Ionization Wave Splitting at the T-Junction of a Dielectric Channel

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***Abstract*—Fast ionization waves generated by nanosecond pulses are capable of delivering intense electric field, UV light, and charged and excited species to spatially distant locations. In this paper, the splitting of a fast ionization wave in a N_2 plasma in a T-shaped dielectric channel is numerically investigated. Images of electron impact source function and density are presented.**

***Index Terms*—Ionization wave, plasma simulation, plasma transport processes.**

FAST IONIZATION waves, generated by nanosecond-duration high-voltage pulses, are of interest in plasma-assisted combustion, material processing, and biomedical applications due to their ability to deliver intense electric field, UV light, and charged and excited species from the plasma source to distant locations [1]. Many atmospheric-pressure low-temperature plasma sources are operated in the "plasma bullet" mode, having discrete fast-traveling ionization fronts [2]. A better understanding of the propagation dynamics of this type of ionization wave in complex discharge channels can improve the design and operation of low-temperature plasma sources.

In this paper, we have numerically investigated the splitting of a fast ionization wave, in a 2-D T-shaped dielectric channel filled with 10 torr of N_2 (see Fig. 1). The full vertical section of the channel is 10 cm high and intersects the horizontal section which is 20 cm long with a width of 1 cm. The channel is surrounded by air, and the thickness of the dielectric wall is 0.5 cm, with $\varepsilon/\varepsilon_0 = 4$. Three electrodes are located at the ends of the channel, with the cathode being at the top and two anodes (grounded) at the bottom. The applied voltage is -40 kV with a 5-ns rise time. The initial electron density is zero everywhere except for a small region near the cathode in which a seed electron density of 10^8 cm^{-3} is specified.

The numerical modeling platform is *nonPDPSIM*, which is a 2-D plasma hydrodynamics model with radiation photon transport. Continuity equations for charged and neutral species and Poisson's equation are solved coincident with the electron energy equation with transport coefficients obtained from solutions of Boltzmann's equation. The spatial discretization is based on a finite-volume method on an unstructured mesh (no centerline symmetry enforced), and the time advancement is implemented with a fully implicit Newton iteration method [3].

Immediately following the rapid voltage rise, the gas breaks down near the cathode, and an ionization wave starts to propagate downward in the vertical section at a speed about 0.5 cm/ns or 5×10^8 cm/s. The propagation and splitting of the ionization wave at the junction from 18 to 36 ns, as represented by the electron impact ionization source and the electron density, are shown in Fig. 1.

For $t < 18$ ns, the ionization wave propagates inside the vertical section and has its peak close to the channel wall. The ionization source ($\approx 10^{20}$ cm$^{-3} \cdot$ s^{-1}) and electron density ($\approx 2 \times 10^{11}$ cm$^{-3} \cdot$ s) are the highest near the wall. The gradient in dielectric constant from the plasma to the wall produces electric field enhancement which increases the electron temperature and ionization rates. As the ionization front leaves the vertical section and enters the T-junction, it bows out and spreads laterally. At $t = 26$ ns, the ionization front crosses the junction and intersects the bottom wall. The impingement charges the bottom wall, producing lateral electric fields. This results in a thin layer of ionization near the bottom and two thicker roll-up areas at its sides. During the expansion and intersection with the bottom wall, the ionization rates decrease by nearly an order of magnitude from that in the vertical section. Meanwhile, the high-electron-density regions near the wall do not extend to the side channels as the expansion of the plasma comes primarily from the center low-density region. From $t = 32$ ns to 36 ns, the two split ionization waves start to propagate horizontally in opposite directions, both toward the anodes and away from the negative charges deposited at the junction. Both the ionization source and electron density have similar shapes as in the vertical sections (higher in the electric-field-enhanced region near the wall) once they have fully developed.

As the now two horizontal ionization waves propagate, the magnitude of ionization increases. This is due to the enhanced electric field in the horizontal section brought by the conductive plasma in the vertical section, which makes the T-junction appear to be a virtual cathode. This also gives rise to new ionization zones close to the junction at $t = 36$ ns.

In conclusion, we have presented images of a splitting ionization wave in a T-shaped dielectric channel. The splitting of ionization waves ultimately depends on the synergies between surface charging, geometry, and electric field enhancement due to gradients in dielectric constant.

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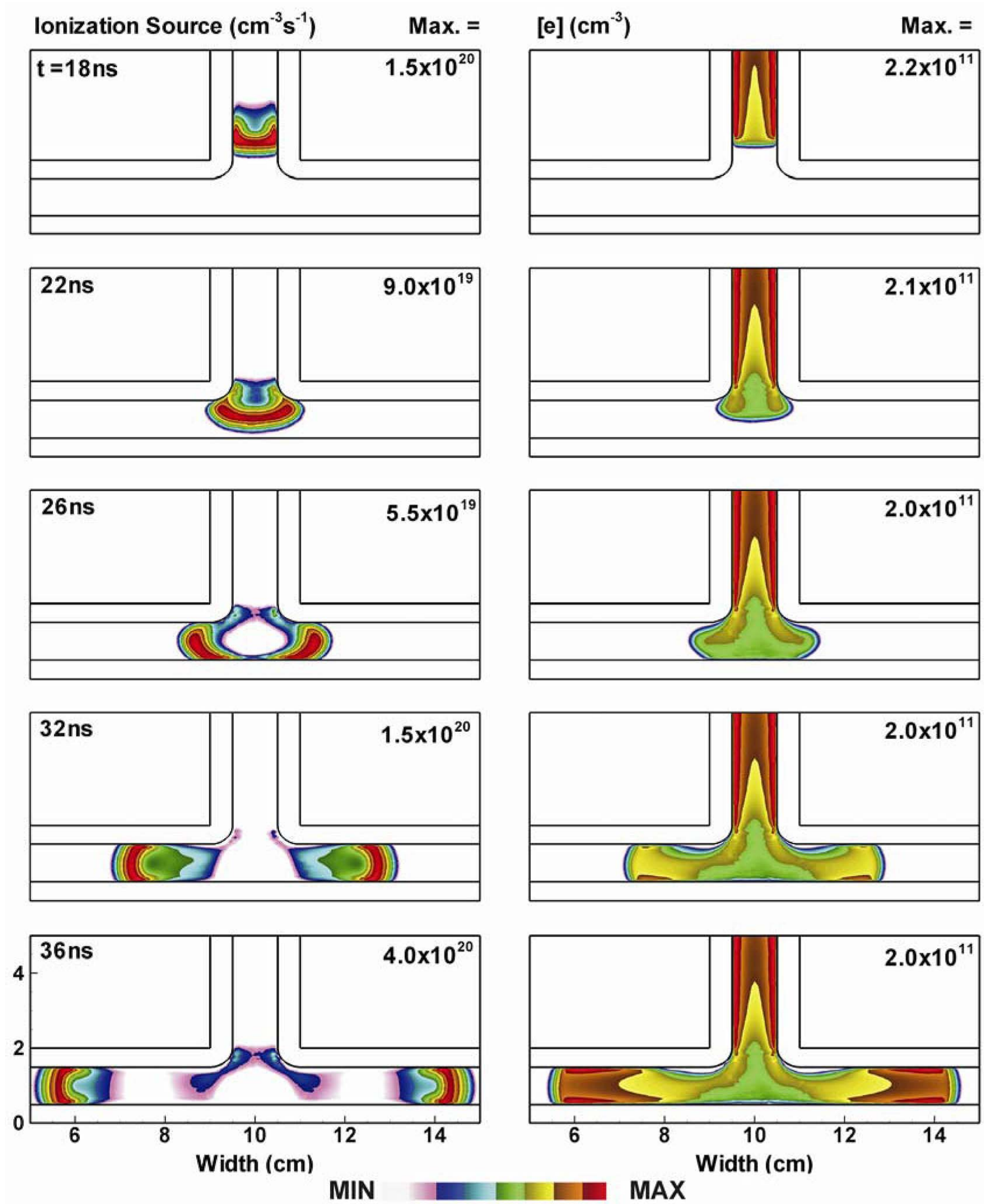

Fig. 1. Splitting of an ionization wave in an (inverted) T-shaped dielectric channel filled with nitrogen at 10 torr. The total height and width of the channel are 10 and 20 cm, respectively, and the incoming ionization wave is traveling down. (Left) Electron impact ionization source and (right) electron density are shown. The maximum values of the variables are noted at the top of each figure.

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