Interaction of Multiple RF Micro-Dielectric Barrier Discharges

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Abstract:

Arrays of radio-frequency excited micro dielectric barrier discharges (mDBD’s) are attractive as planar sources of radicals and charged species. The devices of interest have apertures tens of microns in diameter with spacing of tens to hundreds of microns. Displays using independent addressing of mDBDs are optimized for producing of UV photons and for isolation between discharges. When using the mDBDs to produce plumes of excited states and charged species, there are potential interactions between the mDBD devices. This is particularly the case when auxiliary electrodes are used to extract the charged species. In this paper, we numerically investigate the properties of small arrays of mDBDs and their interactions.

Keywords: dielectric barrier discharge, micro-plasma

1. Introduction

Micro dielectric barrier discharges (mDBD’s) [1] have been developed for stable, high pressure and non-thermal plasma sources as well as UV photons. mDBDs consist of micro-plasma devices (10-100 µm diameter) in which the electrodes are fully or partially covered by dielectrics. The electrodes are driven with radio frequency (rf) wave forms, and operated at atmospheric pressure. In certain applications, a third electrode [2, 3] is required to extract electron current out of the mDBD arrays for micrometer scale surface treatment [4]. These arrays of mDBD’s excited by rf voltage are attractive as planar sources of radicals and charged species. The devices of interest have apertures of tens microns in diameter with spacings of tens to hundreds of microns. Independently controlled rf mDBDs can be optimized for producing UV photons and for isolation between discharges.

In this paper, we discuss the properties of small arrays of mDBD’s sustained in atmospheric pressure N₂ using results from a two-dimensional simulation. The model geometry of a single discharge aperture is shown in Fig.1. The rf metal electrode is embedded in a PCB board 50 microns below the surface. The negatively DC biased discharge electrode sits on the
top of a dielectric layer and has an opening of 35 microns. A less-negatively-DC-biased screen electrode separated from the discharge electrode acts as an anode switch to extract charges out of the cavity and narrow the current beam. Spacing between the mDBDs are tens to hundreds of microns.

The model used in this investigation, nonPDPSIM, is a first principles two-dimensional multi-fluid hydrodynamics simulation [5]. nonPDPSIM solves Poisson’s equation for electric potential, continuity equations and surface charge balance equations for transport of charge and neutral species. The electron energy conservation equation is solved for electron temperature. A Monte Carlo simulation is used for tracking the ionization and excitation sources produced by sheath accelerated secondary electrons. Rate and transport coefficients for bulk electrons are obtained from local solutions of Boltzmann’s equation for the electron energy distribution. Radiation transport is addressed using a Green’s function approach.

2. Surface properties on mDBD

The adjacency of multiple apertures of mDBDs and the dielectric properties of the materials being treated are important in determining how independently the mDBDs operate. For example, the electron plumes (flood) and electric potentials (contour lines) are shown in Fig. 2 for repetitive pulsing (25 MHz) of mDBDs in nitrogen at 1 atm. The voltage of the three rf electrodes are in phase and the top dielectric current collection surface has $\varepsilon/\varepsilon_0 = 1$ (a low value chosen for demonstration purposes). The voltages on the rf electrodes are -2 kV DC plus 1.4 kV rf. The potentials on the discharge and screen electrodes are -2 kV and -1950 V, respectively. The electron plumes extracted from micro-cavity are incident onto this dielectric sheet. For early pulses, the quasi-potential lines are essentially flat and the electron plumes onto the dielectric are not perturbed. There are some concavities near the apertures which has the effect of slightly focusing the electron plume while extracting the electrons towards the dielectric. As the extracted current negatively charges the dielectric, electric potential lines are trapped inside the dielectric and produce lateral electric fields. As a result, the local electric field perpendicular to the potential lines has large components and broadens the electron plumes. This situation worsens with successive pulses.

At later pulses, the outside electron plumes are not only broadened in width but are also warped. The charging of the top dielectric is sufficient so that the extracting electric field
directs the electrons towards less charged regions of the dielectric. The large surface charge density significantly reduces the voltage across the gap. As a result, the electron density is lower and eventually the electron extraction will be stopped by the negative potential.

Time sequences of instantaneous electron flux on dielectric surface having \( \varepsilon/\varepsilon_0 \) of 20 and 1 are shown in Fig. 3. For \( \varepsilon/\varepsilon_0 = 20 \), the electron flux at the first rf cycle (10 ns) has a FWHM of 140 \( \mu \)m. Due to positive ions accumulating in the gap, the extraction field is enhanced and therefore the electron flux increases after the first rf cycle. At the same time, the surface negative charge density also increases with successive rf cycles. These negative charges decrease the potential across the gap and so decrease the extraction field. The magnitude of the electron flux is reduced and the FWHM expands to 240 \( \mu \)m at 210 ns. For the dielectric having \( \varepsilon/\varepsilon_0 = 1 \) with a shorter charging time, the electron flux peaks at the first rf cycle at 10 ns with a FWHM of 160 \( \mu \)m. The electron flux then decreases with successive pulses. The possible increase in electron flux due to positive space charge in the gap is overpowered by the charging of the dielectric which decreases the flux. When the negative surface charge directly above the discharge apertures accumulates to a critical value, the voltage drop in the gap is too small to extract electron current upward. Instead, the electron plumes propagate laterally and charge “fresh” dielectric.

3. In Phase/Delayed phase excitation

With simultaneous excitation of electron current, the integrated electron flux onto the surface can be uniform provided the plumes are below the “space charge” limit of affecting their neighbors. The time integrated electron fluxes onto the dielectric surface (\( \varepsilon/\varepsilon_0 = 20 \)) at the end of tenth rf cycle (400 ns) are shown in Fig. 4. Two cases are shown - with rf voltage applied to the center electrode being in-phase with the outer apertures and with the center electrode being a quarter-period delayed in phase with respect to its adjacent rf electrodes. For the in-phase case, the integrated peak electron flux on the dielectric surface is as large as \( 28 \times 10^{11} \text{ cm}^{-2} \), while the flux between apertures is \( 7 \times 10^{11} \text{ cm}^{-2} \). The electron plumes incident on the dielectric above the three apertures are uniform because the electron plumes and density are below the
“space charge” limit, hence they will not affect their neighbors. For the center electrode being out of phase, the peak integrated electron flux remains at $28 \times 10^{11}$ cm$^{-2}$ however the flux between apertures increases to $10 \times 10^{11}$ cm$^{-2}$. Due to the delayed-phase on the center electrode, there is a period of time when the electron plume propagates without interference by its neighbors. During this time, the electron plume propagates not only upward to the top surface, but also diffuses laterally without being limited by its neighbor plumes. As a result, the electron flux between apertures increases.

4. Concluding Remarks

A numerical study of the interaction of adjacent mDBDs has been presented. The dielectric properties of the materials being treated are significant to the independent control of the mDBDs operation. The shape of the collected electron flux can be moderately controlled with time delays between apertures.

References


