Origin of Electrical Signals for Plasma Etching Endpoint Detection

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To investigate the electrical changes observed at plasma etching endpoints, experiments were performed in an inductively coupled, rf-biased reactor, during CF4/Ar plasma etches of silicon dioxide films on silicon substrates. The rf bias current, voltage, and impedance were measured vs. time during etching. Simultaneously, a Langmuir probe measured the electron and ion densities, ion current density, and electron energy distribution function (EEDF). At endpoint, we detected changes in the Langmuir probe parameters caused by changes in the flux and density of oxygen-containing etch products. Measured changes in ion current density, EEDF, and voltage, when input into a numerical model of the plasma and sheaths, fully explain the change in discharge impedance measured at endpoint. Changes in the yield of electrons emitted from the wafer surface were not significant. The understanding provided by this work should enable electrical endpoint detection to be used with greater reliability and confidence.

I. Introduction

In plasma etching, it is important to have an endpoint signal that detects when the layer being etched is nearly or completely removed, so that the etch may be stopped at the appropriate time, before it proceeds to etch or damage underlying layers. One technique often used for endpoint detection is optical emission spectroscopy [1], but difficulties may arise if the emission signals are too weak. Alternatively, one may use electrical parameters, e.g., fundamental, harmonic, or dc components of voltage, current, or impedance [2]. Compared to other methods for endpointing, electrical measurements are less expensive and more compatible with manufacturing, but they are poorly understood. Because the origins of electrical changes observed near endpoint are not known, it is difficult to know how much confidence to have in the reliability of electrical endpointing. The need for better understanding of electrical endpoint signals motivated this study.

II. Experiment

Experiments were performed in an rf-biased, inductively coupled plasma reactor. The inductive source was powered at 13.56 MHz and was equipped with an electrostatic shield. The substrate electrode was an aluminum chuck of diameter 102 mm, which was water-cooled and rf biased at 10 MHz. A current probe and a voltage probe were mounted in the rf bias circuitry, as close as possible to the electrode. Signals measured by these probes were digitized by an oscilloscope and transferred to a computer, which Fourier analyzed the wave forms and accounted for the effects of propagation delays, probe calibration factors, and stray impedance.

The Langmuir probe was a commercial, rf compensated probe, equipped with internal, broadband rf filters and a capacitively coupled compensation electrode. The probe tip was a tungsten wire 5.1 mm long and 0.18 mm in radius. It was located 2 cm from the center and 9 mm above the top surface of the wafer. A capacitive wire probe was used as a reference probe to measure and account for the effect of probe current on plasma potential.

Silicon dioxide films 1.0 µm thick, thermally grown on silicon wafers of diameter 100 mm, were etched in Ar/CF4 plasmas. No photoresist was deposited on the wafers; the entire surface of the oxide was exposed to plasma and etched. Etching was performed with Ar and CF4 flows each set to 15 standard cubic centimeters per minute, at a total pressure of 1.3 Pa (10 mTorr), an inductive source power of 225 W, and a fundamental rf bias voltage of 115 V.

III. Experimental results

The most useful electrical signal for endpoint detection was found to be the impedance defined by the fundamental components of rf bias voltage and current. This impedance, denoted Z, has a magnitude $|Z|$ as well as a phase $\phi$. The dominant contributions to Z are a sheath capacitance in parallel with a sheath conductance. Thus it is useful to define the elements, $1/G$ and $1/B$, where

$$1/G = |Z| / \cos \phi,$$

$$1/B = -|Z| / \sin \phi,$$
and $G$ and $B$ are, respectively, the equivalent parallel conductance and susceptance.

Values of $1/G$ and $1/B$, measured vs. time during an etch, are shown in Fig. 1. Both begin to decrease at time $t \approx 3$ min., when the etch breaks through the oxide at the center of the wafer. At $t \approx 6$ min., the decreases level off, indicating that all oxide has been removed out to the wafer edge. The behavior of $|Z|$ and $\phi$ (not shown) was similar. Each of the elements, $1/G$, $1/B$, $|Z|$, or $\phi$, provides a useful endpoint signal.

Langmuir probe parameters also changed during etching, in ways that were highly correlated to the electrical signals. For example, Fig. 2 shows the ion current density $J_+$ measured vs. time, during the same oxide etch as in Fig. 1. An increase in $J_+$ occurred over the same time period, roughly 3 min to 6 min, during which the impedances in Fig. 1 were decreasing. During the same period, we also observed changes in the EEDF that correspond to increases in the floating potential and average electron temperature. The changes in Langmuir probe data are explained by oxygen-containing etch products or by-products, particularly CO, which are believed to suppress the electron density, ion current density, and electron temperature. Thus, these parameters rise at the end of the etch, when the oxide is consumed and those products are no longer being produced.

IV. Model Results

The experimental results were analyzed using a numerical model [3,4] that has been developed for (and validated in) similar high-plasma-density, low-pressure discharges. The model includes both sheaths, the plasma resistance, and the wafer capacitance. It is valid at all bias frequencies, including the intermediate frequency regime. It now includes the effects of non-Maxwellian EEDF and electron emission from the wafer surface. Inputs required by the model include the EEDF and the total, time-averaged ion current at each electrode. Values for these inputs were obtained from the Langmuir probe data, either directly or after suitable calibrations, enabling the model to predict the change in impedance caused by each model input. The results are shown in Fig. 3. For comparison, the measured change in impedance from Fig. 1 is also shown. The most important of the model inputs is the ion current at the wafer. It alone accounts for most of the measured change in $1/G$ and $1/B$. The agreement with experiment is improved by adding additional effects: the ion current at the ground electrode, the EEDF at both electrodes, and the small change in voltage waveform that was measured during the etch. The net effect predicted by the model agrees with experiment, within their uncertainties, which are each about ±0.5 percentage points in both $1/G$ and $1/B$.

The model was also used to investigate the effects of electron emission from the wafer surface. But no changes in electron emission were needed to obtain the agreement between the model and experiment in Fig. 3. Thus, changes in the yield or other surface properties do not appear to play an important role in causing the electrical endpoint signals. They are instead primarily a gas-phase phenomenon, caused by etch products and their effects on ion current and EEDF.

V. References


Fig. 1. Electrical endpoint signals $1/G$ and $1/B$. 
Fig. 2. Ion current density measured by Langmuir probe during the same etch as in Fig. 1.

Fig. 3. Model predictions (dotted) for the cumulative change in $1/G$ and $1/B$ due to measured changes in model input parameters including the ion current at the wafer $\langle I_+ \rangle_{ps}$, the ion current at the ground electrode $\langle I_+ \rangle_{gs}$, the EEDF, and the voltage wave form. The measured change in $1/G$ and $1/B$ is also shown (solid, "expt").