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Spatial dynamics of the light emission from a microplasma array

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The spatial dynamics of the optical emission from an array of 50×50 individual microplasma devices is reported. The array is operated in noble gas at atmospheric pressure with an ac voltage. The optical emission is analyzed with phase and space resolution. It has been found that the emission is not continuous over the entire ac period, it occurs only twice in each cycle. Each of the observed emission phases shows a self-pulsing of the discharge, with several bursts of emission of a fixed width and repetition rate. Cross-talk between the individual devices can be observed through spatially resolved measurements. © 2008 American Institute of Physics. [DOI: 10.1063/1.2894227]

Atmospheric pressure plasmas and, in particular, micro-discharge devices have tremendous application potential and are already been used and targeted for a variety of technological and biomedical applications.^{1–5} The interest in such discharges arises primarily in their ability to treat small dimensions and also the significant cost reduction for processing compared to their low pressure counterparts. A subcategory of the recently developed microplasmas is represented by the so-called microstructured electrode devices,⁶ including microplasma arrays;⁷ these devices have the added advantage of homogeneous large area treatment. The microplasma arrays investigated in this letter are well suited for a variety of applications, e.g., plasma display panels, photodetectors, UV sources, etc.^{8,9}

The electrical characteristics of such arrays have been well described by current voltage measurements.^{10–12} A recent approach to model a single microdischarge of an array operated in dc mode has been made by Kushner.¹³ Although this model provides a good picture of a single microdischarge device, the interaction of several devices within an array and the effect of ac operation have not yet been considered. There are still many open questions, in particular, the fundamental physics of the ignition phase and sustaining mechanisms remain poorly understood. Experimental investigations are challenging, primarily due to the small dimensions and the operating conditions under atmospheric pressure.

In the present study, we report on phase resolved optical emission spectroscopy (PROES) measurements on a microplasma array. These measurements offer a technically easy access for the investigation of the time dependent ignition and sustaining mechanisms. The array consists of 50×50 single pyramidal Si electrode microdischarges, each has a $50 \mu\text{m}$ squared base, composite $\text{SiO}_2\text{--Si}_3\text{N}_4$ polymer dielectrics and a grid of Ni serves as the other electrode. A detailed description of the setup of the array can be found in Refs. 7 and 8. The array is operated in either argon or an argon/neon-mixture (4:1) at atmospheric pressure (1 bar). The Si base is

grounded and the upper Ni grid is powered by a triangular voltage waveform with amplitude up to 400 V and frequency between 2 and 20 kHz. The triangular waveform allows keeping dV/dt constant in each half period. For time dependent measurements of the emission a photomultiplier (PMT) is mounted in front of the array. To obtain additional spatial information, an intensified charged coupled device (ICCD) camera is also used. The principle of PROES using an ICCD is explained in Refs. 14–17. Here, a brief description is given. The camera is synchronized to the phase of the excitation frequency. A gate interval of 200 ns is used over which light is collected. Light is integrated over several cycles for good signal to noise ratio; the total integration time used in this work is approximately 1 s. The available repetition rate of the camera is much higher than the excitation frequency of the ac cycle used here and, therefore, every cycle can be used for integration. For phase resolution within the ac cycle, over the entire cycle, measurements are taken every 200 ns. An optical system magnifies the emission from the array by a factor of 2 onto the sensitive chip of the camera ($13.2 \times 8.8 \text{ mm}^2$, 576×384 pixels). This yields a spatial resolution of $15 \mu\text{m}/\text{pixel}$. For both phase resolved measurements using the PMT and phase and space resolved measurements using the ICCD camera, no spectral discrimination by means of, e.g., a spectrograph or filter is applied. Emission over all emission lines is integrated. Current and voltage probes are also used to monitor the discharge during the measurements.

Measurements of the optical emission using the PMT phase resolved within one ac cycle for an Ar/Ne mixture ($p=1 \text{ bar}$; $f=5 \text{ kHz}$; $V_{p-p}=780 \text{ V}$) as well as the excitation waveform of the measured voltage are presented in Fig. 1. It can be observed that there are only two light emission phases per each ac cycle; once when the powered Ni grid on the top of the array is positive and once in the other half of the cycle when the Ni grid is negative. The emission occurs after passing a voltage threshold (weakly dependent on dV/dt) in bursts of a fixed width and frequency. The bursts stop upon reversal of dV/dt . The emission behavior in both half cycles is comparable, but the intensity is much weaker in the second half period due to the geometrical asymmetry of the discharge.

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FIG. 1. PMT intensity signal (black) and driving voltage (gray) over an ac cycle at $f=5$ kHz, $p=1$ bar, $V_{p-p}=780$ V, and Ne/Ar-mixture (4:1).

The development of the initial burst is comparable to an electron avalanche of a Townsend discharge. After passing the voltage threshold, a free electron gains enough energy in the electric field to create an ion-electron pair under collision with a neutral, and an electron avalanche can be developed. This avalanche yields an emission pulse. Due to a lack of secondary electron production at the cathode and charge accumulation on the dielectric silicon-nitride (Si_3N_4) layers on top of the electrodes (Ni grid and Si base), the discharge extinguishes. However, with the external driving voltage continuously increasing, a second electron avalanche can be developed after passing a certain voltage and a second emission burst occurs. In the presented measurement in Fig. 1, the threshold voltage to produce the initial electron avalanche is 290 V while to produce the second avalanche this threshold is only an additional 50 V. The much lower voltage for the second pulse can be explained through residual metastables, produced during the initial avalanche and remaining in the discharge volume. Since metastables require lower electron energy for ionization, compared to ground state atoms, the discharge ignites at a lower threshold voltage. Furthermore, surface processes which cause a charge reduction on the dielectric layers, e.g., recombination of charged particles and tunneling of electrons through the thin dielectric barrier ($0.5\text{ }\mu\text{m}$) toward the anode, can also yield to an increase of the electric field over the discharge gap. The discharge self-pulses and with it emission bursts until the driving voltage no longer increases.

When the polarity reverses a large threshold voltage is again necessary to cause an electron avalanche in the opposite direction. The Townsend-like behavior of the discharge is in good agreement with the modeling of a single microdischarge mentioned earlier.¹³ Similar bursts in the emission have been observed and modeled in dielectric barrier discharges at atmospheric pressure.^{18–21} However, these discharge configurations had parallel plane plate electrodes with at least one covered by a dielectric and a discharge gap in the order of $0.5\text{--}3$ mm. The microplasma array, on the other hand, has a geometric asymmetry, the discharge gap is approximately $40\text{ }\mu\text{m}$ for each single discharge, and the entire array is a parallel circuit of 2500 single discharges.

The emission within the ac cycle shows a strong time dependence, we now examine the spatial behavior of the emission over the entire array. Integrating the measured in-

FIG. 2. (Color online) The intensity of the optical emission of a 10×10 segment of the array integrated over the entire excitation cycle and averaged over 10^4 periods in argon at $f=10$ kHz, $p=1$ bar, and $V_{p-p}=780$ V. (a) False color plot. (b) Emission profiles of two rows and two columns of the segment.

tensity of the emission over an entire ac period, and averaging over 10^4 periods, it is found that the emission over the entire array is uniform and each microdischarge emits homogeneously. This is presented in Fig. 2. Figure 2(a) shows a two-dimensional (2D) map of the emission of the 10×10 section after the integration and Fig. 2(b) shows emission profiles of two rows and two columns of the section.

The intensity variation of the emission within the profiles is approximately $\pm 15\%$. This suggests that ignition and plasma sustainment is uniform over the entire array. Similar conclusions can be drawn from photographs in Ref. 22

However, the time resolved measurements show a strong time dependence of the emission within the ac cycle. For improved insight into the dynamics of the discharge, PROES is applied for additional phase resolution. From the PMT measurements in Fig. 1, it is clear that the emission of the discharge occurs only during two phases per cycle; therefore, we concentrate our spatially resolved investigations during these time intervals. Figure 3 shows a 2D map of the optical emission for a 10×10 pixel section of the whole array plotted in false color for four different time steps. The presented pictures are taken during the initial burst of the emission phase when the upper Ni grid is powered positive in pure argon ($p=1$ bar; $f=10$ kHz; $V_{p-p}=780$ V). It can be observed that the individual microdischarges of the array does not ignite simultaneously rather they ignite in a wavelike pattern as the emission burst travels across the array. For the plots shown in Fig. 3 the wave starts at the top right corner and propagates down to the bottom left corner. The direction of the wave is independent of the polarity of the electrodes. Statistical phenomena can be excluded since they are averaged out in the measurement where the emission is integrated over 10^4 cycles. The results clearly illustrate crosstalk between the individual discharge devices in the array. The velocity of the wave is estimated to be 3 km s^{-1} . This is significantly slower than the spatial buildup time of the voltage across the array. The wave travels across the entire array in a time of $2.3\text{ }\mu\text{s}$.

We could show that each individual microdischarge of the array behaves like a non-self-sustained Townsend discharge. This results in a self-pulsing of the devices consisting of several bursts in the optical emission of fixed width and frequency. After crossing a voltage threshold, the non-self-sustained Townsend breakdowns are caused by the slowly increasing driving voltage until the reversal of dV/dt . From phase and space resolved investigations of the emission, it is

FIG. 3. (Color online) 2D maps of the optical emission from a 10×10 pixel segment of the microplasma array plotted in false color. Here, dark color represents a low intensity and bright color represents a high intensity. The temporal evolution of the initial burst of the emission phase with a positive Ni grid in argon at $f=10$ kHz, $p=1$ bar, and $V_{p-p}=780$ V is shown.

obvious that each individual discharge does not act independently and cross-talk and collective phenomena play important roles in the ignition and sustaining mechanisms of the array.

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