Numerical Simulations of Dielectric Barrier Discharges in a High Resolution Ion Print Head

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Abstract

A newly developed ion head architecture for high resolution ionographic printing, with a spot size capability of ~100 µm, utilizes a dielectric barrier discharge (DBD) to produce an atmospheric pressure plasma that is the source of the charge. The DBD is produced using a radio frequency (rf) voltage and extracted with biased electrodes having designs which focus the charge. To aid in the development of the ion head and interpretation of experiments, a first principles program of multi-dimensional computer modeling of the ion head devices has been conducted. Results from the model will be discussed showing the dependence of the magnitude and shape of extracted charge from the ion head and current waveforms as a function of driving voltage and frequencies of the rf excitation, dielectric materials and geometry of the head.

Introduction

Dielectric barrier discharges (DBD's) [1] are often used for non-thermal plasma sources at atmospheric pressure. DBDs are typically powered with rf voltages (100s kHz to a tens MHz) and have large area electrodes, at least one of which is covered by a dielectric. The plasma often consists of a forest of micro-filaments hundreds of microns in diameter. These micro-filaments occur nearly randomly in space and during the rf voltage cycle. After the plasma is initiated, charging of the dielectric may terminate the discharge by reducing the gap voltage below its self-sustaining value. When the polarity of the applied voltage changes, the dielectric surface charges from the previous rf cycle enhance the gap voltage so that the electrons avalanche is more intense. Micro-dielectric barrier discharges (mDBDs) are a variant of DBDs where, through use of MEMS technologies, the random plasma filaments in macroscopic DBDs can be controlled in both space and time. In certain applications such as micrometer surface treatment [2], a third electrode [3, 4] can used to extract electron current or excited states out of the mDBD. As such, arrays of mDBDs can be used as sources of charge in ionographic printing.

Microarrays of DBD's excited by rf voltages at atmospheric pressure are being developed for use in high resolution ion print heads. The mDBD's have apertures tens of microns in diameter with spacing between individual mDBD plasma sources of tens to hundreds of microns. Independent control of individual mDBDs in these arrays can be optimized for extracting precise amounts of charge and for isolation between discharges.

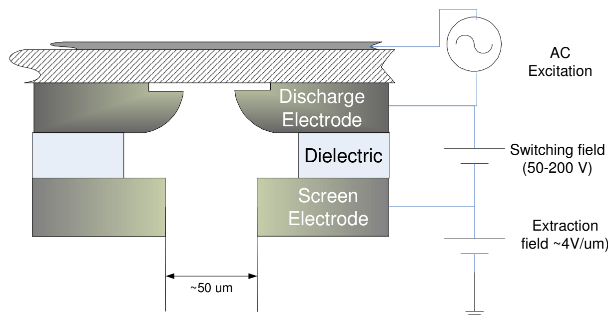

Figure 1. *Schematic of a typical single mDBD aperture*

A schematic of a typical, single ion head architecture is shown in Fig. 1. An rf biased metal electrode is embedded in a dielectric substrate and is covered by a dielectric sheet. A negatively DC biased discharge electrode sits on the top of the dielectric sheet and has an opening of ten's of microns [5]. A less-negatively-DC-biased screen electrode separated from the discharge electrode by another dielectric sheet acts as an anode switch to extract charges out of the cavity and narrow the current beam. Spacing between the mDBDs ion heads are tens to hundreds of microns.

In this paper we discuss results from a computational investigation of ion head architectures using arrays of mDBDs. The modeling used in this investigation, *nonPDPSIM*, is a first principles two-dimensional multi-fluid hydrodynamics simulation performed on an unstructured mesh [6]. *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. Radiation transport is addressed by a Green's function propagator. A Monte Carlo simulation is used for tracking the ionization and excitation sources produced by sheath accelerated secondary electrons from surfaces. The secondary electrons are produced by ion and photon impact onto all surfaces. Rate and transport coefficients for bulk electrons are obtained from local solutions of Boltzmann's equation for the electron energy distribution.

mDBD Plasma Properties

The fundamental properties of an individual mDBD will first be discussed. The operating conditions are 1 atm of N_2 with an rf

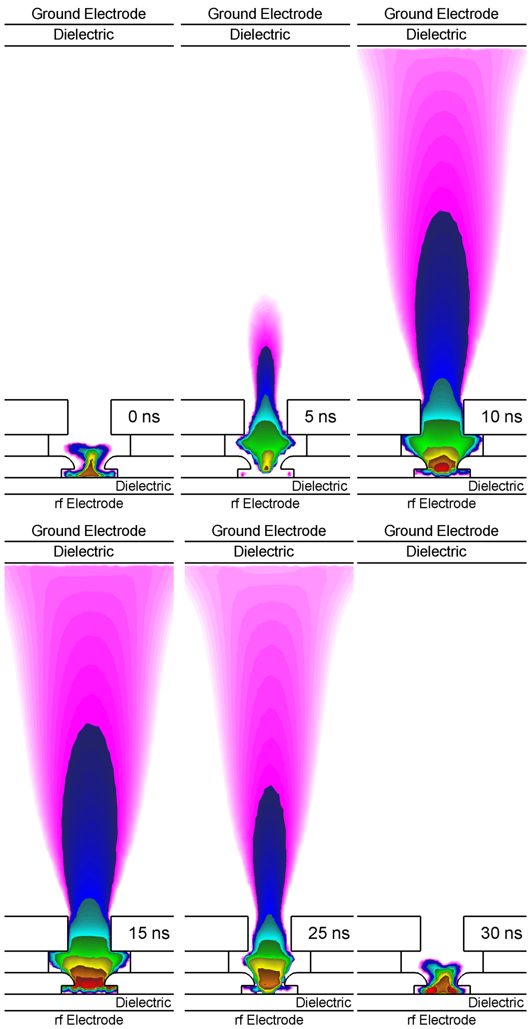

__Figure 2__. Electron density at different times during an rf cycle of 25 MHz (40 ns_. The densities are plotted on a 4-decade log scale from 2 x 10^{11} cm^{-3} to 2 x 10^{15} cm^{-3}. .

frequency of 25 MHz. The bias on the rf electrode is -2 kV DC plus 1.4 kV rf. The potentials on the discharge and screen electrodes are -2 kV and -1950 V, respectively. A grounded electrode is placed approximately 400 µm above the screen electrode. The grounded electrode is covered by a dielectric sheet. The electron density during the rf cycle is shown in Fig. 2. The cycle begins with -600 V on the rf electrode, which is its most positive value and positive with respect to the discharge and screen electrodes. This produces an electron flux towards the dielectric sheet above the rf electrode which charges the sheet negative. As the voltage on the rf electrode becomes more negative, the electrons in the mDBD cavity are expelled into a plume that is focused by the screen electrode. The plume is extracted across the gas gap and charges the dielectric on the ground electrode. When the rf electrode approaches its most negative value (-3400 V at 20 ns), secondary electrons emitted by the lower dielectric sheet are avalanched to sustain the plasma in the mDBD cavity. As the voltage begins increasing electrons are pulled back into the mDBD

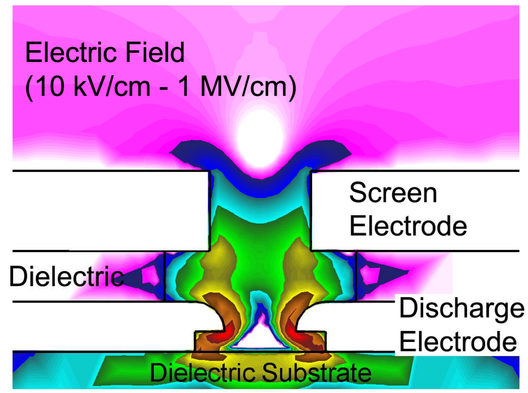

__Figure 3__. Electric field in the mDBD cavity and in the surrounding dielectric materials. Electric fields in excess of 1 MV/cm are produced during the rf cycle for up to 10 ns.

cavity, thereby terminating the electron plume. The electron density is as high as 2×10^{15} cm^{-3} in the DBD cavity, and about 4×10^{11} cm^{-3} in front of the top dielectric sheet. These large electron densities are supported by electric fields that can exceed 1 MV/cm, as shown in Fig. 3. These large fields result from space charge around the electrodes and on surfaces that shield and compress the applied voltage

Small Arrays of mDBDs

When electrons are extracted out of the mDBD cavitiy and deposited on the top dielectric, a negative voltage is produced on the dielectric. This voltage produces electric fields that interact with the electron plumes. These trends are illustrated by the results in Fig. 4 for an array of 3 mDBDs. The electron density for the three mDBD devices is shown in the color flood and the electric potential is shown as contour lines. The voltage on the three rf electrodes are in phase and the top dielectric has $\varepsilon/\varepsilon_0 = 1$ (a low value chosen for demonstration purposes). The electron plumes extracted from the ion heads are incident onto this dielectric target. For early pulses, the 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 top dielectric, a negative potential is produced at the surface, electric potential lines are trapped inside the dielectric target and lateral electric fields are produced. A consequence of these lateral electric fields is a broadening of the electron plumes. This situation worsens with successive discharge pulses and occurs at a rate inversely proportional to the capacitance of the dielectric. That is higher dielectric constant sheets charge more slowly. At later pulses the outside electron plumes are not only broadened in width but are also warped towards the less charged region. The charging of the top dielectric target is sufficiently large that the extracting electric field directs the electrons towards the lateral region with less charging on the

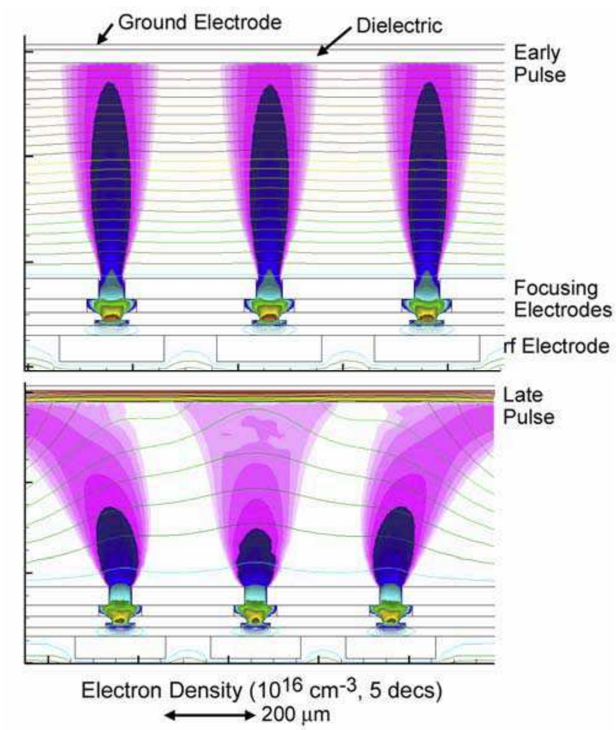

***Figure 4**. Electron density (flood) and electric potential (contour lines) for multiple rf excited mDBDs incident onto a target dielectric sheet. The plumes of the early pulses are unperturbed. The plumes of the latter pulses are warped toward less charged region.*

target. 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.

Sequences of instantaneous electron flux onto the top surface having $\varepsilon/\varepsilon_0$ of 20 and 1 are shown in Fig. 5. For $\varepsilon/\varepsilon_0 = 20$, the electron flux on the first rf cycle (10 ns) has a FWHM of 140 μm. Due to positive ions accumulating in the gap, the extraction electric field is intensified and therefore the electron flux increases during the first few rf cycles. 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 μm at 210 ns as lateral electric fields are produced by the dielectric charging. For the dielectric surface having $\varepsilon/\varepsilon_0 = 1$, the charging effect starts earlier due to its lower capacitance and shorter charging time. The electron flux peaks on the first rf cycle at 10 ns with a FWHM of 160 μm. The electron flux then decreases with successive rf pulses. The possible increase in electron flux due to accumulation of positive space charge in the gap is overpowered by the charging of the dielectric which decreases the flux. During formation of the latent image on the target, the negative surface charge directly above the ion head apertures accumulates to a critical value and repels the incoming charges so that the dot size becomes larger than the diameter of the charge source beams. This "blooming" problem can reduce the image quality.

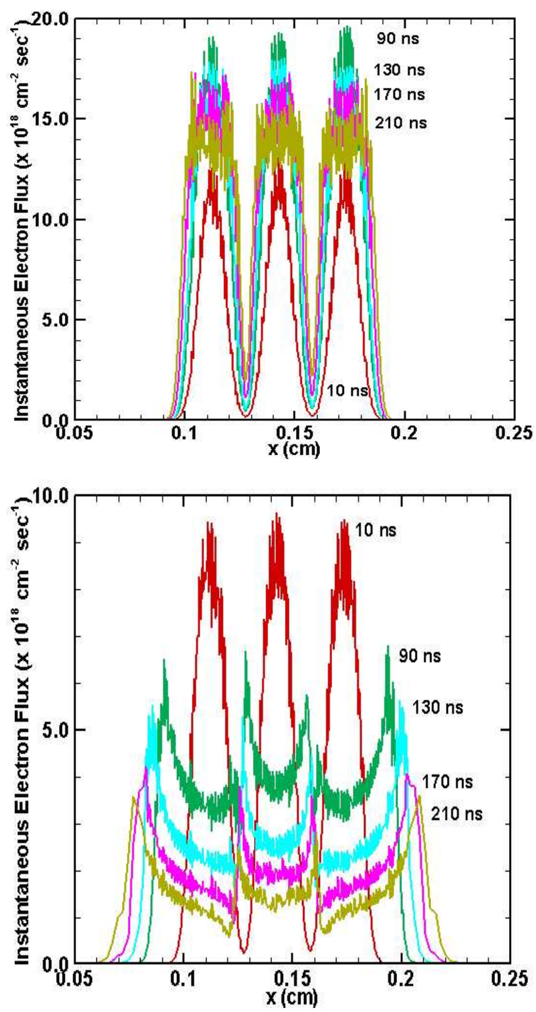

***Figure 5.** Instantaneous electron flux on the top surface for $\varepsilon/\varepsilon_0$ of (top) 20 and (bottom) 1. For $\varepsilon/\varepsilon_0$=20, the flux increases before it decreases due to surface charging. For $\varepsilon/\varepsilon_0$=1, the flux decreases starting from the first pulse due to the shorter dielectric charging time.*

RF Frequencies

The electron density in the plumes above the ion heads are a strong function of rf frequency. A probe adjacent to the target dielectric above the center ion head, shown in Fig. 6, is used to monitor the extracted electron density. Three rf electrodes are driven in-phase with frequencies from 2.5 to 25 MHz. The dielectric constant of the top surface is $\varepsilon/\varepsilon_0 = 12.5$. The maximum electron densities at successive pulses at different driving frequencies are shown in Fig. 6. At higher frequencies, the electron density in the plume increases during the first few pulses due to positive ions accumulating above the mDBD cavities. Meanwhile, negative surface charges collect on the dielectric target which reduces the voltage drop and decreases the extraction electric field adjacent to the dielectric. The electron plume then

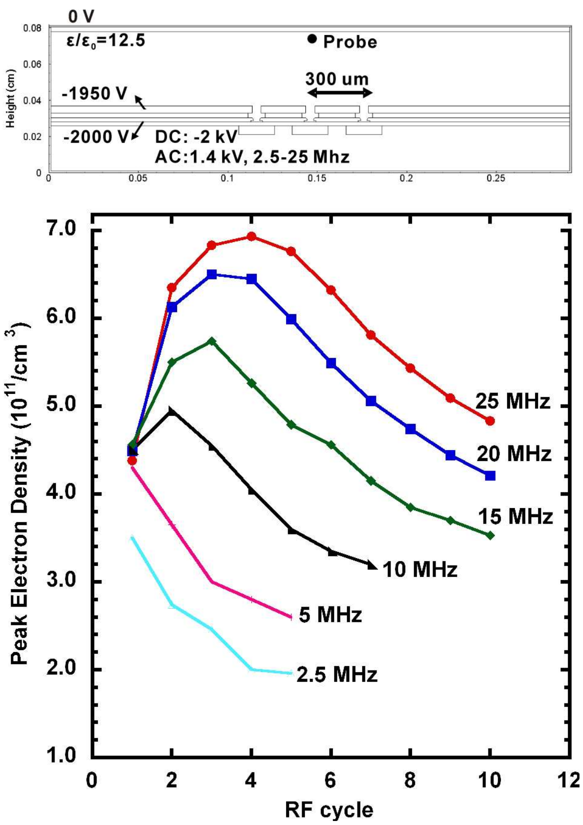

***Figure 6**. Electron densities in the plume adjacent to the dielectric target (top) Geometry and location of probe. (bottom) Peak electron density at the probe as a function of the number of rf pulses at frequency of up to 25 MHz. At high frequency, the electron flux is limited by the rf voltage. At low frequency, the electron flux is limited by target surface charging.*

diminishes. At lower frequencies, the electron density in the plume decreases with successive rf pulses. The negative potential resulting from charging of the target overpowers the positive space charge accumulation above the ion heads. The charging effect starts at the first rf pulse and warps the electron plumes. The electron density then decreases and eventually the plume is extinguished.

Concluding Remarks

Computer modeling of mDBDs as used in ion heads has been used to investigate scaling laws and for design optimization. The computer model accounts for the plasma-hydrodynamics of the mDBD cavity, the production of charged, neutral and photon fluxes onto surfaces, the extraction of electrons from the mDBD cavity and the charging of imaging surfaces. We found that the mDBD devices can be optimized based on choice of rf frequency and dielectric constant of the charging surface, in addition to geometry of the mDBD cavity. The mDBD devices can be independently biased to achieve precise control of these properties. We found that at high frequencies, the electron density in the plume first increases and then decreases with successive rf pulses. The negative potential resulting from charging of the target eventually overpowers the positive space charge accumulation above the ion heads. At low frequency, the surface charging dominates and charge extraction typically decreases with successive pusles.

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Henryk Birecki is a Senior Scientist at Hewlett Packard Laboratories. He received PhD in physics from MIT in 1976 and joined HP Labs in 1978. While at HP he worked on displays, optical computing, optical recording and other mass storage technologies. He managed projects on optical recording materials and devices and organized international conferences on the subject. Since 2006 he has been working on printing technologies.

Omer Gila is managing the "Printing Processes for Digital Commercial Print" department in HP Labs Palo Alto California. Prior to HP Labs, Omer held the positions of COO of Oniyah PSP in Israel and the color control manager in Indigo Rehovot. He holds a B.Sc. (1989) in Physics and Mathematics from the Hebrew University (Jerusalem, Israel) and M.Sc. (1992) in Applied Physics and Electro-optics from the Weizmann Institute of Science (Rehovot, Israel) with honors in both.