SiO_2 ETCH RATE AND PROFILE CONTROL USING PULSE POWER IN CAPACITIVELY COUPLED PLASMAS

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Abstract: Pulsed capacitively coupled plasma (CCPs) are attractive for controlling electron energy distributions, *f(ε)*, and plasma properties for microelectronics fabrication. In these systems, *f(ε)* can be controlled through choice of the pulse repetition frequency (PRF) and duty cycle as these determine the relative role of overshoot of E/N and electron thermalization. As a result, the fluxes to the wafer can also be controlled with these parameters. The etch properties during pulsed-operation may be controllably different than with continuous wave (CW) excited plasma. In this paper, we present computed results of time resolved *f(ε)* during a pulse period and etch properties in fluorocarbon gas mixtures. We found that the *f(ε)* and the ratio of fluxes to the wafer are controllable by PRF and duty cycle in a manner not otherwise attainable using CW excitation. The tail of the *f(ε)* is enhanced with lower PRF in order to compensate for electron losses during the longer inter pulse period. As a result of different dissociation patterns of feed stock gases by the modulated *f(ε)*, F, O and polymer fluxes increase relative to ion fluxes with decreasing PRF and duty cycle.

Keywords: pulse plasma, electron energy distribution, EEDF, CCP

1. Introduction

In capacitively coupled radio frequency (rf) discharges, as used in plasma processing of semiconductors, controlling the electron energy distribution *f(ε)* is important for controlling the flux of radicals and ions to the substrate. Multi-frequency capacitively coupled plasmas (CCPs) provide an opportunity to customize *f(ε)* and so excitation rates through choice of frequencies and using pulsed plasmas.[1] By pulsing, one can modulate *f(ε)* to produce shapes that are not otherwise attainable using continuous wave excitation. For example, *f(ε)* may be produced that has both a high energy tail and a large thermal component. These *f(ε)* will produce different dissociation patterns of the feedstock gases. This strategy has been applied in inductively coupled plasmas.[2] In this paper, we show results for plasma properties in a pulsed CCP.

2. Description of the Model

The model used in this investigation is a two-dimensional fluid hydrodynamics described in detail in Ref. [3]. *f(ε)* is obtained from a kinetic solution of Boltzmann's equation using a Monte Carlo simulation (MCS) with electric fields obtained from fluid simulations. The transport of secondary electrons emitted from surfaces is also calculated in the MCS. This particular MCS uses a particle mesh technique for electron-electron collisions. We investigated SiO_2 etching using a $Ar/CF_4/O_2$ = 75/20/5 gas mixture at 40 mTorr and 200 sccm. The species in the simulation are Ar, Ar^+, Ar^*, Ar^{**}, Ar^{***}, CF_4, CF_3, CF_2, CF, C, F, F_2, CF_3^+, CF_2^+, CF^+, C^+, F_2^+, CF_3^-, F^-, O_2, O_2^*, O_2^+, O, O^*, O^+, O^-, COF, COF_2,

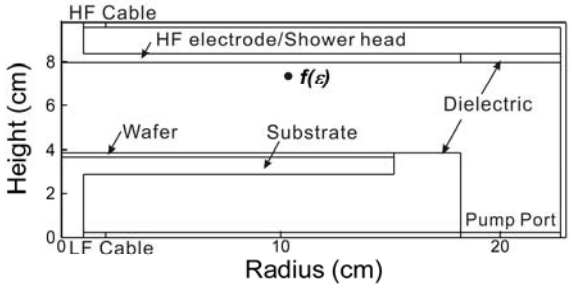

Figure 1. Schematic of the pulsed CCP reactor. The location for *f(ε)* is noted.

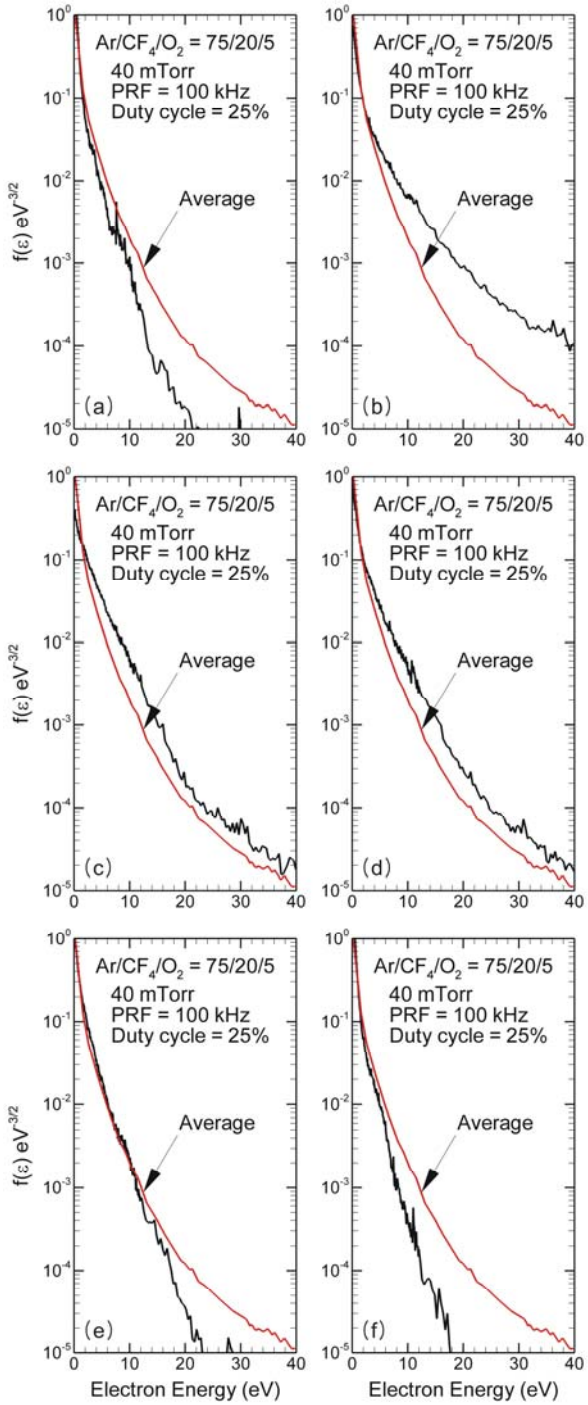

Figure 2. Time resolved $f(\varepsilon)$ during the pulse period. (a) Before pulse, (b) beginning of pulse, (c) and (d) during power-on, (e) and (f) during afterglow.

CO_2, FO, SiF_4, SiF_3, and SiF_2.[4] Ar* represents Ar(4s) metastable, radiative states of Ar(4s) are represented by Ar^{***}, and Ar(4p) radiative states are represented by Ar^{**}. To obtain the energy and angular distributions of neutrals and charged species striking the wafer, the Plasma Chemistry Monte Carlo Module (PCMCM) is used.

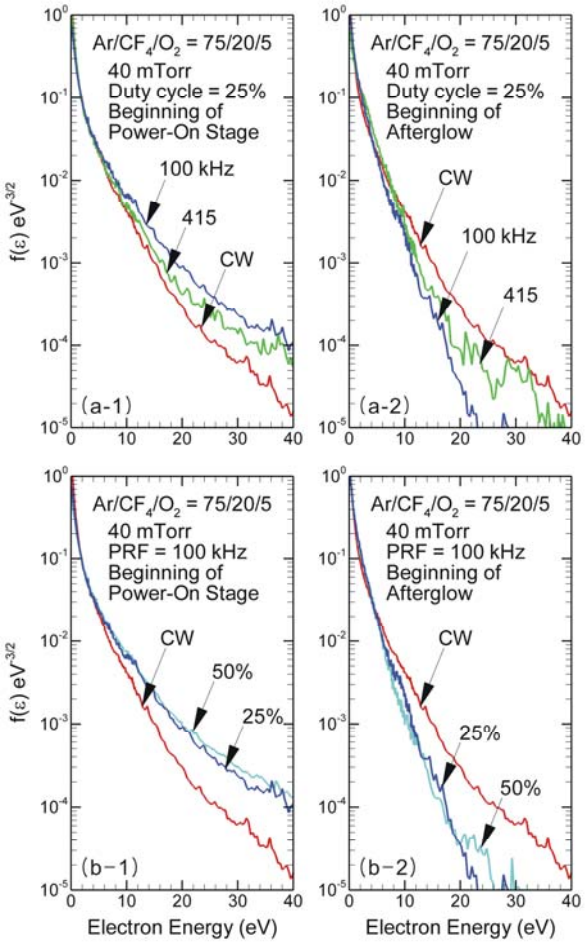

Figure 3. Snap shot comparison of the distribution functions between power-on and afterglow with different (a) PRF, and (b) duty cycle otherwise under the same conditions.

3. Distribution Functions and Fluxes

The CCP etching reactor, schematically shown in Fig. 1, has a low frequency, 10 MHz, applied to the bottom electrode, 30 cm in diameter, and a high frequency (*HF*), 40 MHz, applied to the top electrode. The power deposition at 10 MHz is 500 W. The *HF* power is applied with a pulse-repetition frequency (PRF) of 100 kHz (pulse period 10 μs), duty cycle of 25% and time averaged power of 500 W. The PRF is high enough that the plasma density does not significantly change over the rf cycle.

Time resolved $f(\varepsilon)$ are shown in Fig. 2 over a pulsed period near the edge of the *HF* sheath at the site shown in Fig. 1. High energy electrons are rapidly generated at the beginning of the pulse-on cycle due to the impulsive stochastic heating of electrons which are accelerated by the rapidly expanding *HF* sheath. Simultaneous to the stochastic heating, the

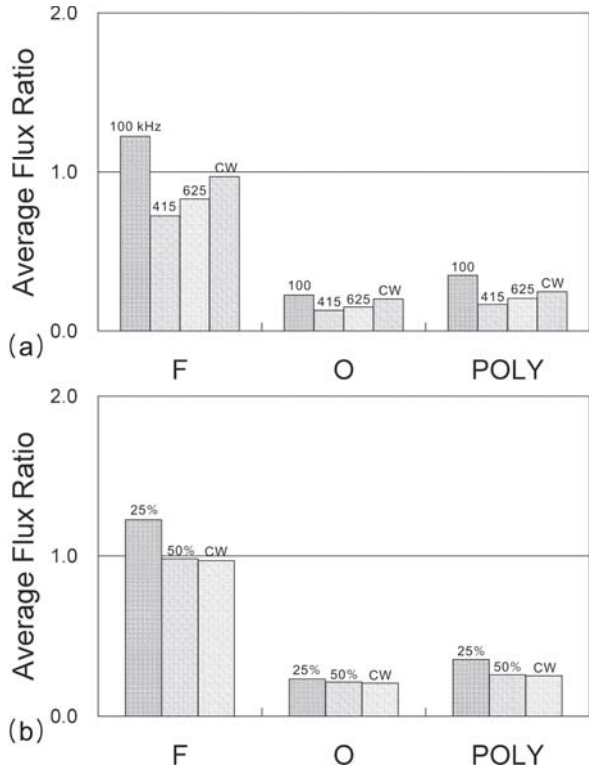

Figure 4. Ratios of fluorine atoms, oxygen atoms and polymerizing fluxes to ion fluxes for different (a) PRF and (b) duty cycle.

pulse-on *HF* power also enables ionization by sheath accelerated secondary electrons produced by ion bombardment. As the pulse power is toggled on-and-off, the high energy electron population in the tail of the $f(\varepsilon)$ is modulated. At the beginning of the power-on stage, the tail of the $f(\varepsilon)$ reaches its highest value due to the overshoot of E/N above the steady state value, as shown Fig. 2(b). $f(\varepsilon)$ then adjusts quickly to the steady state after rebounding, as shown in Figs. 2(c) and 2(d). When the power is off, high energy electrons are quickly lost due to inelastic collisions and diffusion losses.

Snap shot comparisons of $f(\varepsilon)$ with different PRF and duty cycle at the beginning of the power-on stage and at the beginning of the afterglow are shown in Fig. 3. The tail of the $f(\varepsilon)$ is more likely to reach higher values at lower PRF, as shown in Figs. 3(a-1). The $f(\varepsilon)$ at the beginning of the afterglow are similar for different PRF and duty cycles as a quasi-steady state has been achieved.

The rates of high threshold inelastic collision processes are determined by the population of high energy electrons in the tail of the $f(\varepsilon)$. As a result, the density and fluxes of the reactive species can be controlled through the process variables which control the shape of $f(\varepsilon)$. For example, the ratio of F atom, O atom and polymerizing radical fluxes to ion fluxes are shown in Fig. 4 while varying PRF and duty cycle. The polymerizing fluxes include CF_3, CF_2 and CF. Compared to CW excitation, pulsed plasmas have larger flux ratios due, in part, to a decrease in ion fluxes. The flux ratios approach their CW values with increasing PRF. The flux ratios approach their CW value with increasing duty cycle. Although not monotonic, there is an ability to control these flux ratios with duty cycle and PRF.

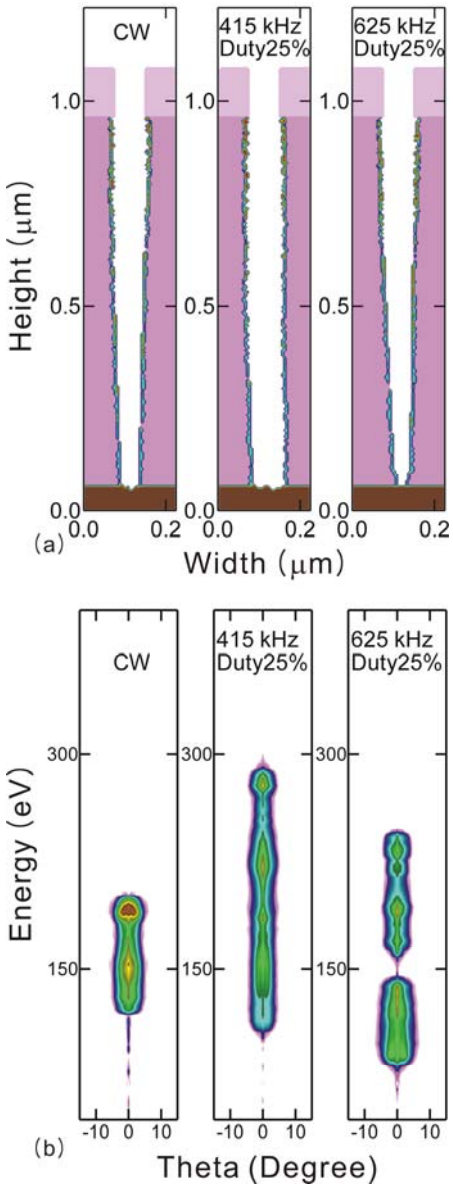

Figure 5. Etch profile and ion energy angular distribution (IEAD) with different PRF. (a) Etch profile and (b) IEAD.

To demonstrate the ability to control etch profiles using pulse power parameters, we utilize the Monte-Carlo Feature Profile Model (MCFPM) which is described in detail in Ref. [5]. The fluxes of reactant species and their angular distributions from the PCMCM are used as input to the MCFPM. The MCFPM resolves the surface (e.g., PR, polymer, and semiconductor) of the wafer using a 2D rectilinear mesh.

Etch profiles and ion energy and angular distributions (IEAD) for the nominal base case conditions are shown in Fig. 5 ($Ar/CF_4/O_2$ = 75/20/5, 40 mTorr, *LF* 500 W, *HF* 500 W). Profiles are shown for CW excitation and PRFs of 415 kHz and 625 kHZ. The etch rate depends on the ion energy and polymerizing flux ratio onto the wafer. The etch rate for a PRF of 415 kHz, is highest due to the higher ion energies and lower polymerizing flux ratio. Note the tapering of the profile with CW and 625 kHz, and the straighter feature at 415 kHz. These differing profiles result from the different composition of fluxes produced by the change in PRF and in the broadening (or narrowing) of the IEAD.

4. Conclusion

We investigated control of $f(\varepsilon)$ in pulsed CCPs using PRF and duty cycle as control variables. The PRF and duty cycle provide possibilities to control $f(\varepsilon)$ due to there being transients in E/N above the steady state and different lengths of the afterglow period during which thermalization occurs. The end result is that the ratio of fluxes to the wafer can be controlled through manipulation of $f(\varepsilon)$ using these process variables. This in turn enables some degree of control of the etch profiles.

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References

[1] V. Georgieva and A. Bogaerts, "Numerical simulation of dual frequency etching reactors: Influence of the external process parameters on the plasma characteristics", J. Appl. Phys. **98**, 023308 (2005).

[2] G. A. Hebner and C. B. Fleddermann, "Characterization of pulse-modulated inductively coupled plasmas in argon and chlorine", J. Appl. Phys. **82**, 2814-2821 (1997).

[3] M. J. Kushner, "Hybrid modeling of low temperature plasmas for fundamental investigations and equipment design", J. Phys. D **42**, 194013 (2009).

[4] A. V. Vasenkov, X. Li, G. S. Oehrlein and M. J. Kushner, "Properties of C_4F_8 inductively coupled plasmas. II. Plasma chemistry and reaction mechanism for modeling of $Ar/c\text{-}C_4F_8/O_2$ discharges", J. Vac. Sci. Technol. A **22**, 511-530 (2004).

[5] A. Sankaran and M. J. Kushner, J. Vac. Sci. Technol. A **22**, 1242 (2004).