Time-resolved microplasma electron dynamics in a pulsed microwave discharge

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Abstract

Microwave-driven microplasmas are typically operated in a steady-state mode in which the electron temperature is constant in time. Transient measurements of excitation temperature and helium emission lines, however, suggest that short microwave pulses can be used to increase the electron energy by 20–30%. Time-resolved optical emission spectrometry reveals an initial burst of light emission from the igniting microplasma. This emission overshoot is also correlated with a measured increase in excitation temperature. Excimer emission lags atomic emission, however, and does not overshoot. A simple model shows that an increase in electron temperature is responsible for the overshoot of atomic optical emission at the beginning of each microwave pulse. The formation of dimers and subsequent excimer emission requires slower three-body collisions with the excited rare gas atoms, which is why excimer emission does not overshoot the steady-state values. Similar results are observed in argon gas. The overshoot in electron temperature may be used to manipulate the collisional production of species in microplasmas using short, low-duty cycle microwave pulses.

1. Introduction

Microplasmas have been the subject of many studies due to their potential applications in lighting, nanoparticle charging, chemical sensing, materials processing and biomedicine [1–6]. Although there are many types of microdischarge, we focus on microwave-driven microplasmas that can be generated using microstrip transmission line resonators. These devices consume less than 1 W of microwave power and exhibit stable operation in a variety of gases [7–9]. Recently, arrays of microplasmas have been developed in order to increase the total surface area or volume of the microdischarge device [10–13]. Distribution of energy to multiple microplasmas operating in parallel is a challenge due to the negative differential resistance of the high pressure discharge as well as ionization-overheating instabilities [14]. In discharge arrays with more than one microwave resonator, efficient energy coupling among identical resonators allows a single power source to drive all resonators [15]. Using one- and two-dimensional arrays of microplasma opens the possibility to generate stable atmospheric plasma over a wider spatial span [15, 16]—a property that is potentially useful for treating large substrates or large gas flows. The focus of our previous studies has been exclusively on continuous steady-state microplasmas. In the current work, however, we will investigate the characteristics of pulsed microplasmas generated using a seven-element array of resonators driven at 1 GHz. The overall goal is to understand how the electron energy in the plasma may be controlled using short pulses of microwave power.

The effect of pulsed microwave power on plasma surface treatment has been studied previously by different groups [17, 18] using conventionally sized discharges. By changing the pulsing frequency and duty cycle, it is possible to emphasize the initial plasma ignition phase, the steady-state plasma, or the afterglow plasma. In this work, we typically use microwave pulse trains with 1 µs ‘on’ time and variable ‘off’ time. In both helium and argon we observe a burst in atomic emission intensity at the early stage of plasma development during each pulse of power. After the burst, the emission intensity settles quickly to its steady-state value on the order of 100 ns, and then decays to zero within 20 ns after
Figure 1. (a) General geometry of microwave arrays used in this work. (b) Three microplasma array boards with discharge gap sizes 100, 500, and 1000 µm from left to right, respectively. (c) Ignited plasma is shown in 400 Torr helium both with and without photoflash illumination (discharge gap size = 100 µm).

the pulse is turned off. (Readers may wish to preview the emission data in figure 4 for clarification of the phenomena.) The ratio of peak to steady-state emission intensity (i.e., overshoot) can be as large as 100:1 which suggests that these plasmas are more energetic during their early stages of development. Using time-resolved emission spectroscopy we find that the emission overshoot is correlated with an increase in the excitation temperature as determined using the Boltzmann method. A simple model is then developed which confirms the burst of atomic emission intensity is due to electron energy overshoot and also demonstrates that excimer emission lags the excited states due to slower three-body dynamics. Finally, we discuss different possible physical mechanisms including the enhancement of reduced electric field ($E/N$) prior to sheath formation and the release of electrical energy stored in the microstrip resonators.

2. Experimental detail

2.1. Microwave resonator arrays

The microwave resonator arrays used to generate microplasma in this work have a similar design to the large arrays described previously [15], but only 7 parallel resonators were used here in order to reduce power consumption. We fabricated three similar arrays using an LPKF circuit board prototyping machine. The three test devices were identical except for the length of the discharge gaps which were 100, 500 and 1000 µm. The base material was made from RT/Duroid 6006 with a relative dielectric constant of 6.15 and thickness of 2.5 mm. As seen in figure 1(a), each resonator in the array was a 1 mm wide strip of copper (17 µm thick) that was separated from its neighbouring resonator by 0.25 mm. The backside of the Duroid dielectric was covered by a copper ground plane. The devices were operated at their lowest resonant mode frequencies of 1.09, 1.14 and 1.17 GHz for arrays with 100, 500 and 1000 µm discharge gap sizes, respectively. A single power input was attached to the middle resonator of the array using a subminiature type-A connector (SMA). Figure 1(b) shows a photograph of the three plasma generators used in this work. Figure 1(c) shows the seven microplasmas which form in the parallel discharge gaps with both photoflash illumination (top) and natural illumination (bottom).

2.2. Experimental set-up

Figure 2 shows a schematic representation of the experimental set-up. Discharge power was supplied by a 30 W power amplifier (Amplifier Research, model 30S1G4) driven at nominally 1 GHz by a microwave signal generator (Agilent N5181A). A dual directional coupler (NARDA model 3022) and peak power sensors (Agilent E4417A) sample the peak power of the forward and reflected pulses which are displayed by an Agilent E4417A power meter. Due to limitations of
transient microwave power measurement, the discharge power reported in this work ($P_d$) is always the peak forward power measured during the 1 $\mu$s microwave pulse after subtraction of the peak reflected power. The forward power pulse is well-controlled, but the reflected power increases during the plasma formation period, therefore this measurement approximately represents the power absorbed by the steady-state phase of the 1 $\mu$s discharge.

 Plasma arrays were placed in a stainless steel vacuum chamber with an inner diameter of 9.5 cm. The chamber was evacuated to about 0.1 Torr with a rough pump prior to back-filling with 99.998% pure He or Ar gas to the desired experimental pressure. Gas pressure was registered using a capacitance manometer (MKS Baratron). The resonator array was positioned within the chamber such that the line of microplasmas was parallel to the entrance slit of the spectrometer. Emitted plasma light was directed by two imaging lenses (each with 10 cm focal length) onto the entrance slit of a 0.5 m imaging spectrometer (Princeton-SP2500) outfitted with a diffraction grating of 1200 grooves mm$^{-1}$ line density and a blaze wavelength of 500 nm. Instrumental broadening was about 0.3 nm for these experiments. One-to-one imaging let us capture light from all vertical positions of the plasma array at every shot. The spectrometer entrance slit was 120 $\mu$m wide which allowed light to be collected from the entire width of the 100 $\mu$m discharge gap device but only a portion of the plasma emission was captured from the larger discharge gap devices.

The emission spectrum was registered by a gated, intensified CCD camera (Princeton - PI-MAX) attached to the exit of the spectrometer. The camera was triggered by a synchronization pulse from the microwave signal generator. The CCD array dimensions were 1024 $\times$ 1024 pixels which occupied area of about 13.6 mm $\times$ 13.6 mm. The intensifier was gated on for 10 ns during each acquisition. Plasma emission was recorded at 20 ns intervals during the 1 $\mu$s microwave pulse and during the subsequent afterglow.

3. Analysis techniques

Transient optical measurements in helium are based on the intensity of atomic helium and He$_2$ emission. For intensity measurements, the measured emission was first fit with the instrument broadening function of the spectrometer and then the integrated area under this curve is reported. The strongest He transition, He 587.5 nm (2p$^3$P–3d$^3$D), was used to represent atomic emission [19] and the strongest emission in the excimer bandhead at 640 nm ($b^3\Pi_u – d^3\Sigma_u^+$) was reported for the dimer. Using any of the other atomic emission lines or other lines of the dimer band led to similar results. The details of the fitting process and quality of the fits were similar to those previously discussed by Monfared et al [20]. We determined the spectral response of the spectrometer from 350 to 800 nm using a calibrated tungsten lamp (Ocean Optics LS-1-CAL).

Excitation temperature measurements were based on Boltzmann plots of five atomic helium lines. This technique was previously described in detail [4, 20, 21]. Table 1 lists the specific lines used in the current work as well as their spectral properties.

Figure 3 shows two representative Boltzmann plots from a 400 Torr helium plasma obtained during the initiation phase ($t = 100$ ns) and steady-state phase ($t = 640$ ns) of the pulsed plasma. These excitation temperatures show that the higher energy excited states of helium are more populated during the plasma ignition phase shortly after the beginning of the microwave pulse. A detailed time-evolution of the microplasma’s excitation temperature will be described in the following sections.

4. Results and discussion

The detailed analysis of the plasma emission that follows is based on emission from the central 10% of the microplasma array. To confirm that the central portion of the microplasma

| $\lambda$ (Å) | Configuration | $E_{up}$ (eV) | $g_A$ (s$^{-1}$) | $g_A$ uncertainty |
|---------------|---------------|---------------|-----------------|-----------------|
| 3888.6        | 2s$^3$S–3p$^3$P | 23.007        | 8.53E+07        | 1%              |
| 5015.7        | 2s$^3$S–3p$^1$P | 23.087        | 4.01E+07        | 1%              |
| 5875.7        | 2p$^3$P–3d$^3$D | 23.074        | 1.06E+09        | 3%              |
| 7065.4        | 2p$^3$P–3s$^3$S | 22.718        | 8.33E+07        | 3%              |
| 7281.3        | 2p$^3$P–3s$^1$S | 22.920        | 1.81E+07        | 3%              |
array is representative of the entire array, we first present time-resolved images of the microplasmas taken during the initial 200 ns after the beginning of the microwave pulse as seen in figure 4(a). After a delay of 20–40 ns, the emission from all seven microplasmas increases simultaneously. The emission intensity for these experimental conditions peaks at 80 ns and then decays to a much reduced steady-state intensity by 200 ns. The edges of the array are known to have slightly reduced voltage [15] which explains their slightly reduced brightness. In general, all the microplasmas ignite simultaneously and without any evidence of discharge propagation, unlike the overshoot phenomenon. We prepared three resonator arrays considered to be representative of the microplasmas at any central region of the linear array, but may be reasonably expected to be representative of the microplasmas at any part of the array.

In figure 4(b) the spatially integrated transient emission intensity of atomic species in atmospheric helium and argon plasmas are compared. The microwave pulsed power had ‘on’ and ‘off’ times of 1 µs and 4 µs, respectively. There is a peak to steady-state emission ratio of ~100 : 1 from the He discharge intensity, similar to the images shown in figure 4(a). This overshoot is significantly larger than that of Ar emission (~4 : 1). The physical origins of the burst of emission and differences between Ar and He will be revisited in the modelling section. The existence of such large emission overshoots is interesting, and shows that these microplasmas are highly dynamic in their early stages of evolution. Since this may potentially enable us to control plasma characteristics by changing the microwave pulse properties, it is desirable to identify possible causes for this phenomenon.

4.1. Reduced electric field

To study the possible role of reduced electric field (E/N) on the overshoot phenomenon, we prepared three resonator arrays with different discharge gaps ≥100 µm in an effort to decrease the electric field. All array characteristics other than the discharge gap size were identical to the array described above. While we had good operational consistency from plasmas generated using the array with the normal gap size (100 µm) at all pressures up to 1 atm, the 500 µm and 1000 µm discharge gaps only generated consistent plasmas when operated in helium pressures lower than 500 Torr (~0.7 atm). Therefore, for the purposes of comparing E/N, all of the experiments are operated below atmospheric pressure. Figure 5 shows transient emission intensity (top panels) and measured excitation temperature (bottom panels) for microplasmas generated from devices with gap sizes of 100, 500 and 1000 µm. This experiment was performed at a reduced pressure of 350 Torr helium to accommodate the larger discharge gaps.

Figure 5 shows that for every gap size the overshoot in emission intensity corresponds to an overheating of the excitation temperature above the steady-state value. The nominal gap size of 100 µm has the most sharply peaked emission intensity and >30% overshoot in excitation temperature. Extending the discharge gaps to 500 and 1000 µm results in a <20% excitation temperature excursion and a flatter, broader transient emission profile. For a given input power, the gap voltage created by the resonators is roughly the same in each device; the devices with larger gaps, however, will have lower electric fields and (prior to plasma formation) will also produce a lower reduced field (E/N). Here E is electric field and N the neutral He density. These two parameters control the electron temperature through the Boltzmann equation. Therefore, the results of this section are consistent with temporal electron overheating by the microwave electric field in the period prior to full plasma formation. Once the plasma is formed, the electric field exists primarily in the electron-depleted sheath regions adjacent to the resonator’s tip and the ground electrode. The central microplasma, shielded by the fully formed plasma sheath, is nearly field-free and therefore the electron temperature relaxes later in the pulse.

4.2. Residual plasma density

The effect of residual plasma on the initial transient is summarized in figure 6. In this series of experiments the plasma pulse is held constant at 1 µs while the ‘off’ time is increased from 1 µs to 30 µs. The relative emission intensity overshoot of figure 6(a) is minimum for short off-times, but the overshoot increases as the plasma is allowed to more completely decay for longer ‘off’ times. Beyond approximately 15 µs of plasma decay, the degree of emission overshoot is found to saturate. Korzec et al [23] report that the lifetime of metastable helium in a dielectric barrier discharge is approximately 6 µs at 1 atm. Wang et al [24] attribute reignition of microplasma to photoelectrons emitted by long-lived excited states, while also observing that residual electrons are much more rapidly depleted. Using these previous studies, it is reasonable that this pulsed microwave source is more readily reignited for ‘off’ times of less than 10 µs due to residual metastable atoms. Increasing the time that the plasma decays between power

Figure 3. Typical Boltzmann plots used for excitation temperature measurements. To demonstrate the initial overheating of the microplasma electron energy, sample plots are shown at 100 and 640 ns after plasma initiation. Plasma was generated in 400 Torr He using a resonator array with 100 µm gap size.
Figure 4. (a) Time-resolved images of a seven-element helium microplasma array showing spatial uniformity and optical emission overshoot (400 Torr, 3 W). (b) Emission spectroscopy of excited atomic species intensity comparing the temporal profiles in pure He (587.5 nm, red circles) and Ar plasmas (811.5 nm, blue diamonds) at one atmosphere. The microwave pulse had ‘on’ and ‘off’ times of 1 and 4 µs. Power was ∼2 W and ∼10 W for helium and argon, respectively.

Figure 5. Emission intensity (top row) and excitation temperature (bottom row) during a 1 µs pulse in 350 Torr He for plasmas generated using devices with gap sizes of 100, 500 and 1000 µm. Typical error bars for the peak and steady-state temperatures are added to the first panel. Peak plasma power was ∼3 W in all cases. The solid lines represent the modelled excited state density as described in the text. The dashed lines are the piece-wise linear approximations of the electron temperature used in the simulations.

Pulses also increases the time required to re-strike the discharge as shown in figure 6(b) and the ‘off’ time scale is also consistent with that reported for metastable decay.

Time-resolved measurements of the afterglow period (t > 1000 ns) show that the microplasma emission is quenched on the order of 10 ns (see figure 7). This observation is independent of the discharge gap size. The electron energy rapidly relaxes at high pressure once the power is off and optical emission decays on the order of the lifetime of the upper-level excited states. Although the plasma emission decays
Figure 6. Effect of plasma ‘off’ time on (a) the He emission intensity overshoot and (b) the delay of the next emission burst. In all cases, a 1 µs pulse with peak power of 3 W was applied to 100 µm devices at 1 atm.

Figure 7. Atomic He emission intensity decays within 20 ns after the end of the microwave pulse (t = 1000 ns).

rapidly, some cold electrons and metastable atoms remain in the vicinity of the discharge gap for longer time scales. It is primarily the metastables which are believed to contribute to the ‘off’ period phenomena reported in figure 6 by seeding the next discharge pulse with photoelectrons, thus diminishing the electric field required for the next discharge ignition transient.

4.3. Stored energy

The microwave resonators used to initiate the microplasma have high quality factors and large stored energy. This section considers how the energy stored in a resonator prior to plasma ignition might affect the transient electron temperature. When power is initially applied to a resonator, energy is stored in the device. The voltage at the resonator’s tip builds to a value on the order of 150 V at which point the microplasma is initiated. In the steady-state, the resonator voltage is reduced by the discharge impedance to only the order of 20 V while sustaining an atmospheric pressure plasma in argon [25]. The rapid decrease in resonator voltage during ignition indicates there is a dissipation of the energy that was stored during the startup transient. This stored energy may be partially responsible for the observed burst of emission.

The amount of stored energy can be estimated from the definition of the quality factor $Q$:

$$Q = \frac{2\pi f E_{\text{stored}}}{P_{\text{loss}}}$$

Here $P_{\text{loss}}$ is the dissipated power. Provided that the input power is slowly increased when determining the ignition power, the resonator’s stored energy is in equilibrium and $P_{\text{loss}} = P_{\text{in}}$. Using this relation, we calculate the stored energy in resonators with 100, 500 and 1000 µm gap sizes at the moment of ignition. The quality factor was measured using a vector network analyser (Agilent E5061B). Startup power was experimentally determined as the minimum power required to turn on one resonator in the array. This was measured by gradually increasing microwave power and recording the power at which emission was first observed. Results comparing the three discharge gap sizes for normalized energy stored are summarized in table 2.

The devices with larger discharge gaps required an increased input power to start the plasma. The additional power increases the gap voltage at initiation and, more importantly, increases the stored energy in the resonators. The data of figure 5 show that the two devices with the larger discharge gaps had less intensity overshoot, but the duration of that overshoot was longer (full-width at half-maximum). The last column in table 2 shows the duration of intensity overshoot as determined from figure 5. The intensity overshoot lasts longer if there is an increase of the stored energy immediately before plasma ignition. The actual situation is not so simple, however, because the larger discharge gaps also decrease the power density and therefore will support a less dense plasma. In addition to lower electron density, the longer discharge length will result in a larger plasma resistance. A larger energy stored in the resonator which is dissipated more slowly through the longer, more resistive plasma is consistent with the observed longer, less peaked startup transient. The mechanism is somewhat speculative at this point, but it is demonstrated that the larger discharge gap dimensions will increase the

| Gap size (µm) | $P_{\text{in}}$ (W) | $E_{\text{stored}}$ (J) | $E_{\text{stored}}$ Normalized | Normalized overshoot duration |
|---------------|----------------------|-------------------------|-----------------------------|-----------------------------|
| 100           | 370                  | $0.40 \times 10^{-8}$   | 0.46                        | 0.25                        |
| 500           | 340                  | 0.98                    | $4.65 \times 10^{-8}$       | 0.98                        |
| 1000          | 320                  | 1.09                    | $4.74 \times 10^{-8}$       | 1.00                        |

Table 2. Properties of microwave resonator arrays used in this work and the normalized stored energy upon discharge ignition.
duration of the excitation overheating even though the degree of overheating is less (see figure 5).

5. Modelling of excited state and dimer densities

It is counter-intuitive that the rather small measured increase in excitation temperature could generate such a large overshoot in plasma emission intensity. To investigate this phenomenon more closely, a simple model is presented which predicts the time-dependent densities of He* and He₂ based on the appropriately scaled measurements of the transient excitation temperature. The purpose of the model is not to provide a rigorous treatment of the transient microplasma, but to test the validity of the overheating hypothesis. Only two production reactions are considered in this model. The generation of a ‘jumped’ excited state of the rare gas, 

\[ \text{He} + e \rightarrow \text{He}^* + e, \]

with a rate constant given approximately by \( K_{\text{ex}}(T_e) = 4.3 \times 10^{-7} \text{e}^{-26/T_e} \text{cm}^{-3} \text{s}^{-1} \) [26] with \( T_e \) in eV, and a three-body collision that creates dimers, 

\[ \text{He}^* + 2\text{He} \rightarrow \text{He}_2 + \text{He}, \]

with a rate constant given by \( K_{\text{dimer}} = 1.6 \times 10^{-32} \text{cm}^{-6} \text{s}^{-1} \) [27].

The latter three-body reaction depends on the ground state helium atom density and therefore is much more rapid at higher pressures. The excited state of helium is lost by a number of processes, but we combine all of the loss mechanisms into a single rate which is based on the experimentally observed decay of emission in figure 7, \( K_{\text{de-ex}} \sim 1/(10 \text{ns}) \).

The loss of the dimer is attributed to dissociative ionization and collisional quenching with surfaces and impurities (M),

\[ 2\text{He}_2 \rightarrow \text{He}^+_2 + 2\text{He} + e \]

\[ \text{He}_2 + M \rightarrow 2\text{He} + M. \]

The dissociative ionization rate constant is found in the literature to be \( K_{\text{diss}} = 1.5 \times 10^{-9} \text{cm}^{-3} \text{s}^{-1} \) [27]. The rate constant for the quenching reaction is unknown, but is found to have little effect on model results for the short time scales of these pulsed discharges. An estimated rate constant of \( K_{\text{quench}} \sim 10^{-14} \text{cm}^{-3} \text{s}^{-1} \) for self-quenching allows the model to predict the slow saturation of excimer emission reported by the Schoenbach group, however [28]. This minimal set of collision reactions gives the following differential equations:

\[ \frac{d}{dt} [\text{He}^*] = K_{\text{ex}}(T_e)n_e [\text{He}] - K_{\text{de-ex}} [\text{He}^*] \]

\[ \frac{d}{dt} [\text{He}_2] = K_{\text{dimer}} [\text{He}^*] [\text{He}]^2 - K_{\text{diss}} [\text{He}_2] [\text{He}^*] - K_{\text{quench}} [\text{He}_2] [M] \]

As a first approximation, we assume that the free electron temperature is proportional to the measured excitation temperature. Our measured excitation temperature \( T_{\text{exc}}(t) \) is next scaled to estimate \( T_e(t) \) as shown in figure 5. The scale factor was set according to Kono’s steady-state Thompson scattering measurement of \( T_e \) in helium at 1 atm (\( T_e \sim 1.2 \text{eV} \)) [29]. The two differential equations are then readily solved for generation and loss of He* and He₂ by assuming that the electron density is constant at \( n_e = 10^{13} \text{cm}^{-3} \) for the duration of the microwave pulse from \( 0 < t < 1000 \text{ns} \).

The normalized excited state helium density from this crude model is included in figure 5 and predicts the salient feature of the experimental observations, namely the large initial overshoot in He* emission. The model also predicts that the excimer density does not overshoot, but increases slowly after the plasma lights. This rise in excimer density is pressure-dependent and is slower at low pressure (i.e. 200 Torr) due to the reduced three-body collision rate with excited helium. Finally the model captures the very gradual increase in He₂ observed by Schoenbach’s group near the end of each pulse. These models for dimer density are superimposed on the measurements of the helium excimer emission (\( b^3\Pi_g^+ \rightarrow a^3\Sigma_u^- \)) at 640 nm and the atomic helium emission at 587.5 nm (2\( p^3P \rightarrow 3d^3D \)) in figure 8.

The model also predicts similar results for argon microplasmas. The rate constants are changed to reflect those for total argon excitation and argon dimer formation: \( K_{\text{ex}}(T_e) = 2.2 \times 10^{-7}\text{e}^{-12.2/T_e} \text{cm}^{-3} \text{s}^{-1} \) [30] and \( K_{\text{dimer}} = 1.7 \times 10^{-32} \text{cm}^{-6} \text{s}^{-1} \) [31]. The electron density is increased to \( n_e \sim 10^{14} \text{cm}^{-3} \) based on experimental data from Miura and Hopwood [25]. The steady-state electron temperature is adopted from the Thompson scattering measurements of argon microplasma by the Donnelly group: \( T_e = 0.9 \pm 0.3 \text{eV} \) [32]. We have not measured the transient excitation temperature in pulsed argon plasma, so we simply reuse the helium.

![Figure 8. Time evolution of normalized atomic He (587.5 nm) and He₂ (640 nm) emission intensities in (a) 200 and (b) 500 Torr He plasmas (discharge gap = 100 \( \mu \text{m} \)). The solid and dashed lines represent the model output for excited and dimer helium density, respectively, as described in the text.](image-url)
temperature evolution, rescaled to Donnelly’s data. The Ar* production is compared with helium in figure 9. The peak excited state density for argon was $7 \times 10^{12}$ cm$^{-3}$ which is consistent with laser diode absorption measurements of the dominant metastable state density [33]. Most notably, the model reproduces an emission intensity overshoot in argon similar to that of helium. The degree of overshoot in argon is significantly less than that of helium plasma in agreement with the experimental comparison given in figure 4(b). Physically, the excitation threshold for argon is much lower than that of helium, making the production of Ar excited states less sensitive to small increases in electron temperature. The minimal reaction set and fixed electron density make this model an approximation at best. In the future, the effect of transient electron density $n_e(t)$ will be measured and used to further refine the model.

6. Conclusion

Pulsed microwave discharges show dramatically increased optical emission and excitation temperature during the first $\sim 100–200$ ns after ignition. The degree of overshoot is greater for smaller discharge gap dimensions, suggesting that the electrons are being overheated by unshielded electric fields prior to plasma sheath formation. The duration of the energetic overshoot is found to be extended in microplasmas formed in discharge gaps with greater lengths. A possible explanation for the expansion of this overshoot timing is greater stored energy in the resonant circuit combined with a slower dissipation of that energy in the longer, more resistive discharge. The degree of energetic overshoot was also found to be correlated with the ‘off’ time of the microplasma between pulses. Longer ‘off’ periods allow the excited state density in the afterglow to decay more completely. This decay then requires a higher restart voltage for the following pulse, producing a higher $E/N$ and more stored energy in the resonator. All of these conditions contribute to greater overshoot and a longer delay to restart the plasma.

A model for the pulsed plasma is used to verify that an electron temperature overshoot on the order of 20–30% may generate optical emission overshoots of 100 : 1 in helium at atmospheric pressure. The simple simulation of excited state density and dimer density provides qualitative agreement with the experimental observations of transient emission. Specifically, excited states are overproduced by ratios on the order of 100 : 1 in the initial phases of the helium plasma and $\sim 10 : 1$ in argon plasma. The rare gas excimer emission, however, does not show any overshoot and the model confirms that this observation is due to the slow three-body reaction for dimer formation.

In summary we find that it is possible to control the electron energy in microwave microplasmas by selecting the pulsing width and duty cycle of the power source. Short pulses of approximately 100 ns with long ‘off’ periods will allow the energetic initial plasma to dominate and significantly enhance electron collisional production rates relative to the steady-state discharge. The afterglow at high pressures is very short ($\sim 10$ ns) and probably does not offer much practical benefit in rare gases.

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