

# Time-Resolved Electron Energy Distributions and Plasma Characteristics in a Pulsed Capacitively Coupled Plasma

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**Abstract**—Pulsed capacitively coupled plasmas (CCPs) are attractive for controlling electron energy distributions  $f(\varepsilon)$  and plasma properties for microelectronic fabrication. A conceptual design of a pulsed CCP is discussed which provides additional control over the magnitude and composition of the reactive fluxes to the wafer. We present computed images of time-resolved  $f(\varepsilon)$  and electron density during a pulse period.

**Index Terms**—Electron energy distribution, plasma simulation, pulsed plasma.

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

The model used in this investigation is a 2-D fluid hydrodynamics described in detail in [3].  $f(\varepsilon)$  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<sub>2</sub> etching using a CF<sub>4</sub>/O<sub>2</sub> = 80/20 gas mixture at 40 mtorr and 200 sccm. The species in the simulation are CF<sub>4</sub>, CF<sub>3</sub>, CF<sub>2</sub>, CF, C, F, F<sub>2</sub>, CF<sub>3</sub><sup>+</sup>, CF<sub>2</sub><sup>+</sup>, CF<sup>+</sup>, C<sup>+</sup>, F<sub>2</sub><sup>+</sup>,

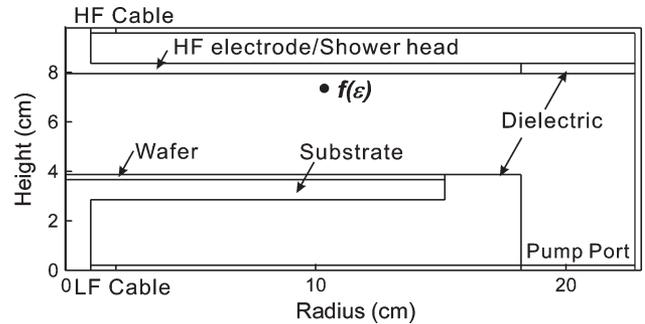


Fig. 1. Schematic of the pulsed CCP reactor. The location for  $f(\varepsilon)$  shown in Fig. 2 is noted.

CF<sub>3</sub><sup>-</sup>, F<sup>-</sup>, O<sub>2</sub>, O<sub>2</sub><sup>\*</sup>, O<sub>2</sub><sup>+</sup>, O, O<sup>\*</sup>, O<sup>+</sup>, O<sup>-</sup>, COF, COF<sub>2</sub>, CO<sub>2</sub>, FO, SiF<sub>4</sub>, SiF<sub>3</sub>, and SiF<sub>2</sub> [4]. The raw data for the images were generated on an HP rx2660 workstation. The data were postprocessed with Tecplot 360. The images are combined using Photoshop v7 and annotated using CorelDraw 12.

The CCP etching reactor, schematically shown in Fig. 1, has a low frequency of 10 MHz applied to the bottom electrode, 30 cm in diameter, and a high frequency (HF) of 40 MHz applied to the top electrode. The power deposition at 10 MHz is 300 W. The HF power is applied with a pulse-repetition frequency (PRF) of 100 kHz (pulse period is 10 μs), a duty cycle of 25%, and a time-averaged power of 500 W. The PRF is high enough that the plasma density does not significantly change over the RF cycle. The time-resolved  $f(\varepsilon)$  is shown in Fig. 2 over a pulsed period near the HF sheath edge at the site shown in Fig. 1. The electron density and ionization by sheath-accelerated secondary electrons are also shown at selected times during the pulse period. 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 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 electron sources by these beamlike secondary electrons are also modulated, while the bulk electron density does not significantly change. When the HF power is off, energetic secondary electrons are still produced by the LF sheath.

In conclusion, images of  $f(\varepsilon)$  and plasma properties for a pulsed CCP etching tool have been presented. This configuration provides additional freedom for controlling ionization rates by modulating  $f(\varepsilon)$ .

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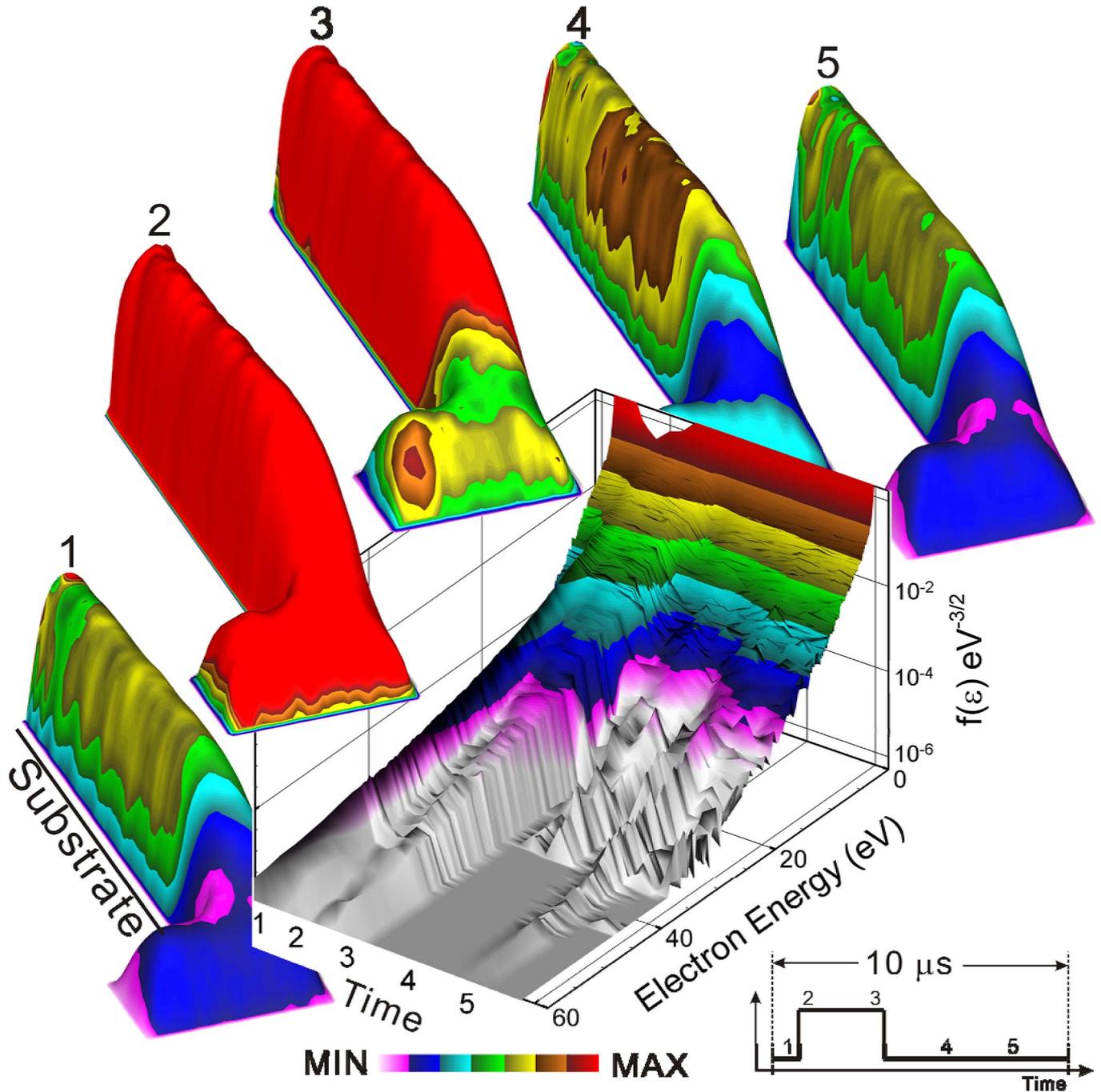


Fig. 2.  $f(\epsilon)$  and plasma characteristics for a pulsed CCP during a pulse period of  $10 \mu s$ . The time-resolved  $f(\epsilon)$  at the center of the figure shows excursions of the tail of  $f(\epsilon)$  during the pulse on and off. The electron densities at five times during the pulse period (noted in the inset) are shown by the height of the 2-D contour plots having a maximum of  $1.8 \times 10^{11} \text{ cm}^{-3}$ . The location of the substrate is noted. The color coding of the contour plots represents the ionization by sheath-accelerated secondary electrons, having a maximum value of  $4.3 \times 10^{15} \text{ cm}^{-3}\text{s}^{-1}$ .

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.*, vol. 98, no. 2, p. 023308, Jul. 2005.

[2] G. A. Hebner and C. B. Fleddermann, "Characterization of pulse-modulated inductively coupled plasmas in argon and chlorine," *J. Appl. Phys.*, vol. 82, no. 6, pp. 2814–2821, Sep. 1997.

[3] M. J. Kushner, "Hybrid modeling of low temperature plasmas for fundamental investigations and equipment design," *J. Phys. D, Appl. Phys.*, vol. 42, no. 19, p. 194013, Oct. 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/ $C_4F_8$ / $O_2$  discharges," *J. Vac. Sci. Technol. A, Vac. Surf. Films*, vol. 22, no. 3, pp. 511–530, May 2004.