $[F]_{act}$ and is only present as 5% of our etch gas. Thus, we assembled the OES system using techniques normally reserved for high-noise photodetector systems. Cooling the PMTs reduces thermal noise, and also improves measurement repeatability by removing temperature-based drifts in the gain of these devices. Chopping and lock-in detection were used to reduce the $1/f$ noise contributions from both the PMTs and electronic amplifiers, and to correct for possible offsets in high gain amplifiers.

By using a bifurcated fiber instead of two separate fibers, we reduce light collection efficiency variances that can appear in the ratio in $[F]_{act}$. We chose the $\frac{1}{2}$ m monochromators because these are the smallest monochromators equipped with μ-stepper grating motors. These motors have a very small wavelength step size, which allows the maximum intensity of the emission line to be more reproducibly located. (With 1200 grooves/mm gratings, the motor has a wavelength step size resolution corresponding to 0.00025 nm, which is useful for resolving the broadening of the peak by the instrument and finding its peak. Overall, the absolute accuracy of the wavelength setting is only 0.05 nm, which is adequate for emission line identification.) From a control perspective the transimpedance amplifiers are not essential in the construction of a robust sensor system (in fact, the experiments presented here were run without them, and our controller had no obvious problems attributable to the absence of the amplifiers), but without them in place our intensity response showed nonlinearity at very low light intensities due to cable leakage and, therefore, should be included for linear response over a wide dynamic range.

We have found that despite attempts at shielding, the chopper speed controller is affected by our rf plasma power supply, and thus the phase detected at the lock-in amplifier varies with applied rf power. However, we have verified that the frequency reported at the lock-in amplifier is accurate to within 1 Hz, and the automatic phase correction by the lock-in amplifiers eliminates the problems caused by the chopper speed variation.

Under our relatively dim plasma conditions, this system results in approximately a 30 dB SNR in $[F]_{act}$. The observed noise has an essentially flat power distribution versus frequency, and there is no measurable noise with the plasma turned off. These results, and the fact that the SNRs in I_F and I_{Ar} increase as the square root of signal strengths, are consistent with photon statistics-limited SNRs, but further measurements will be required to verify this point. We would like to point out that the bandwidth of our feedback control system is not constrained by the sensor noise, but rather by the multivariable interactions in the reactor.

III. REFLECTOMETRY SENSOR SYSTEM

We have constructed a real-time film thickness monitor using normal incidence spectral reflectometry (Fig. 2). This
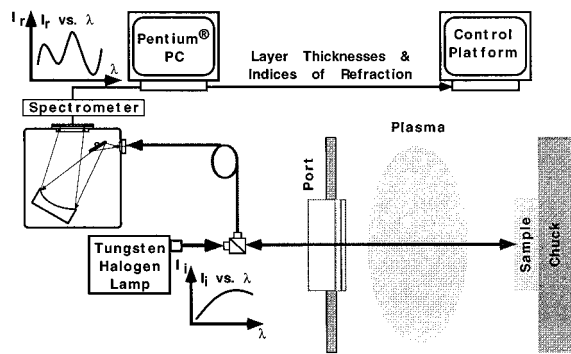
FIG. 2. Schematic of spectral reflectometry system.

Sample No.	Material	SR (Å)	SE (Å)
A	SiO_2	6122 ± 2	6120 ± 1
B	SiO_2	1946 ± 32	1956 ± 1
C	a:Si	1688 ± 1	1690 ± 2
	SiO_2	1956	1956
D	Poly roughness	305 ± 3	135 ± 2
	Poly bulk	3043 ± 4	3279 ± 2
	Poly total	3348 ± 7	3414 ± 4
	SiO_2	385	385
E	Poly roughness	243 ± 44	322 ± 2
	Poly bulk	5506 ± 35	5506 ± 2
	Poly total	5749 ± 79	5828 ± 4
	SiO_2	321	321

technique allows measurement of transparent and semitransparent thin films without optical order ambiguities and with minimal chamber modification. Thickness calculations are performed based on a rigorous thin-film optical model[16] using nonlinear regression.

In this work we are etching unpatterned polysilicon/ silicon dioxide/silicon test wafers. We model the polysilicon, which has significant surface roughness as deposited, as a bulk layer and a surface roughness layer.[17] We fit those layers' refractive indices using the Bruggeman effective medium approximation (BEMA).[18] *Ex situ* spectroscopic ellipsometry measurements of silicon wafers etched using our standard etch conditions have shown evidence of less than 20 Å of optically observable surface damage and less than 15 Å of oxides or polymers on the surface, so no corrections of these effects are included in the optical model for polysilicon etches.

We first calibrate the system using a bare silicon wafer, to eliminate run-to-run variations in the system such as changes in the lamp intensity, window coatings, etc. We then load our test wafer and, before etching, calculate layer thicknesses and the parameters for the BEMA refractive indices. This takes only about 10 s and eliminates the need for *ex situ* measurements. During the etch, only the thickness of the film(s) being etched is allowed to vary in the nonlinear regression. (We have observed no effects in our measurements due to window coating during 20 min runs.)

The reflectometry data were obtained using an Ocean Optics system. It uses a tungsten halogen lamp as the source of incident radiation, and detects the reflected radiation with a 1100-element CCD array. For our thickness calculations, we found that by selecting 25 evenly spaced wavelengths between 400 and 800 nm, we can perform fast data analysis without sacrificing the quality of the fit.[17] A Computer Boards™ timer board provides a clock with 1 μs accuracy that is used to calculate etch rates from our thickness calculations; more will be said about etch rate calculation in Sec. IV. A full spectrum of data is collected in a single pass, which takes approximately 40 ms, and the thickness calculations take 35–55 ms on a Sun Sparc 20, depending on the complexity of the model used and the optical properties of the polysilicon. We have investigated the noise in our

thickness measurements by repeated measurements with the plasma off and also by looking at a series of measurements during an etch with nearly constant etch rate. In both analyses, we determined that the random errors were well approximated by zero-mean gaussians, and the typical standard deviation of our thickness noise (σ_d) was 2–3 Å with no additional averaging, so a single collection of data at 40 ms is sufficient. Thus the total time required to sample and calculate the thickness is at most 95 ms.

To check the accuracy of the *in situ* spectral reflectometry system, we compare the calculated thicknesses with those obtained from *ex situ* spectroscopic ellipsometry, a more accurate but much slower and more expensive measurement technique. Table I shows those results for different samples, with materials whose optical constants are well-established. As can be seen, the film thicknesses can be obtained accurately by the use of our sensors and models, with agreement to within a few Å for films with negligible surface roughness.

IV. EXPERIMENTAL DEMONSTRATION

Using techniques from multivariable control theory, we have designed feedback controllers to simultaneously control $[F]_{act}$, V_{bias}, and pressure by making real-time adjustments of throttle valve position, power, and percentage of O_2 flow. Our control-oriented models and algorithms have been discussed in other publications.[4,5,19]

Our open-loop etch process uses a nominal operating point of 1000 W power, 20 mTorr pressure, and a flow rate of 30 sccm. It should be noted that the lack of a load lock on the etcher introduces moisture into the etch chamber, a disturbance found in all of our etch runs. Experiments have shown that we can reduce the effect of this disturbance through increased pumping times, but the time required is not realistic for normal applications.

We designed two different feedback control experiments. In one, the controller was designed to keep $[F]_{act}$, V_{bias}, and
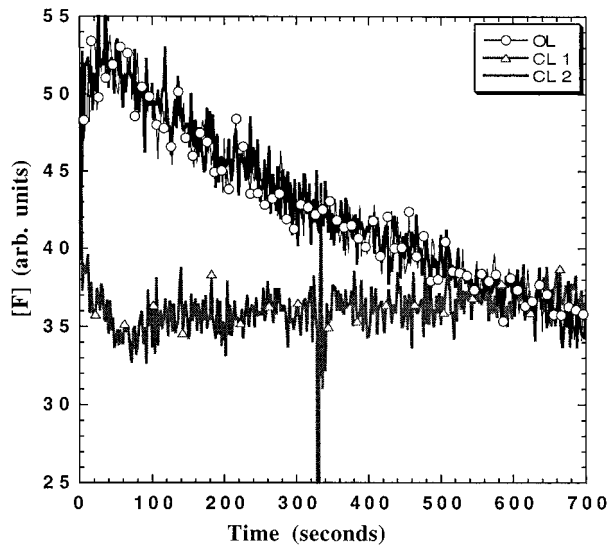
FIG. 3. Open-loop (open circles) and closed-loop data (CL1: line with triangles; CL2: thick solid line) from actinometry. The data presented were taken every 2 s. The disturbance at 330 s in CL1 is due to a power surge during that run. An additional water disturbance (due to the lack of a load lock) is present in all of the runs, but the effects from this disturbance are not easily identifiable. Note that CL2 is virtually indistinguishable from OL.
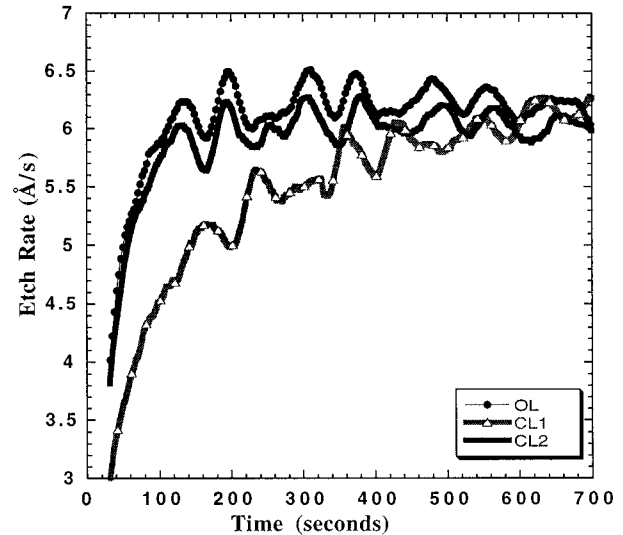

FIG. 4. Open-loop (circles) and closed-loop (CL1: line with triangles; CL2: thick solid line) etch rate results. The disturbance at 330 s in CL1 is due to a power surge during that run.

pressure constant (CL1). Our thesis is that keeping these plasma variables constant should give us a more constant etch rate, and this experiment also demonstrates our ability to make our controlled variables follow a constant trajectory. In the other, the real-time plasma controller was required to track the trajectories of $[F]_{act}$, V_{bias}, and pressure from the open-loop case (CL2). This experiment was designed mainly to demonstrate the ability to force the controlled variables to follow a predetermined trajectory that changes with time, a feature we may wish to use in future control work. We expect the controlled variables to match the open-loop case, and that our etch rate would also match the open-loop etch rate.

In Fig. 3 we present the open-loop (OL) and two closed-loop outputs for $[F]_{act}$. These indicate that our controller does a good job of controlling the $[F]_{act}$ values to their desired set points or trajectories based on input from our sensor systems. Note that the CL1 response for $[F]_{act}$ is essentially flat, and the CL2 response is indistinguishable from that of the OL case, as intended. Pressure and V_{bias}, the other controlled variables, indicate similar trends, but are not shown here because their sensor systems are not the focus of this article.

We show the results of our monitored etch rate for these three experiments in Fig. 4. The etch rate for CL2 matches in shape and nearly in magnitude the OL etch rate, and the CL1 etch rate is not as constant as we expect. We stated earlier that our standard deviation of the noise in our thickness measurement (σ_d) was between 2 and 3 Å. This low value, while good for end point detection, gives us an etch rate estimation noise with a standard deviation of $\sigma_e = \sqrt{2}\sigma_d/\Delta t$, where Δt is the sampling time. For $\Delta t = 0.5$ s, such as that used in our experiments, $\sigma_e \sim 5.5-8.5$ Å/s. This is on the order of our

etch rates, so filtering (smoothing) is required to obtain less noisy etch rate information. It should be noted that even with a factor of 10 improvement in σ_d, the etch rate noise would still be $\sim 10\%$ of our etch rate and filtering would still be required for future use in feedback control. We are looking into improving our SNR in the reflection measurement by increasing integration time, which should lead to a reduction in σ_d and an improved thickness calculation. However, by increasing the integration time, we are averaging data measurements taken at slightly different times. Since the film is being etched, the thickness and therefore the mean reflectance intensity will be different for each of these measurements. Thus, when determining the optimal integration time, the reduction of noise must be weighed against the thickness variation during the measurement.

The data presented in Fig. 4 are obtained by quadratic smoothing[20] over a 31 s window. Even with this smoothing, oscillations are present in the etch rate estimates. These seem to be due to small variations in the calculated polysilicon surface roughness (of the order of a few Å), which we believe are caused by limitations in our model. The oscillations are more severe in the thick layers (>1.5 μm) used for the tests in Fig. 4, and are less severe for thinner polysilicon layers (<0.6 μm) more commonly used for IC gate electrodes. Similar tests on SiO_2 samples show no such oscillations. We will continue to study this issue.

Since the major goal of our control effort is the control of etch rate, we will now discuss a few issues concerning the etch rates obtained from our closed-loop control experiments. In these experiments, only $[F]_{act}$, V_{bias}, and pressure, and not the etch rate itself, were being controlled. While etch rate is a function of the fluorine concentration, ion energy, and polymer formation, we are currently trying to control only the former two of these. And, since neither of these is directly measurable, we estimate their values using actinom-

etry to determine concentration and the dc bias as an indicator of ion energy.

One possible reason our etch rate for CL1 is not as constant over time as we would expect may be the limitations of these estimators. Such issues are currently under investigation both here and at other institutions.[15,21–24] Another possible source of variation are changes in the polymer deposition rate, a factor we hope to be able to monitor in the near future. Also, other factors such as the wafer temperature, which are not currently being controlled or even measured in our system, may have an effect which is currently unaccounted for. More research needs to be done to determine how control of plasma parameters must be carried out in order to provide for a more constant etch rate, and in Sec. V we will discuss some of the directions we will be pursuing.

V. CONCLUSIONS

We have discussed our sensor efforts in RTC of RIE of polycrystalline silicon. In particular, we described the fluorine actinometry and the many RTC issues that influence the choice of components in that system. We can build controllers that can either keep the actinometry model values constant or have them follow a predetermined trajectory, and the actinometry outputs presented demonstrate the performance of the sensor system we have assembled. We also described our reflectometry sensor efforts in order to directly monitor the etch rate of the film being etched. We have shown that we get accurate and fast measurements from this sensor system on unpatterned wafers.

Both the open-loop and closed-loop etch rates versus time are lower in magnitude and show qualitatively different time responses than in our previous work.[3,4] We have observed, in particular, that the behavior of I_{Ar} is much less constant in our present machine state than in our previously reported experiments. We have verified, using simultaneous measurements of our current and previous OES systems, that this is truly a change in the response of our etcher and not in the actinometry system. We speculate, but cannot yet prove, that this is indicative of a rf power transfer problem. This in turn would result in our V_{bias} control being a poor estimate of the delivered power, since the measurement is at the matching network rather than at the electrode. Other possibilities for this change in our system response include changes in the polymer formation rate, changes in chemistry due to chamber wall state, or wafer temperature effects.

The etch rate results show that while we can perform real-time control of certain plasma parameters through sensing and feedback, we are not obtaining as constant an etch rate as we expect. We are confident that our sensor outputs are providing us with reliable data. Therefore, we are looking toward solutions to achieve a more constant etch rate. These include improving our models for fluorine concentration and ion energy, attempting to measure other factors that influence the etch rate, and using the reflectometry data to further stabilize the etch rate.

To investigate whether $[F]_{act}$ and V_{bias} properly model the fluorine concentration and ion energy, more understanding of these plasma parameters are essential. Noninvasive measurements of ion energy flux are currently not available, but more sophisticated rf monitors[21–24] should provide more reliable estimators for ion energy flux. To improve the fluorine concentration estimator, we have added an Extrel mass spectrometer to our RIE to monitor the argon concentration to account for the dilution of the argon due to dissociation of the process gases after the plasma ignites, which will lead to a more accurate measurement.[25]

We currently do not have methods to monitor either the polymer formation or wafer temperature, among other plasma parameters that affect the etch rate. We intend to develop sensors to monitor the wall polymerization and to add an UV absorption monitor for $[CF_2]$,[26] which may provide more control for this part of the system. We are also looking into methods to measure changes in wafer temperature and possibly absolute temperature at the wafer surface.

Finally, we are currently working on adding data from our reflectometry sensor system into our feedback controller. We have recently acquired an NVision Instruments Wizard Optical Monitor, which provides a detector which is temperature stabilized to 0.02 °C to reduce intensity and wavelength variations. Our RTC integration work is divided into two main efforts: determining empirical models that relate the etch rate to the plasma parameters, and designing and implementing an etch controller which will utilize the real-time etch rate information.

ACKNOWLEDGMENTS

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