Fiber-optic polymer residue monitor

SAND98-2005C
SAND-98-2005C
CONF-981119--

Kent B. Pfeifer^a, Robert L. Jarecki, Jr.^a, Timothy J. Dalton^b

^aSandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185-1425

^bDigital Semiconductor, 75 Reed Rd., Hudson, MA 01749

ABSTRACT

Semiconductor processing tools that use a plasma to etch polysilicon or oxides produce residue polymers that build up on the exposed surfaces of the processing chamber.

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Figure 1. Diagram of probe tip showing optical fiber, and residue polymer film. The index of refraction of the fiber core is n_1 , the index of the residue polymer is n_2 , and the index of the plasma chamber is n_3 . The physical thickness of the film is d_2 .

These residues are generally stressed and with time can cause flaking onto wafers resulting in yield loss. Currently, residue buildup is not monitored, and chambers are cleaned at regular intervals resulting in excess downtime for the tool. In addition, knowledge of the residue buildup rate and index of refraction is useful in determining the state of health of the chamber process. We have developed a novel optical

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fiber-based robust sensor that allows measurement of the residue polymer buildup while not affecting the plasma process.

Keywords: sensor, fiber-optic, plasma residue

1. INTRODUCTION

We have tested three different versions of the polymer residue sensor in three different etching chambers including a Drytek Quad polysilicon etch tool, a Hitachi M3180-EX electron cyclotron resonance (ECR) polysilicon etch tool, and an AMAT 5300 high-density plasma (HDP) oxide etch tool. A thin film of polymer, when deposited on the end of an optical fiber, produces a change in the reflectivity at the fiber end. The reflectivity data, as a function of time, can be fit to a model to calculate a deposition rate and polymer index of refraction as a function of time during a processing step. This type of sensor allows measurement of residue deposition in plasma chemistries that have previously been too harsh for more conventional means such as a quartz crystal microbalance (QCM). In addition, the sensor active area is very small (2×10^{-9} - 7×10^{-8} m²) allowing measurement of the deposition rate at precise points inside the chamber and potentially enabling three-dimensional mapping of the deposition.

If we examine the reflectivity of the end of an optical fiber with core refractive index (n_1) as a film of refractive index (n_2) is deposited on the fiber end (Figure 1), we can write an equation for the reflectivity (R_{13}) as a function of film thickness:^{1,2}

$$R_{13} = \frac{\rho_{12}^2 + \rho_{23}^2 + 2\rho_{12}\rho_{23}\cos(2\beta_2)}{1 + (\rho_{12}\rho_{23})^2 + 2\rho_{12}\rho_{23}\cos(2\beta_2)} \quad (1)$$

In Eq. 1, R_{ij} is the reflectivity at the fiber tip including the material properties of the materials i and j and the material properties and dimensions of the layers between i and j , ρ_{ij} is the reflection coefficient between layers i and j (defined below) and β_i is the phase shift of the electromagnetic wave with wavelength λ , traversing the film of index (n_i), and thickness (d_i).

$$\beta_i = \frac{2\pi n_i d_i}{\lambda} \quad (2)$$

The reflection coefficient (ρ_{ij}) is defined by the following equation where n_i and n_j are, in general, complex numbers.

$$\rho_{ij} = \frac{n_i - n_j}{n_i + n_j} \quad (3)$$

It is clear from Eqs. 1 and 2 that the reflectivity (R_{13}) is a cosinusoidal function of the parameter β_i and, for a fixed wavelength of light, is determined by the optical thickness (n_2d) of the film. Thus, the film behaves as a micro Fabry-Perot interferometer with interference fringes produced when the light reflected from the fiber/film interface interferes with the light reflected from the film/vacuum interface. However, it is not possible to infer the physical thickness (d) of the film directly from the phase of the interference fringes without knowledge of the index of refraction (n_2). The index of

refraction (n_2) can be inferred from a non-linear least squares fit of Eq. 1 to the amplitude and fringe phase data. This allows the physical thickness to be calculated.

2. SYSTEM DESIGN

Plasma etching tools present challenges to optical fiber insertion, since tool diagnostic access is often limited and the reactive plasma environment can attack fiber surfaces,

Figure 2. Schematic diagram of sensor end with fiber protective layer of Al_2O_3 . Figure also illustrates the stainless steel sleeve and vacuum epoxy used to protect the fiber from the plasma and seal the chamber. Simulations indicate that one quarter wavelength of Al_2O_3 enhances the sensitivity to the polymer layer.

depending on the details of the etch processes employed. In the case of the Drytek Quad polysilicon etching system, the fused silica fiber was inserted directly into the chamber with no concern about the survival of the sensor since SiO_2 is only slowly etched by the

relatively low electron density HBr/Cl₂ chemistry utilized. The generation of fluorine (Hitachi) and CF_x (AMAT 5300) radical-containing, high-density plasmas in the other tools required protection of the sensor tip from etching. This was accomplished using two different approaches. In the case of the Hitachi system, we inserted the fiber through the chamber wall with a sleeve of stainless steel and vacuum epoxied the fiber tip such that only the end was exposed. The fiber end was then coated with a quarter wavelength layer of Al₂O₃ that was electron-beam deposited onto the fiber. The fiber sensor itself was used to monitor the Al₂O₃ deposition such that the correct optical thickness was obtained. In this case we have the sensor geometry of Figure 2. Accounting for the additional Al₂O₃ film between the fiber and deposited polymer, the reflectivity is:

$$R_{14} = \left| \frac{\rho_{34}e^{-j2\beta_2} + \rho_{23}e^{j2(\beta_3-\beta_2)} + \rho_{12}e^{j2\beta_3} + \rho_{12}\rho_{23}\rho_{34}}{\rho_{12}\rho_{34}e^{-j2\beta_2} + \rho_{12}\rho_{23}e^{j2(\beta_3-\beta_2)} + \rho_{23}\rho_{34} + e^{j2\beta_3}} \right|^2 \quad (4)$$

Calculation of R_{14} for various thicknesses (d_2) of Al₂O₃ indicates that the optimum sensitivity to the thickness of the polymer layer is achieved when $d_2 = \lambda/4n_2$, the quarter wavelength thickness.

Figure 3a. Schematic diagram of optical system for monitoring residue buildup in etch chambers. System uses all commercially available fiber optic sources and 3 dB splitters. Having separate reference and signal photodiodes allows normalization of optical power fluctuations.

Figure 3b. Schematic diagram of optical system for HDP etch chamber. System uses commercially available full duplex optical transmitter/receiver package rather than 3 dB splitters. This limits the ability to normalize for fluctuation in optical power.

For the case of the HDP machine, which is specifically designed for the high-rate etching of silicon dioxide, a more aggressive approach to fiber protection was required. An etch-resistant 300/330 μm sapphire optical fiber was purchased for insertion into the vacuum chamber rather than the 50/125 μm silica fiber that was used in the previous systems.³ Changing to this optical fiber presented several problems: unavailability of commercial

fiber optical components for this fiber size, and the high price of the sapphire fiber. In the two earlier systems, the optical system was constructed as illustrated in Figure 3a, using commercial fiber optical sources and 3 dB splitters to inject the light into the fiber and then analyze the reflected signal. The reflectivity analysis hardware has been described

Figure 4. Plot of reflectivity data from fiber end and thickness from the QCM recorded during the etch of 15 blank Si wafers in the chamber. Polymer film restructuring is observed during intervals when wafers are changed and when the wafer cassette is changed due to opening of the process chamber to the transfer chamber and the resulting change in background atmosphere.

elsewhere.^{2,4} For the HDP system, commercial 3 dB splitters were unavailable for the sapphire fiber size. Thus, a commercial full duplex transmitter/receiver package was purchased to fulfill the role of the 3 dB splitters.⁵ The full duplex package was constructed with 860 nm components for both the LED and the photodiode. The trade-off

for this engineering compromise was the inability to normalize the reflected data to remove source power fluctuations. The application in a semiconductor fabrication facility implied that the environment would be very stable thermally and thus, the system did not drift at an unacceptable rate. Application of the system in non-thermally stabilized environments would require the LED and photodetector to be thermally stabilized.

3. RESULTS

The initial testing of the sensor used a bare silica fiber (50/125 μm) inserted in a

Figure 5. Comparison of deposition rate calculated from fiber data and QCM rate data for each recipe.

polysilicon etching system (Drytek Quad). A commercial (Leybold-Inficon) quartz crystal microbalance (QCM) deposition monitor also monitored the deposition data. An example of typical data for the test is shown in Figure 4, which illustrates both the QCM results and the fiber sensor results. It is clear that the optical sensor responds to material deposition in a cosinusoidal manner as predicted by Eq. 1. The QCM results verify that

material is being deposited during the process. A non-linear least squares fit of Eq. 1 to the data from 19.5 hrs through 21 hrs allows calculation of the average index of refraction of the film to be $n_2=1.627\pm0.005$. This was done using a fiber core index of refraction of $n_1=1.4665$ and a value of $n_3=1.000$ for the vacuum chamber.

Next, a series of etch recipes were run to verify that the optical sensor and QCM responses were similar. These recipes included various partial pressures of Cl_2 and HBr in the chamber and various etch power levels. The polymer deposition rates from the optical sensor were then calculated for each recipe and compared to the QCM data. This result is shown in Figure 5, which is a plot of the measured sensor deposition rate compared to the measured QCM rate. It is clear that the deposition rate measured by the fiber sensor is consistent with the rate measured by the QCM for most of the recipes. For the cases where the two rates differ significantly, we believe that temperature changes in the QCM may have contributed to the discrepancy. For example, the cooling water on the QCM fixture was started flowing at the beginning of recipe #1; in addition, the power was changed from 400 W to 275 W during recipe #12. In general, the data indicates similar trends in most cases.

In the case of the fiber deposition monitor, the film refractive index must be deduced in order to obtain a thickness, and subsequently, a thickness deposition rate. Similarly with the QCM deposition monitor, the film density must be known or deduced in order to extract a thickness or thickness deposition rate. The material properties of the residue

polymer are tool and recipe specific. In addition, the materials are very reactive in air making post processing analysis very challenging.

Figure 6. Plot of reflectivity as a function of time for the Hitachi etcher. Initially, the plasma was run resulting in some deposition of residue. Then the system was allowed to become idle until 89 Hrs into the run. Next, the plasma was restarted resulting in more deposition as indicated by the fringes observed. Finally, the system was placed in "dry clean" mode and the plasma residue was removed.

The sensor was next tested on a Hitachi etcher for the purpose of evaluation of the sensor under fluorine-based plasma conditions that are designed to "dry clean," or remove all substantial residue films from the chamber surfaces. In this case, the fiber tip was coated with an Al_2O_3 film of optical thickness equal to one quarter of the wavelength as described above. Thus, an optical wavefront traveling across the film and reflected back through the film is delayed by one half wavelength. Figure 6 is a plot of the data taken over approximately 94 hrs in the machine. During the first hour, a plasma was run that

resulted in polymer deposition as indicated by an initial drop in the reflectivity and subsequent recovery. The fringe visibility is small due to the small index of refraction difference between the polymer film and the Al_2O_3 protective coating. We were unable to independently verify the index of refraction of the residue due to its reactive nature. Any attempt to remove the film from the chamber results in film chemistry that changes the nature of the film including the index of refraction. Film restructuring even occurs in the chamber as observed by the downward drift in the reflectivity over the 86 hrs following deposition. At approximately 89 hrs into the run, the plasma was restarted and further polymer deposition was observed as indicated by the 4 fringes seen in the data. Finally, the "dry clean" recipe in the machine was activated and the polymer film was rapidly removed from the sensor. Drift in the electronics or aging of the Al_2O_3 film in the chamber may account for the mismatch in the beginning and ending values of reflectivity.

Figure 7. Plot of normalized etch rate and particle count for the AMAT 5300 HDP etcher before and after sensor installation. Data indicate that the sensor does not reduce production rates or yield.

The system shown in Figure 3b was then installed in an AMAT 5300 HDP oxide etch tool that was used for wafer production. Again similar data was obtained indicating the deposition of polymer residues. Data was collected from both the fiber sensor and the machine diagnostics to determine if the sensor had any effect on the yield rate and performance of the AMAT 5300. The results are shown in Figure 7, which is a plot of the normalized etch rate for the machine and the particle counts from 120 wafers over a period of 5 months. It is clear that the sensor installation had no measurable effect on the etch rate of the tool or the tool performance as indicated by the particle count data.

In Figure 7 the solid line is the etch rate normalized to the average etch rate prior to installation of the sensor. It is clear that this is a horizontal data set scattered around one. This indicates no effect on the etch rate by the sensor installation. The particle count data

is represented by the filled circles (•) and is a horizontal line averaged around 0.2 counts.

Thus, the sensor did not effect the particle count.

4. CONCLUSIONS

We have developed a sensor based on optical fiber technology that is applicable to measurement of residue polymer buildup on the inside of etch chambers used in the semiconductor industry. We have demonstrated that the sensor can be used to determine the index of refraction of the polymer, which is a measure of the health of the process, and the rate of deposition of the polymer, which allows cleaning to take place when needed rather than on specified intervals. In addition, we have shown the utility of the sensor in environments where QCM thickness monitors would not survive due to the harsh environment such as the AMAT 5300 HDP oxide etch tool. Finally, we have shown that the sensor does not interfere with the operation of the machine by reducing etch rate or increasing particle counts.

5. ACKNOWLEDGEMENTS

The authors would like to thank Digital Semiconductor for their assistance with this work. This work was supported by SEMATECH and the United States Department of Energy under Contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

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