Pulsed power modulation of the chlorine discharge:

A global (volume averaged) model study

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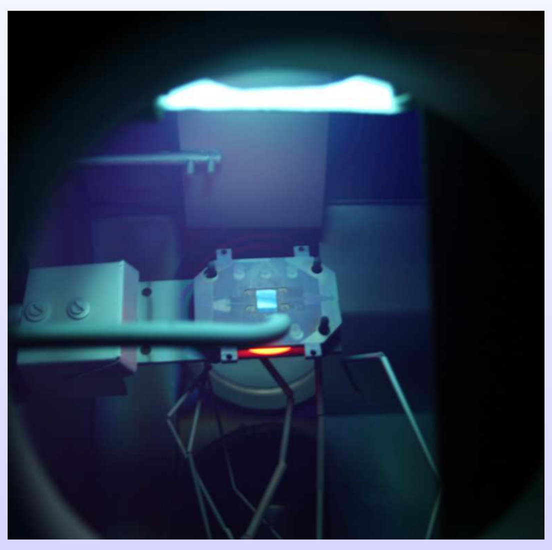

Introduction

- A global (volume averaged) model is applied to study a pulse modulated, low pressure (1 – 100 mTorr) high density Cl_2 discharge.
- Based on a previous model of a pulsed nitrogen discharge (Thorsteinsson and Gudmundsson, 2009b) and a steady state chlorine discharge (Thorsteinsson and Gudmundsson, 2009a). A follow up on Ashida and Lieberman (1997).

The global (volume averaged) model

- In addition to electrons, the discharge consists of ground state chlorine molecules $Cl_2(X\,^1\Sigma_g^+, v=0)$, vibrationally excited chlorine molecules $Cl_2(X\,^1\Sigma_g^+, v=1-3)$, ground state chlorine atoms $Cl(3p^5\,{}^2P)$, negative chlorine ions Cl^- and positive chlorine ions Cl^+ and Cl_2^+.
- Electrons are assumed to have a Maxwellian-like energy distribution in the range 0.01 – 10 V.
- The gas temperature is dependent on both power and pressure (Donnelly and Malyshev, 2000).
- The wall recombination coefficient γ_{rec} is dependent on the dissociation fraction (Stafford et al., 2009).

Results and discussion

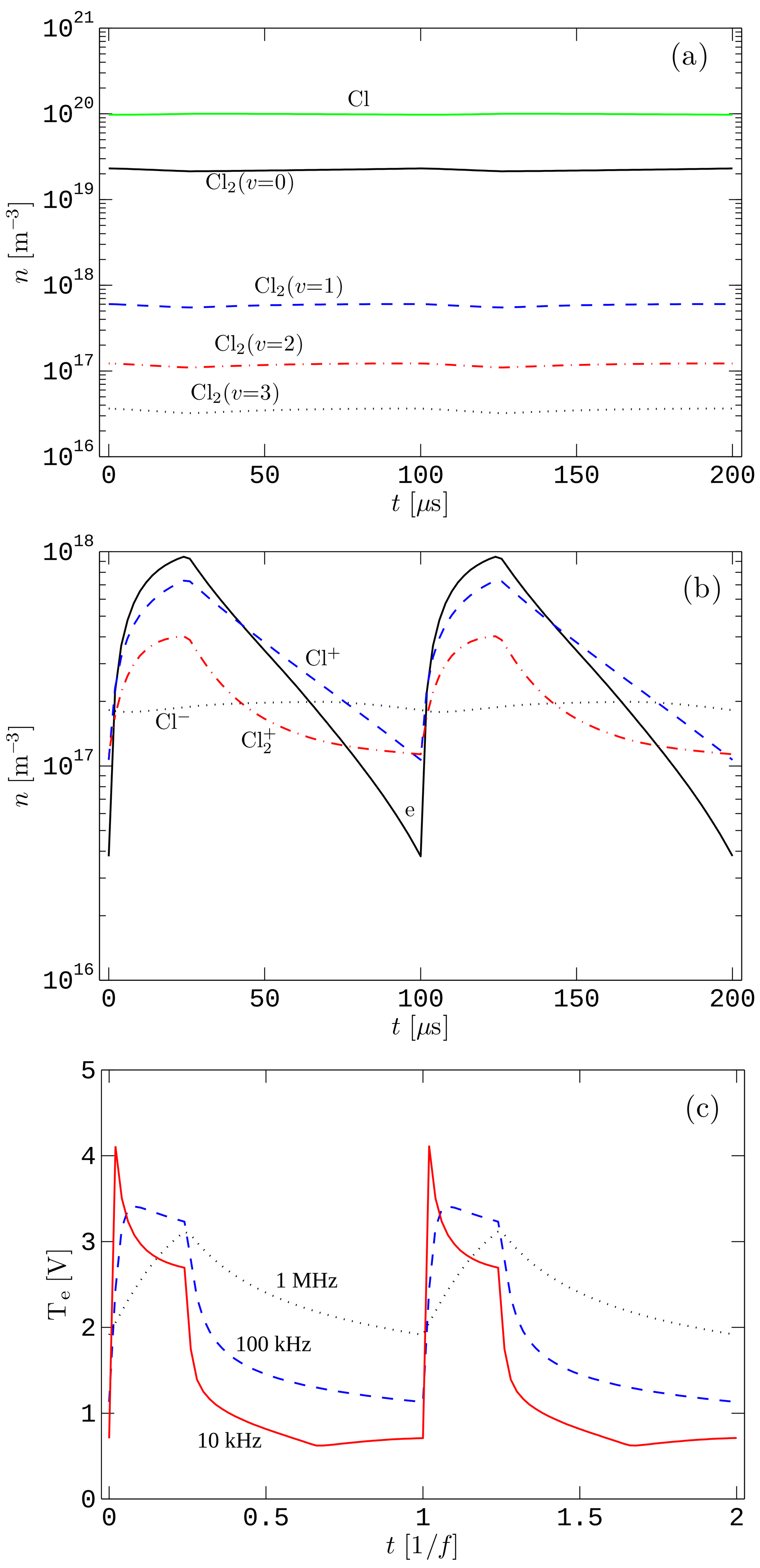

Figure 1: The temporal evolution over two pulse periods of the densities of (a) neutral species and (b) charged species at 10 kHz and (c) the electron temperature at 10, 100 and 1000 kHz.

- The chamber is assumed to be made of stainless steel, cylindrical with the dimensions $R = 10$ cm and $L = 10$ cm.
- The pressure is fixed at $p = 10$ mTorr, the average absorbed power at $\overline{P}_{abs} = 500$ W and the total gas flow rate at $Q_{Cl_2} = 100$ sccm.
- The absorbed power is of the form

$$P_{abs}(t) = \begin{cases} P_{max} & 0 \le t < \alpha T \\ 0 & \alpha T \le t < T \end{cases} \quad (1)$$

where α is the duty ratio, $T = 1/f$ is the pulse period and $P_{max} = \overline{P}_{abs}/\alpha$ is the peak power.
- The duty ratio is 25 % ($P_{max} = 2000$ W) and the frequency 10 kHz.

- The neutral densities, shown in figure 1(a), and the dissociation fraction are almost identical to when the power is continuous.
- As shown in figure 1(b), the densities of positive ions and electrons drop so rapidly during the off period that the simulation fails at frequencies lower than $\sim$ 10 kHz.
- The electron temperature, shown in figure 1(c), hits a minimum of about 0.6 V near the middle of the off period at 10 kHz.

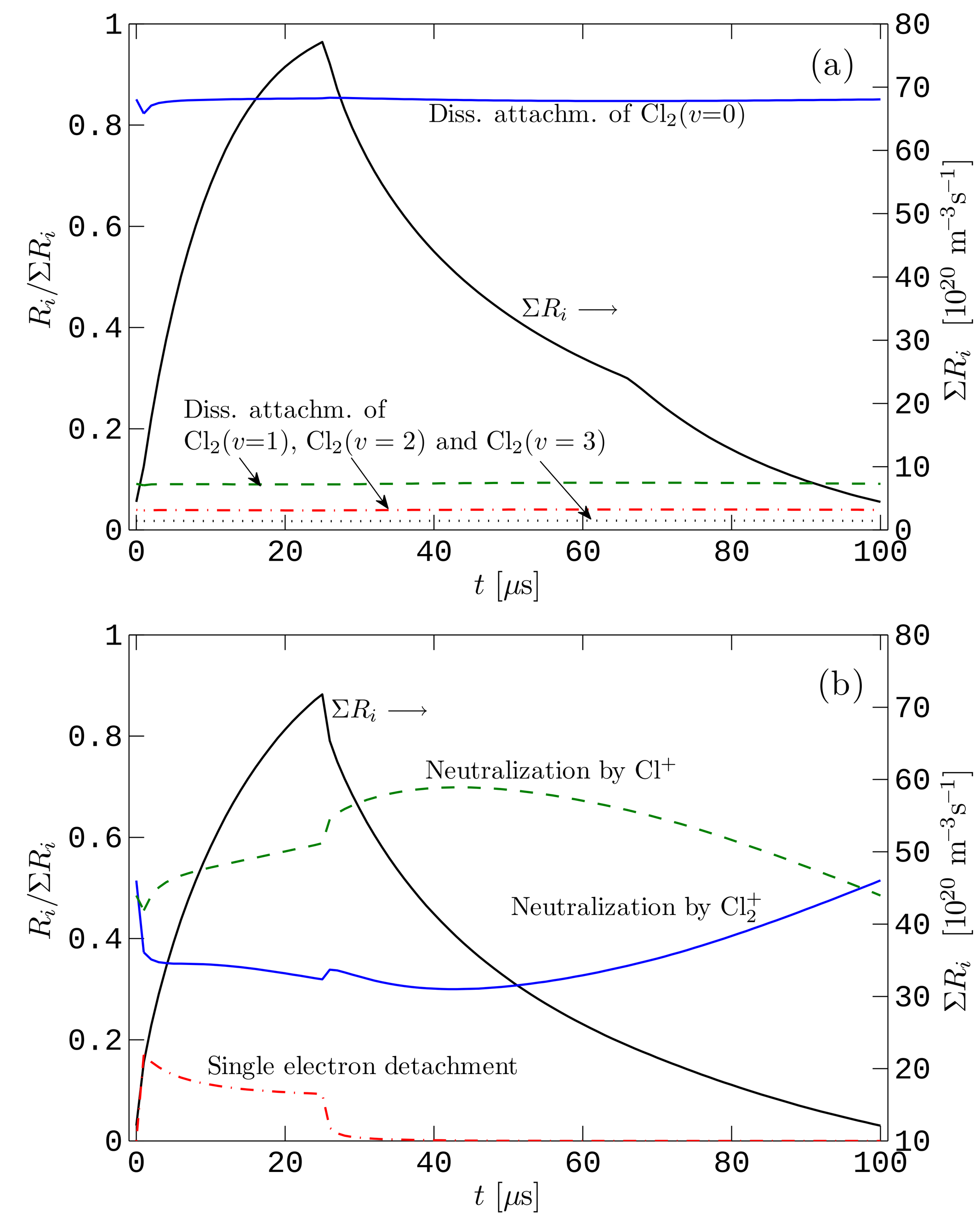

Figure 2: The temporal evolution over a single pulse period of the total and relative reaction rates for (a) the production and (b) the destruction of negative chlorine ions Cl^-.

- The Cl^- production mechanism, shown in figure 2(a), does not change between the the on and off periods, being dominated by dissociative electron attachment.
- Neutralization with positive ions dominates the destruction of Cl^- ions, as shown in figure 2(b), with electron impact electron detachment only playing a minor role during the on period.
- The total production/destruction decreases during the off period as a result of the rapidly decreasing electron and positive ion densities.

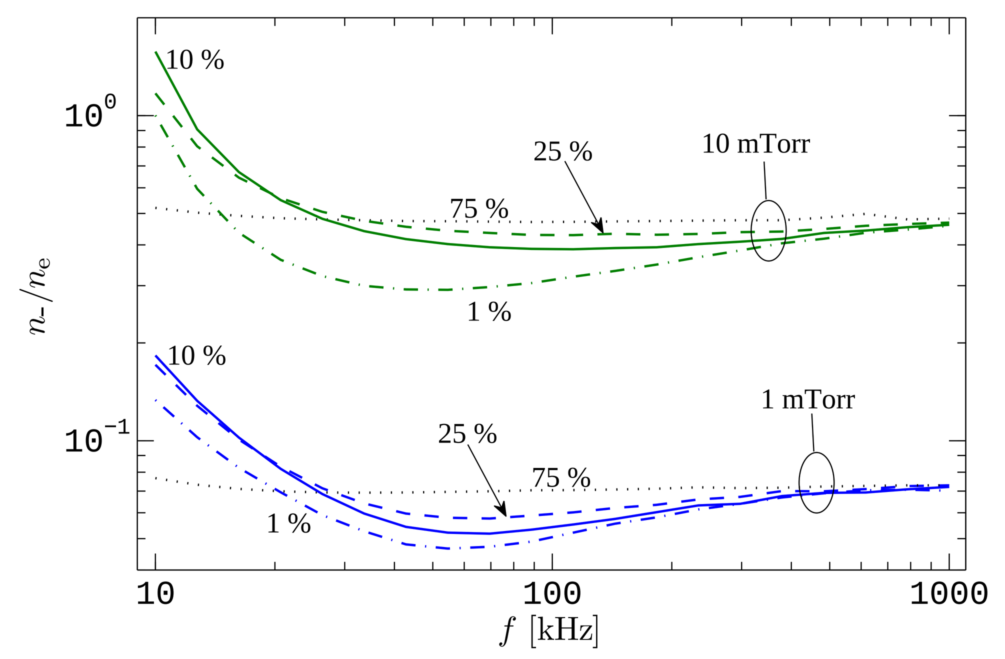

Figure 3: The average electronegativity n_-/n_e versus the modulation frequency for 1, 10, 25 and 75 % duty ratios at 1 and 10 mTorr pressures.

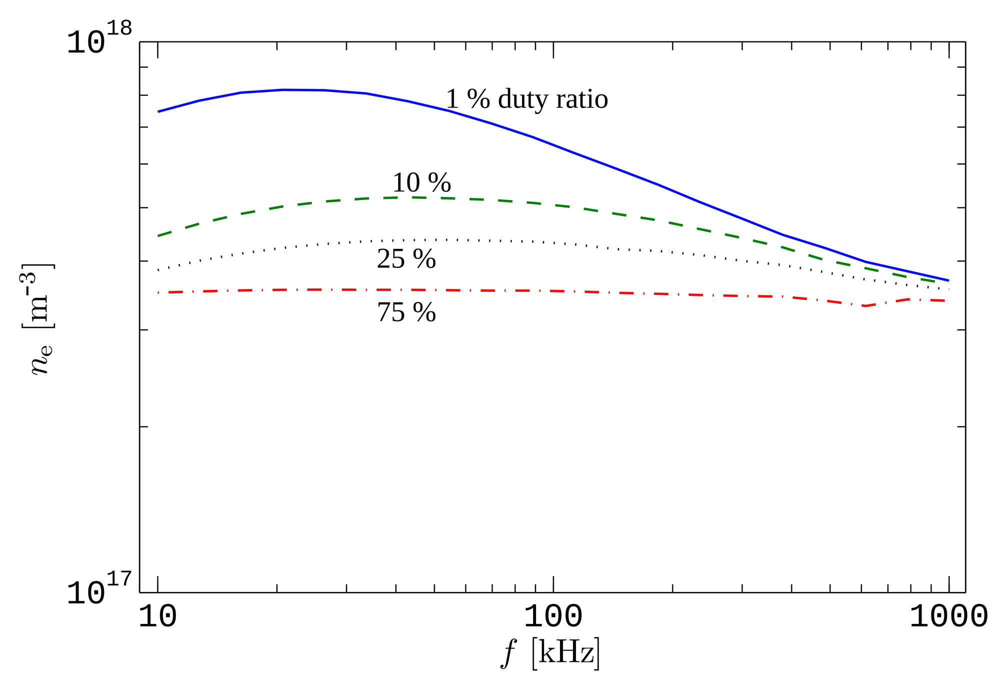

Figure 4: The average electron density n_e versus the modulation frequency for 1, 10, 25 and 75 % duty ratios at 10 mTorr.

- With a 10 % duty ratio the electronegativity, shown in figure 3, can be more than tripled at 10 kHz compared to a continuous power result.
- With a 1 % duty ratio at 20 – 30 kHz, the electron density, shown in figure 4, can be more than doubled compared to a steady state result.

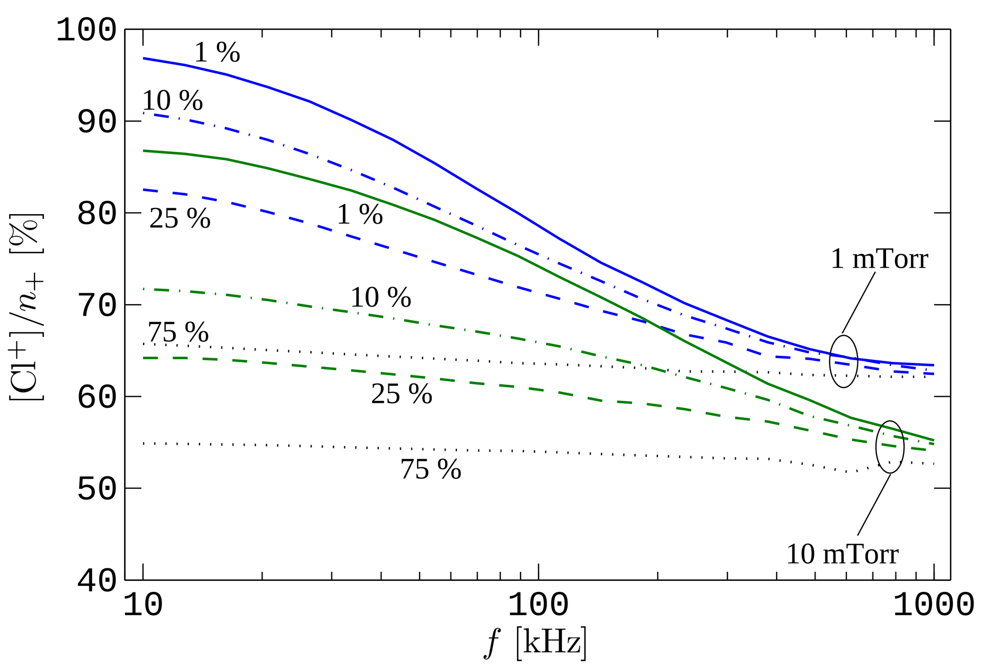

Figure 5: The fraction of Cl^+ positive ions versus the modulation frequency for 1, 10, 25 and 75 % duty ratios at 1 and 10 mTorr pressures.

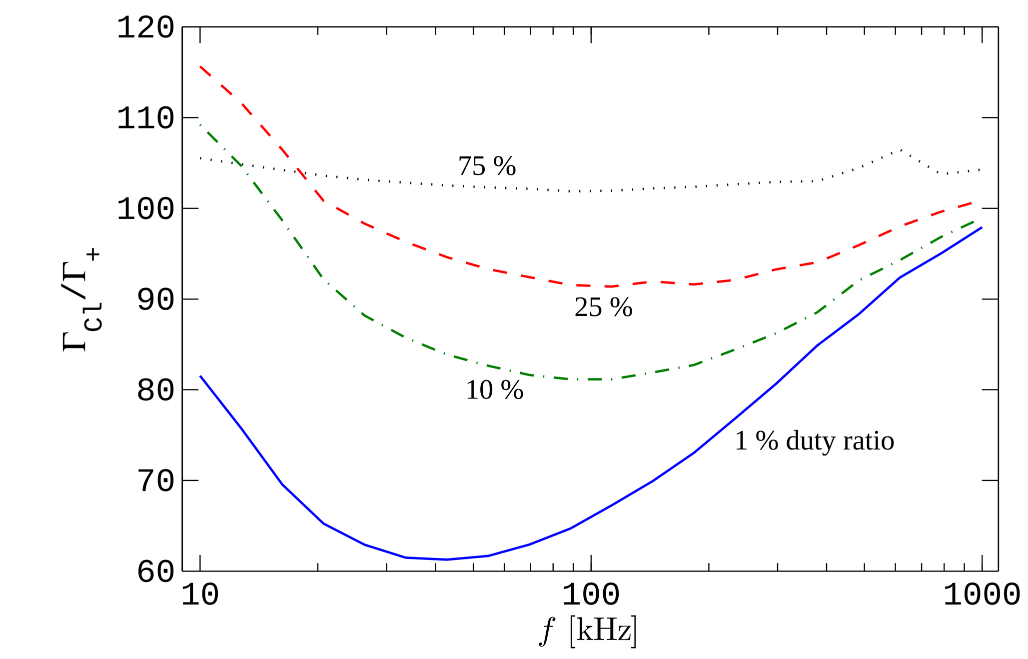

Figure 6: The average ratio of neutral chlorine atom flux to positive ion flux in the axial direction versus the modulation frequency for 1, 10, 25 and 75 % duty ratios.

- The fraction of Cl^+ positive ions, shown in figure 5, increases significantly by pulsing the power at either 1 or 10 mTorr.
- The fractional flux of neutral atoms and positive ions, Γ_{Cl}/Γ_+, shown in figure 6, changes significantly with both frequency and duty ratio.

Conclusions

- The mechanisms for production and loss of Cl^- are fundamentally the same during the on and off periods.
- In addition to pressure and power, the average electronegativity can be controlled effectively with the pulse duty ratio and frequency.
- The neutral densities and the dissociation fraction are mostly unaffected by pulsing the power.
- The electron density responds strongly to the pulsed power and can be more than doubled on the average compared to in the steady state.
- The fraction of Cl^+ positive ions $[Cl]/n_+$ and the etch selectivity Γ_{Cl}/Γ_+ can be controlled as well by the duty ratio and frequency.

Acknowledgments

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