Effect of power modulation on properties of pulsed capacitively coupled radiofrequency discharges

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Abstract. We describe measurements of plasma properties of pulsed, low pressure, capacitively coupled discharges operated in argon. The research aims to determine the effect of modulating the radiofrequency power during the discharge part of the pulse cycle. Measurements of local electron density and optical emission were made in capacitively-coupled rf discharges generated in a Gaseous Electronics Conference (GEC) reference reactor. Gas pressure was in the range 7 – 70 Pa, rf power in the range 1-100 W and pulse durations in the range of 10 μs - 100 ms. The results indicate that the ignition and afterglow decay processes in pulsed discharges can be controlled by modulating the shape of applied radiofrequency pulse.

1. Introduction

For many plasma applications it is necessary to control different plasma properties independently of each other. For example, in low pressure discharges used for applications such as reactive ion etching [1,2], ion flux and ion energy are strongly coupled and it is difficult to change one without affecting the other [3]. For applications that require highly electronegative discharges [4,5], it is desirable to have both low energy and high energy electron populations, which is difficult to achieve in the same discharge. To meet these challenges, a variety of methods have been developed to control plasma properties. Crude control can be achieved by changing gas pressure or applied power, while finer control has been achieved using methods such as discharge pulsing, DC biasing of electrodes and two-frequency operation [6,7].

Pulsing of the discharge has been used to control plasma properties in a range of applications in low pressure discharges. In electropositive plasmas, pulsing of the discharge power [8,9] and/or the bias voltage on substrate-bearing electrodes [10,11] has been shown to be effective at modulating the flux of species to the substrate. In electronegative plasmas, pulsing is used for production of high negative ions yields: the discharge part of the cycle is used to generate high electron density while the afterglow period is used to generate high negative ion densities as the cold electrons attach to molecules, which then form negative ions by dissociative attachment [12]. Studies have shown that some control of the negative ion yield can be achieved by varying the duration and duty cycle of the pulses [4].

The aim of the research reported in this article was to investigate the physical processes that occur in pulsed plasmas when the pulse shape is altered in a systematic way. The principal aims were to understand the way that ionization occurs within the discharge pulse, the way the charged species decay in the afterglow, and the role of the charged particle remnants in ignition of the following discharge pulse. The experiment was performed in an argon capacitively coupled discharge. Measurements of electron properties were made using Langmuir [13] and hairpin [14-16] probes. Plasma emission was measured using a spectrometer and a gated ICCD camera.

2. Experimental setup

The research was performed in a Gaseous Electronics Conference (GEC) reference reactor [17] operated in capacitive mode. The apparatus is shown schematically in Figure 1. The discharge was generated between stainless steel planar electrodes with radius of 101.6 mm and separation of 25.4 mm. The rf power had frequency of 13.56 MHz, and was generated by an Agilent 3250A Arbitrary Waveform Generator whose output was then amplified. This power was modulated by pulses generated by the same device. This system gave pulses, after amplification, with rise times of less than 1.5 μs.

Experiments were performed over gas pressures ranging from 7 to 70 Pa (50 and 500 mTorr), with the majority of measurements being made at a pressure of 27 Pa (200 mTorr). The rf power ranged from 2 to 100 W. Between measurements, the chamber was pumped to a base pressure of less than 10^{-3} Pa.

Measurements of electron properties were made using a combination of a Hiden Langmuir probe and a self-made hairpin probe. The hairpin probe is based on a microwave antenna immersed in the plasma: measurements of the probe's resonance frequency can be used to determine electron density. Details of probe operation can be found in refs [14-16].

An Andor ICCD camera (model DH 534-18F-01) was used to measure plasma emission while a Horiba TRIAX320 spectrometer was used for spectrally resolved measurements.

3. Results and discussion

3.1. The standard case

In the first part of the study, we measured the time dependence of the electron properties for a square rf pulse applied to a discharge at pressure of 27 Pa. This was done in order to provide a reference against which later measurements could be compared. Results are shown in Figure 2, which shows the electron density and plasma emission as a function of time throughout one pulse cycle. The light intensity shown in Figure 2 is plasma emission integrated over wavelengths in the range 300-900 nm. Spectrally resolved measurements of individual emission lines (e.g. the ArI 4*p*-4*s* transition at 750.4 nm), showed the same dependence.

We have chosen to plot emission intensity rather than electron temperature because the eedf changes rapidly throughout the pulse and it is hard to meaningfully assign a single temperature to the electron population. In particular, it is strongly non-Maxwellian in the ignition phase of the pulse, and measurement by Langmuir probe is difficult. Conversely, the light emission is smoothly varying, extremely reproducible and provides is closely related to the eedf.

The results fell into two categories. For applied power greater than 30 W and pulses with afterglow period longer than 500 μs, results characteristic of a typical, pulsed, low-pressure discharge were obtained. The electron density increased in the early part of the pulse, with the two types of probes giving similar results. The light emission peaked strongly in the first 10 μs of the pulse before becoming constant, indicative of an electron temperature that peaked early in the pulse and then settled to a constant value. For lower pulse powers, the electron density behaved similarly but there was no peak in plasma emission and and hence no corresponding peak in electron energy.

This general behaviour is well understood from previous experimental and numerical studies of pulsed discharges [18]. The electron energy falls extremely rapidly after the end of the rf pulse, as the electrons thermalise with the background atoms and ions. The electron density decreases much more slowly as the cool electrons diffuse away to the chamber walls. When the afterglow is sufficiently long, the fewer electrons present at the start of the pulse absorb the rf power and are accelerated to high energies. These electrons undergo inelastic collisions with background gas atoms, causing ionization and emission, and then rapidly come to equilibrium as both the electron energy and density stabilize. When the afterglow period is short (and hence the number of background electrons is high), or the rf power is low (and hence the power per electron is low), the absorption of energy by the background electrons is not as sharp, and hence there is no rapid increase in electron temperature at the start of the pulse and no corresponding spike in plasma emission.

A secondary feature of the results shown in Figure 3 is the small increase in electron density that occurs after the rf pulse has ended. This well-known effect occurs because electrons cool rapidly in the first few microseconds after the end of the rf pulse, which greatly reduces their diffusion, but electron production through Penning ionization remains high [19].

The results shown in Figure 3 arise because of the behaviour of the electrons that remain at the end of the afterglow period. The density of electrons at this time can be controlled to some extent by varying the duration of the rf pulse, which determines the density of electrons at the beginning of the afterglow, and the duration of the afterglow period, which determines the extent to which electrons diffuse from the plasma. Figure 4 shows measurements from a set of pulsed discharges in which the rf pulse time was kept constant while the afterglow period was varied. The results show the afterglow period greatly affects the ignition phase of the discharge cycle.

As for the general case shown in Figure 3 and discussed above, the results of Figure 4 can be understood in terms of the decay of electron energy and density in the afterglow period. If the afterglow period is short, there is a large density of cool electrons to absorb the rf power in the early part of the rf pulse, and so the discharge reignites in a straightforward way and is rapidly re-established. When the afterglow period is long, there are fewer electrons present when the rf power is applied, and this produces a more dramatic ignition phase, as discussed above.

The time required for the discharge to decay sufficiently to produce an energetic ignition phase depends on the time needed for significant electron diffusion in the afterglow period, and so will depend on chamber dimensions and background gas pressure. For this case, a 27 Pa pulsed discharge in the GEC reactor, the time is the order of a few hundred microseconds.

3.2. Effect of pulse modulation

The results shown in Section 3.1 demonstrate that plasma properties can be controlled to some extent by manipulating the pulse cycle. However, while a range of conditions can be obtained, it is still difficult to independently control basic plasma properties. For example, the evolution of electron energy during plasma ignition depends strongly on the electron density at the end of the afterglow.

Following on from those results, we then examined the possibility of further control by testing the effect of modulating the amplitude of the rf pulse during the pulse itself. Experiments were performed using a fixed pulse frequency (1 kHz) and a fixed duty cycle (50%) at a gas pressure of 27 Pa. Measurements of electron density and plasma emission were made for three pulse shapes.

Figure 3, already discussed, shows the measured properties for a square pulse. As noted above, the plasma is characterised by a sudden increase in electron temperature during the ignition phase, a sudden decrease in electron temperature immediately after the pulse end, and more gradual changes in electron density throughout the pulse cycle.

Figure 5 shows results obtained for a pulse that increases linearly in amplitude over the first half of the pulse duration. The results show that there is no 'overshoot' in plasma emission in the ignition phase, corresponding to a much more gradual increase in electron temperature during the first part of the pulse, while the electron density rises more gradually to reach the same value as obtained for the square pulse case. Properties during the afterglow appear to be similar for this pulse and the square pulse case. Generally, the discharge properties appear markedly different in the ignition phase but similar for the rest of the pulse cycle. These results indicate that the ignition phase of the discharge can be controlled by controlling the rise of rf power, and the sudden transient increase of electron energy avoided without significantly affecting the electron density.

Figure 6 shows the results measured for a pulse that starts in the same way as the square pulse but decreases linearly in amplitude over the second half of the pulse. The plasma properties in this case appear to differ significantly from those of the square pulse both during the rf pulse and in the afterglow. While there is a similar 'overshoot' in plasma emission during ignition, it is more sustained for this pulse and settles to a larger equilibrium value. The electron density increases similarly in both cases for the first half of the pulse, then differs markedly as the density in the modified pulse case decreases with the pulse amplitude during the second half of the pulse. The different in properties during the ignition part of the cycle may be due to different electron energy distributions existing at the end of the afterglow (i.e just before the onset of ignition).

These results show significantly different decay in plasma properties as the rf power is reduced. In the square pulse case, the electron energy falls extremely rapidly while the electron density decreases at a rate controlled mainly by diffusion. Hence, the afterglow is characterised by significant electron density and very low electron energy. In the modified pulse case, the electron density falls gradually during the second half of the pulse, where the applied power is linearly decreasing in magnitude. During this part of the pulse, the plasma emission, and hence the electron energy, remains high. This part of the pulse cycle is hence characterised by decreasing electron density but those electrons possess significant energy.

These results show that, as might be expected, the plasma properties are significantly affected by modulating the amplitude of the rf pulse. They also show, however, that the electron energy and the electron density can be manipulated separately so that a wider range of plasma conditions can be obtained.

4. Conclusion

The aim of this research was to investigate the physical processes that occur in pulsed capacitively-coupled plasmas when the pulse shape was altered in a systematic way. Experiments were performed in an argon discharge operated in the GEC reference reactor.

We found that modulating the pulse amplitude had a significant effect on the discharge properties, with changes in both the electron density and the electron temperature being observed. These changes were attributed to the reaction of the electron energy distribution to the changes in applied rf power.

The measurements reported in this article were made using argon, an atomic, electropositive gas. Similar, though possibly more complicated, effects are expected when molecular gases such as SiH_4, Cl_2 and SF_6 are used. Such effects may be useful in controlling the production of radical species and negative ions.

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Figures

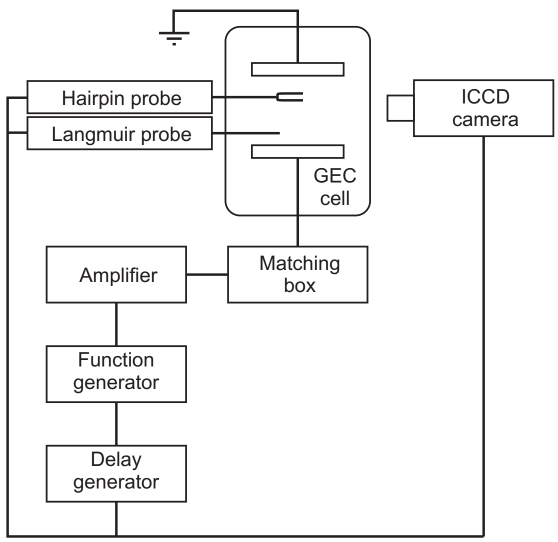

Figure 1. Experimental arrangement

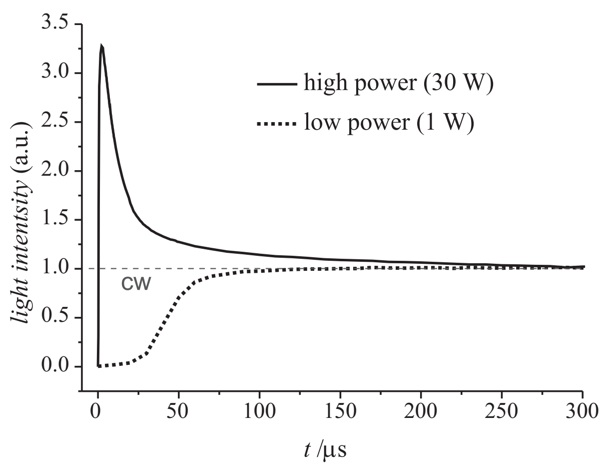

Figure 2. Time dependence of plasma emission form a pulsed discharge, normalized to the value for a continuously operated plasma. The gas pressure was 27 Pa (200 mTorr), the pulse frequency 100 Hz and the duty cycle 50%.

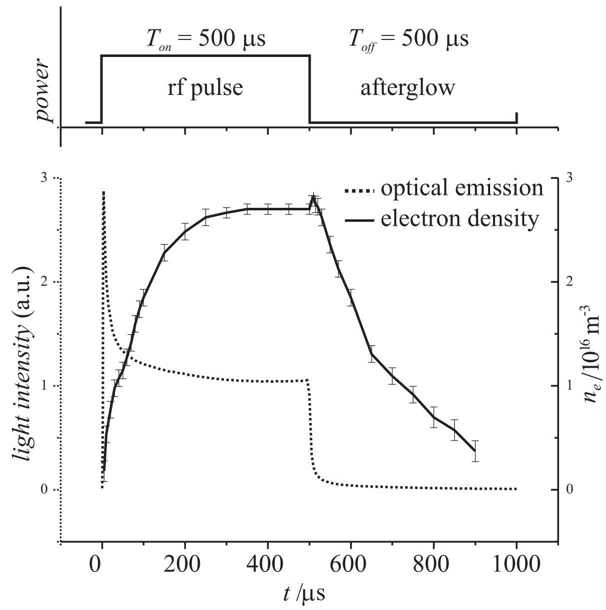

Figure 3. Comparison of the time dependency of the total light emission and electron density in the pulse. The gas pressure was 27 Pa (200 mTorr), the RF power was 50 W, the pulse frequency 1 kHz and the duty cycle 50%.

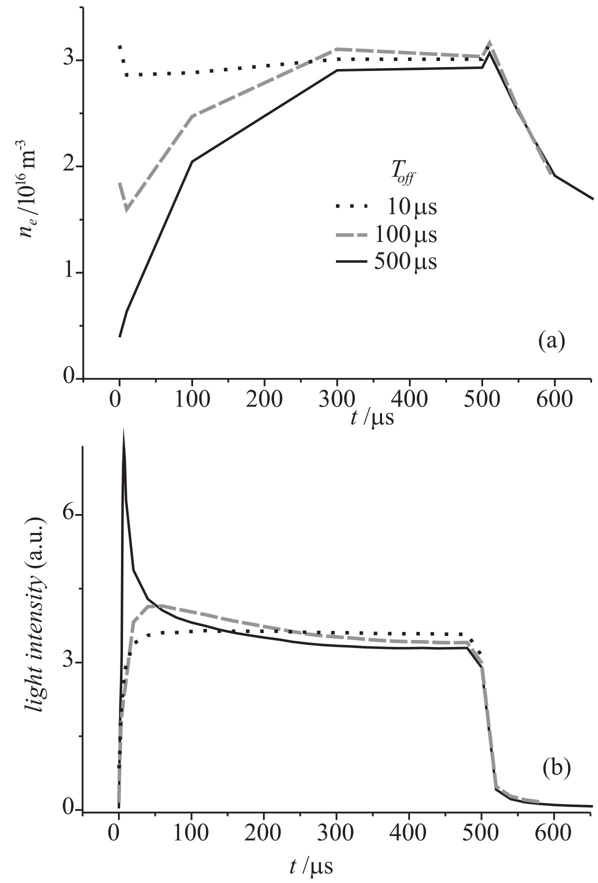

Figure 4. (a) Electron density and (b) light emission, showing the effect of varying the afterglow period while keeping the RF pulse length constant. Plasma conditions were otherwise similar to those for the results shown in Figure 3.

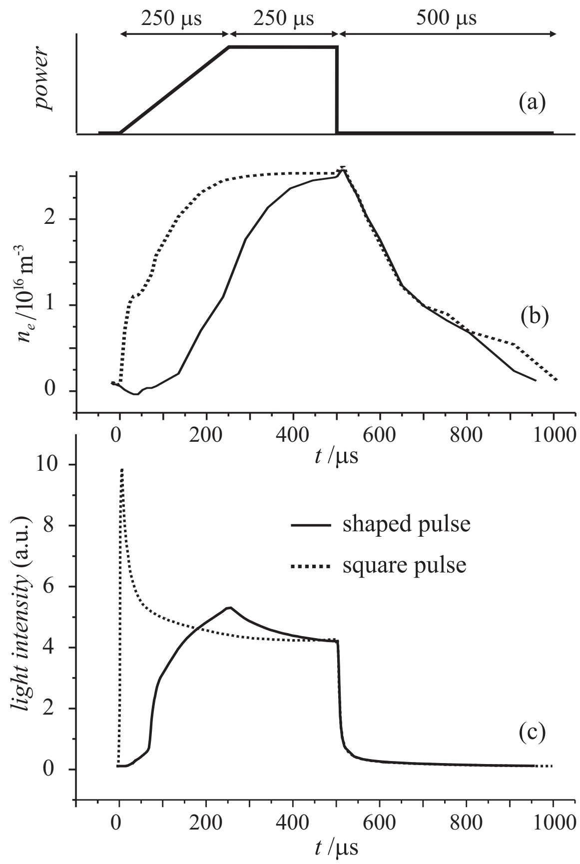

Figure 5. (a) pulse shape, (b) electron density and (c) light emission for the first modified RF pulse. Results for the square pulse are also shown, reproduced from Figure 3.

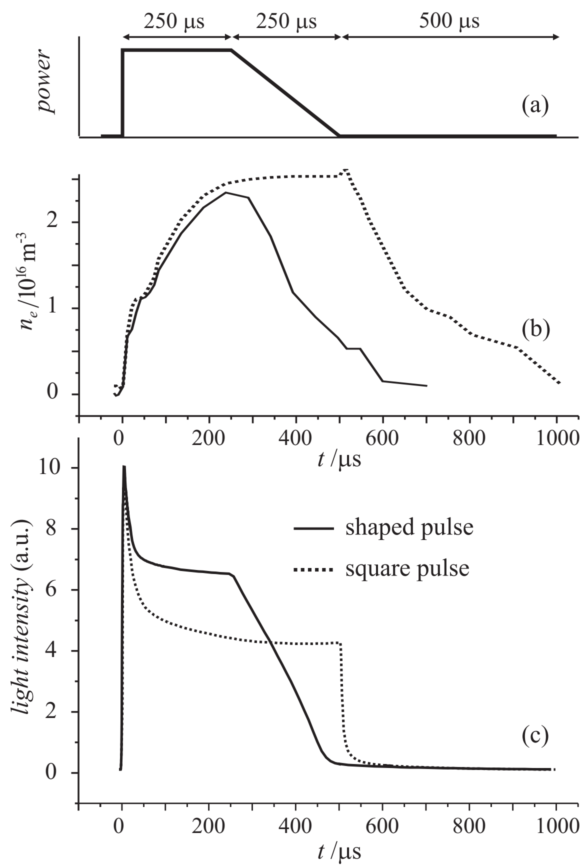

Figure 6. (a) pulse shape, (b) electron density and (c) light emission for the second modified RF pulse. Results for the square pulse are also shown, reproduced from Figure 3.