

## Diagnosics of etching plasmas\*

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*Abstract:* Radio-frequency excited, low-pressure plasmas in halogen-containing gases are widely used to etch submicronic features in a range of materials during integrated circuit manufacture. Costly process-drift problems are often caused by the ubiquitous deposition of polymer layers on the reactor walls. Simple and robust sensors of the reactor performance are needed to monitor and manage these effects. This paper presents results obtained in industrial plasma-etching machines using a deposition-tolerant ion flux probe and broadband UV–vis absorption spectroscopy.

### INTRODUCTION

A critical step in the manufacture of large-scale integrated circuits is the anisotropic and selective etching, via a photolithographic mask, of submicronic features in thin layers of semiconductors (Si), insulators ( $\text{SiO}_2$ ), and conductors (Al, W). This is currently achieved with radio-frequency excited, low-pressure plasmas in halogen-containing gases. For example, silicon and aluminium are etched using chlorine-based gas mixtures (e.g.,  $\text{Cl}_2/\text{HBr}/\text{O}_2$ ) in inductively coupled plasma (ICP) sources. Silicon dioxide is etched in dual-frequency capacitive reactors using fluorocarbon gases (e.g.,  $\text{C}_4\text{F}_8$ ) diluted in argon and other additives. These complex gas mixtures are chosen such that the material at the bottom of the feature is sufficiently volatile as to be removed under the influence of ion bombardment, whereas the side-walls (that are not bombarded) become covered with a passivating layer (“polymer”) that protects them from chemical attack. In  $\text{SiO}_2$  etching, this layer is composed of carbon-rich  $\text{C}_x\text{F}_y$  originating from the feedstock gas, whereas for polysilicon etching the passivating layer is composed of  $\text{Si}_x\text{Cl}_y\text{O}_z$ , originating partly from etch products. In both cases, however, this material can also accumulate on the reactor walls. This leads to a number of problems, including process drift (variations in the etch-rate, selectivity, and electrical characteristics in the finished devices) and generation of contaminating dust particles in the reactor. It is, hence, necessary to periodically remove these films, either by manual cleaning (necessitating prolonged shut-down of the machine) or by plasma cleaning steps (e.g.,  $\text{O}_2/\text{SF}_6$ ). Even so, the etch characteristics can vary as a function of time since the last clean, owing to the effect of changing wall characteristics on the gas composition, and therefore on the fluxes of the different reactive species (ions, atoms, and radicals) to the substrate surface. Diagnostic techniques that can measure these fluxes are necessary to optimize clean cycles and to understand and minimize process-drift phenomena.

A number of sophisticated diagnostic techniques have been developed in university laboratories in order to probe the concentrations and kinetics of many of the reactive species of interest in these systems: for example, laser-induced fluorescence [1], IR diode laser absorption [2], quadrupole mass spectrometry [3], and Langmuir probes [4]. However, these techniques have rarely been applied to genuine production reactors, due firstly to their cost and complexity, but also because of either their perturba-

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tive nature, or due to the lack of adequate physical access to the reactive plasma region in these closed systems. This paper presents results from two diagnostic techniques that are compatible with the industrial environment: a deposition-tolerant ion flux probe at the reactor side-wall, and UV-visible broadband absorption spectroscopy. These techniques nevertheless provide *absolute* measurements of fluxes and reactive species densities.

## ION FLUX MEASUREMENTS DURING POLYSILICON GATE ETCHING

Although it is trivial to measure the ion flux produced by clean plasmas in inert gases using classical electrostatic probe techniques, this is not the case in reactive gas plasmas that deposit insulating layers on exposed surfaces. Furthermore, naked metallic probe surfaces are unacceptable in a production environment owing to contamination issues. These problems can be avoided by using a radio-frequency-biased, capacitively coupled probe technique [5,6]. In these experiments, the probe consisted of a small planar anodized aluminium electrode situated at the reactor side-wall. The ion flux was monitored during wafer processing in an inductively coupled plasma reactor running  $\text{Cl}_2/\text{HBr}/\text{O}_2$  chemistry for polysilicon gate etch [7]. The time variation of the ion flux during the different process steps was observed, showing effects due to pressure and temperature stabilization and RF match optimization (Fig. 1).

The ion flux was recorded during the processing of many thousands of silicon wafers. As shown in Fig. 2, the ion flux was systematically higher (+25 %) immediately following manual cleans, return-

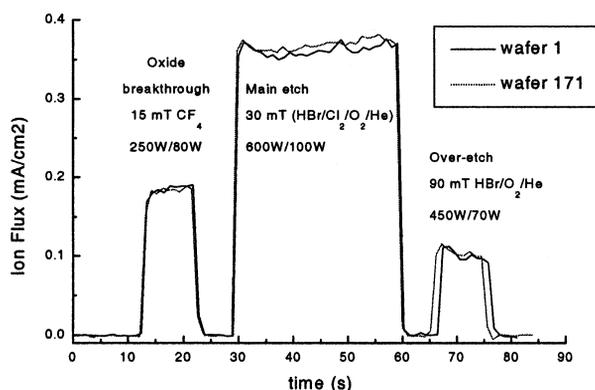


Fig. 1 Ion flux to the reactor side-wall during three process steps, for two identical wafers.

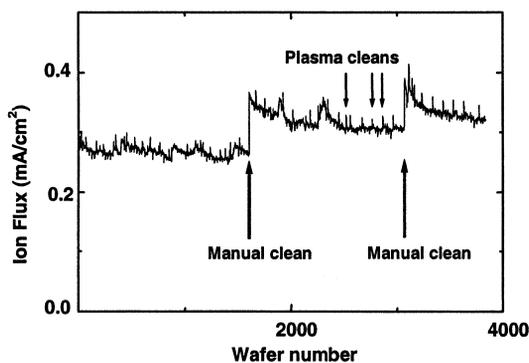


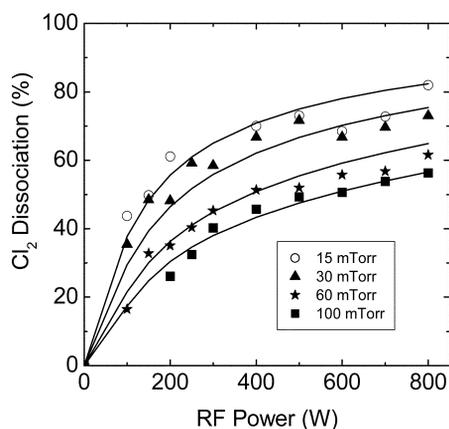
Fig. 2 Average ion flux during the main etch step:  $\text{Cl}_2/\text{HBr}/\text{O}_2$ .

ing to a steady-state value after the processing of a few hundred wafers. Periodic plasma clean steps ( $\text{SF}_6/\text{O}_2$ ) also lead to noticeable increases in the ion flux. The origin of these variations is unclear. One possibility is that the wall chemistry affects the electronegativity of the plasma: for example, if the wall condition causes enhanced recombination of atomic chlorine to form molecular chlorine, this will lead to increased formation of  $\text{Cl}^-$  negative ions, which will in turn decrease the positive ion flux leaving the plasma [8]. Somewhat surprisingly, these dramatic changes in ion flux were not reflected in increased etch rates, as observed by the time taken to reach etch end-point (optical emission end-point detection). However, there was a correlation with increased dispersion of the electrical characteristics of the circuits across the wafer: It would seem this effect is more localized at the edges of the plasma, leading to increased non-uniformity.

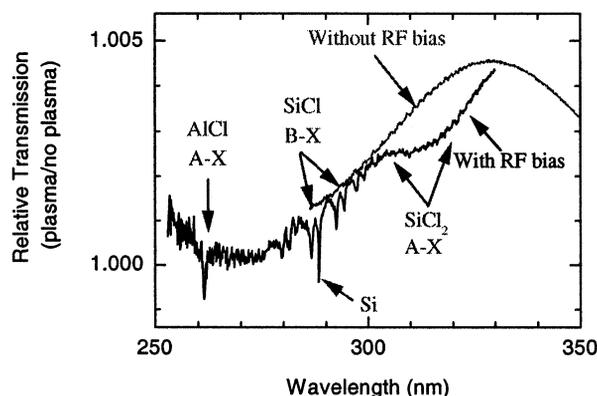
## BROADBAND UV-vis ABSORPTION SPECTROSCOPY

### Chlorine inductively coupled plasma

To further understand these effects, broadband UV absorption spectroscopy [7,9–11] was used to measure the reactive species densities in pure  $\text{Cl}_2$  plasmas in an R&D ICP reactor. The light source was a Xe arc lamp, and the transmitted light was analyzed with a 30-cm monochromator equipped with a CCD camera detector. With this arrangement, the noise level in absorption spectra is equivalent to  $5 \times 10^{-4}$ . The dissociation degree of the  $\text{Cl}_2$  molecules was determined from the weak continuum absorption around 330 nm. The results as a function of  $\text{Cl}_2$  pressure and RF power are shown in Fig. 3, along with the predictions of a simple global model, which includes electron impact dissociation of  $\text{Cl}_2$  and wall-catalyzed recombination [11]. The lower degree of dissociation at higher total pressure is due to a decrease in the electron temperature [12]. The reactor was equipped with a 200-mm substrate holder on which was positioned a polysilicon-coated wafer. When RF biasing was applied, absorption bands were observed due to the presence of etch products. A typical spectrum is shown in Fig. 4. It should be noted that this figure shows relative transmission (plasma on/plasma off): increased overall transmission is observed in the 330-nm region due the consumption of  $\text{Cl}_2$ , which would otherwise absorb light. The etch products  $\text{SiCl}$  and  $\text{SiCl}_2$  were detected. In addition, the  $\text{AlCl}$  radical was also detected. This species, known to be a dangerous silicon pollutant, is presumably produced by sputtering of the alumina reactor walls or the substrate holder.



**Fig. 3** Measured and modeled  $\text{Cl}_2$  dissociation as a function of total pressure and RF power in a pure  $\text{Cl}_2$  ICP plasma.



**Fig. 4** Relative transmission spectrum showing etch product absorption. Pure  $\text{Cl}_2$  ICP plasma, 15 mTorr, 800 W ICP power, 100 W RF bias.

### Dual-frequency capacitive plasma in $\text{Ar}/\text{C}_4\text{F}_8/\text{O}_2$

UV absorption spectroscopy was also applied to an industrial oxide etch reactor, in this case a dual frequency capacitive (27/2 MHz) reactor, running in  $\text{Ar}/\text{C}_4\text{F}_8/\text{O}_2$  mixtures [13]. Using a deuterium lamp source and a 1024 element photodiode array attached to a 0.75-m spectrograph, it is possible to measure absorption spectra across the 200–260 nm range in one shot. In this way, it is possible to detect the radicals  $\text{CF}$ ,  $\text{CF}_2$ , and  $\text{SiF}_2$  (etch product) simultaneously. This technique provides a powerful and rapid tool for evaluating a wide range of different feedstock gas combinations.

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