Control of Electron, Ion and Photon Distributions in Low Pressure Plasmas Using Pulsed Power

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The value of plasma materials processing is determined by selectively controlling the fluxes of radicals, ions and photons, and their energies, incident onto the surface. In some applications, the coincidence in time of these fluxes is also important. These values are ultimately determined by controlling the electron energy distribution $f_e(\varepsilon)$ which determines excitation rates and fragmentation patterns of molecular gases. Strategies for controlling distribution functions of electrons and ions in low pressure inductively and capacitively coupled plasmas, and their coincidence with photon fluxes, using pulsed power will be discussed.

In plasma materials processing, controlling the flux of radicals, ions and photons to surfaces is critically important to the quality of the end product. These quantities are ultimately optimized by controlling the electron energy distributions, $f_e(\varepsilon)$, which determine rates of ionization and dissociation. Once the magnitude of these fluxes are controlled, further control of the ion energy distributions, $f_I(\varepsilon)$, is required to deliver the desired activation energy to the substrate. Multi-frequency excitation of capacitively coupled plasmas (CCPs) and variable frequency inductively coupled plasmas (ICPs) have been shown to improve control of these distributions. Pulsed power and the pulse characteristics are other variables that can be used to optimize and control both $f_e(\varepsilon)$ and $f_I(\varepsilon)$. In this paper, results from computational investigations will be used to discuss strategies for controlling distribution functions of charged particles and photons using pulsed power in ICPs and CCPs as used in microelectronics fabrication. These investigations were performed using the Hybrid Plasma Equipment model with which Monte Carlo simulations are used to obtain $f_e(\varepsilon)$, $f_I(\varepsilon)$ and radiation transport.[1]

We found that using pulsed power to control $f_e(\varepsilon)$ in ICPs using repetition frequency and duty cycle enables one to (some degree) control the composition of fluxes to the substrate. This control comes from the fact that the shape of $f_e(\varepsilon)$ that can be produced in a pulsed plasma averaged over a pulsed period may not be reproducible on a cw basis. On a cw basis, sources and losses of all species must be in instantaneous balance. In a pulsed system, these quantities need only be balanced averaged over the pulsed period. For example, $f_e(\varepsilon)$ and fluxes are shown in Fig. 1 for a 200 W (time average) ICP sustained in a 10 mTorr, Ar/CF_4 = 80/20 mixture with pulsing [duty cycle (dc) = 15%, pulse repetition frequency (PRF) = 83 kHz] and cw

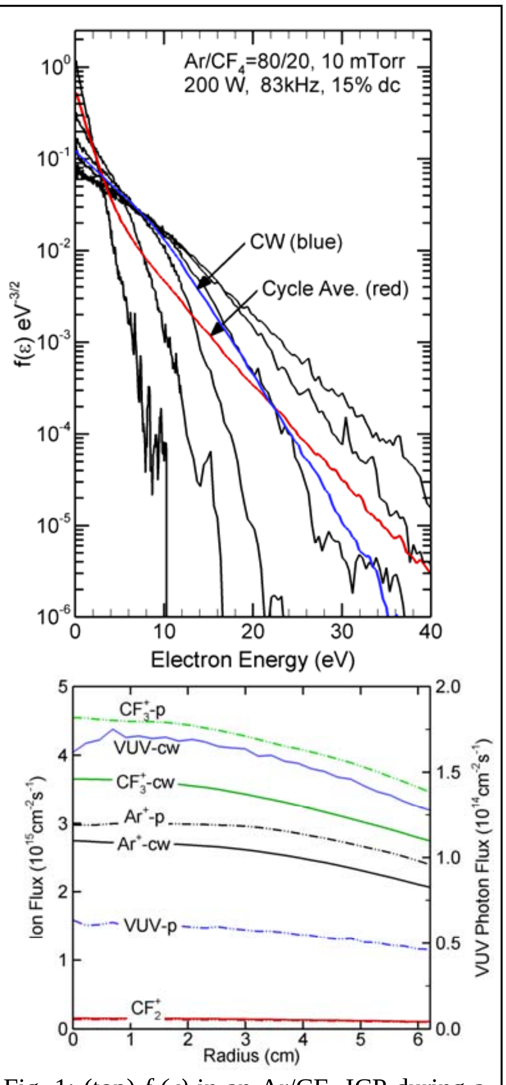

Fig. 1: (top) $f_e(\varepsilon)$ in an Ar/CF_4 ICP during a pulsed period. The cycle averaged and cw $f_e(\varepsilon)$ are also shown. (bottom) Ion and VUV photon fluxes to the substrate during cw and pulsed (p) operation.

power. The $f_e(\varepsilon)$ extends from low energies and being highly thermal during the power-off period to having a highly extended tail during the power-on period. The pulsed average $f_e(\varepsilon)$ has more prominent low and high energy components than the $f_e(\varepsilon)$ obtained with cw power. The end result is that fluxes of ions and photons to the substrate have different ratios between pulsed and cw.

This strategy for controlling $f_e(\varepsilon)$ can be extended to dual-frequency CCPs where one or either of the frequencies are pulsed. For example, $f_e(\varepsilon)$ are shown in Fig. 2 for a dual-frequency CCP sustained in a $Ar/CF_4/O_2$ = 75/20/5, 40 mTorr mixture. The low frequency (LF = 10 MHz) and high frequency (HF = 40 MHz) both deliver 500 W. The HF is either cw or pulsed with a PRF of 50 kHz and dc = 25% or 50%. As in the ICP example, the shape of $f_e(\varepsilon)$ averaged over the pulsed period differs from that obtained with cw excitation, and can be controlled by the choice of dc. Due to the attachment and recombination that occurs during the time that the HF is off, the plasma density decreases and so the impedance of the plasma increases. When the HF power is turned on, the higher impedance produces a larger E/N and so extends the tail of $f_e(\varepsilon)$. This effect increases with decreasing dc since more recombination and attachment occur during the longer power-off period. To compensate, the low energy portion of $f_e(\varepsilon)$ is depressed with shorter dc. This effect is most severe at the beginning of the power-on period, and produces an *overshoot* in $f_e(\varepsilon)$, and so an *overshoot* in high threshold energy electron impact processes. This overshoot can be seen in the electron source rate coefficient (mole fraction weighted sum of rate coefficients for ionization minus attachment-recombination) in Fig. 2. At the start of the HF power, source rates peak by factors of 10-50 compared to the flat portion of the power-on period.

Through this control of $f_e(\varepsilon)$, the ratio of the fluxes of radicals and excited states to ions can be controlled. Since threshold energies for excitation and dissociation are typically lower than for ionization, the proportion of energy going into these modes can be varied with, for example, duty cycle. We found that the ratio of the flux of radicals to ions generally decreases with decreasing dc. As a consequence, the shape of etched features, which is sensitive to this ratio, can be controlled with dc. The control of flux ratios is particularly sensitive to duty cycle for photons. Since for short lived excited states, photon fluxes are more sensitive to real-time changes in $f_e(\varepsilon)$, the ratio of photon-to-ion fluxes can be readily controlled.

The control of $f_e(\varepsilon)$ through pulsing HF power can be combined with the pulsing of LF power to control $f_I(\varepsilon)$. Subtle changes in $f_I(\varepsilon)$ can result from manipulating the plasma potential by the amplitude, shape and frequency of the LF and HF biases. This strategy extends to using pulsed DC boundary voltages, which control the maximum extent of the plasma potential, and so ion energies.

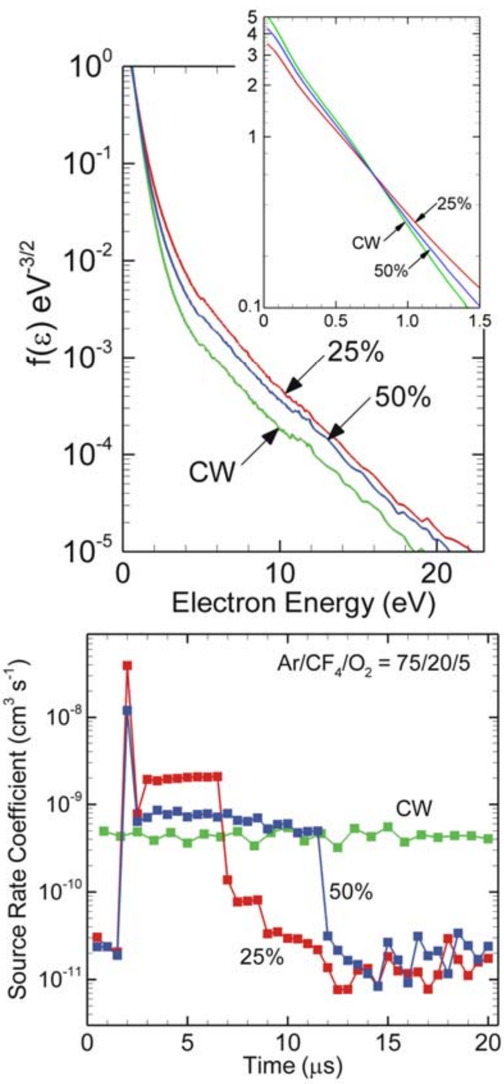

Fig. 2: (top) $f_e(\varepsilon)$ in an $Ar/CF_4/O_2$ dual frequency CCP for cw and with the HF pulsed for a PRF of 50 kHz with dc = 25% and 50%. The inset shows an enlargement at low energy. (b) Mole fraction weighted total electron source coefficient for dc = 25%, 50% and cw.

References

[1] M. J. Kushner, J. Phys. D **42** (2009) 194013.