Effect of Driving Frequency in Filamentary and Uniform APDs Using Three-Dimensional Fluid Model

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Introduction:

In recent years, the uniform atmospheric pressure discharges have been attracting our attention for their effective use in industrial and biological applications but the emergence of sudden non-uniform behaviour in the breakdown phase still demands a special attention for their practical usage. The different kinds of dielectric barrier discharges are discussed at atmospheric pressure in various noble gases, which transfer from uniform to filamentary discharge modes and vice versa with the variation of external operating conditions [1 - 3].

Numerical Simulation Results and Discussion:

In this paper, a close examination of discharge characteristics is performed with three-dimensional fluid model in He-N_2 gas and the conditions under which the uniform and non-uniform discharge plasma regimes are evolved in the breakdown phase.

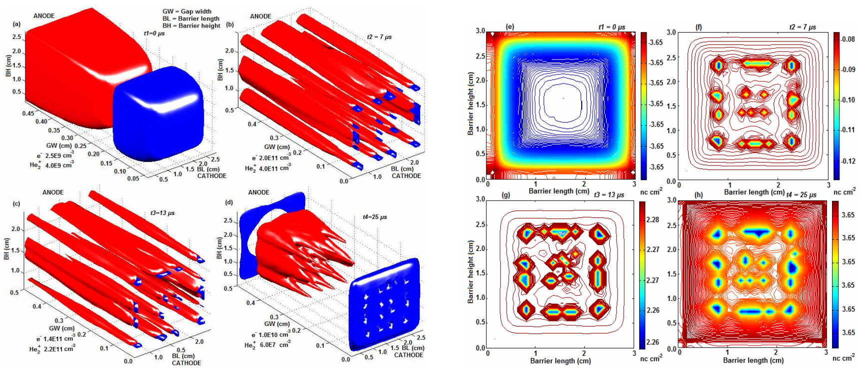

Figure 1. Electrons (red) and He_2^+ ions (blue) (a - d) and surface charge density (e - h) at 10 kHz and -1.6 kV.

The space and time characteristics of electrons and molecular helium ions density are explored from time t1 = 0 to t4 = 25 μs for a breakdown pulse at 10 kHz, which precisely cover the emergence, growth and decay phases of discharge plasma as illustrated in figure 1 (a - d). In case of just before the breakdown at t1 = 0, the electronic avalanche reaches in the middle of gap as shown in figure 1 (a). After breakdown of dielectric barrier material in He-N_2 gas, the creation of charge carriers is suddenly enhanced due to the significant impact of multiple ionization processes and conduction through the dielectric barriers. The thin long filaments are emerged in the gap which show the noticeable influence of overvoltage as exhibited in figure 1 (b) at time t2 = 7.0 μs. This type of filamentary structure is evolved due to the effect of overvoltage and disappeared in the absence of overvoltage. In the smashing phase of cathode fall layer at t3 = 13 μs, the conducting filaments are further volumetrically contracted as shown in figure 1 (c) with the reduction in electron densities. Corresponding, the figure 1(d) represents the start of polarity reversal of electric field for the next breakdown pulse. The behaviour of dielectric barrier surface is elaborated by an examination of spatio-temporal characteristics of surface charge densities at the similar time instants (t1 - t4) as shown in figure 1 (e - h). From t1 to t2, the surface charge density of dielectric barrier is varied from negative to nearly zero, when the discharge current density approaches to the higher values during the emergence of constricted filamentary discharge plasma and then becomes positive in the afterglow phase of a half cycle as shown in figure 1 (g, h).

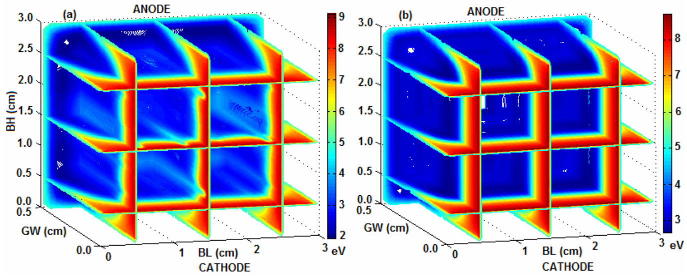

Figure 2 (a, b). Spatial slice distributions of electron mean temperature at 15 kHz and V_{appl} = -1.6 and -1.5 kV.

The electron temperature is started to reduce from the head of filament near the surface of cathode barrier towards the tail near the anode barrier with a numerical value from ~ 9 to 4 eV. It is evident from the figure 2 (a) that the existence of filaments persist their substantial influence in the reactor gap. Subsequently, the gradients are vanished in the absence of overvoltage and the uniform structure of electron mean temperature is enhanced near the momentary cathode with the smaller value from ~ 8 to 3 eV as exhibited in figure 2 (b). The mentioned range of electron temperature is suitable for breaking of chemical bonds in the bio-medical applications, which ultimately produce large number of positive and negative charged particles and free radicals in the discharge plasma. These free radicals are responsible for the various chemical reactions, which explicitly depend on the operating gas and can be useful for medical applications [2].

It is noticed from the volumetric distribution of electrons that the existence of detached filaments is higher in the lower frequency regime with the higher density values as compared to higher frequencies as shown in figure 3 (a - d). The filaments in the bulk of discharge plasma are small, thin and independent as compared to the structure of filaments near the open boundaries of a parallel plate reactor because of strong asymmetric breakdown at lower frequencies.

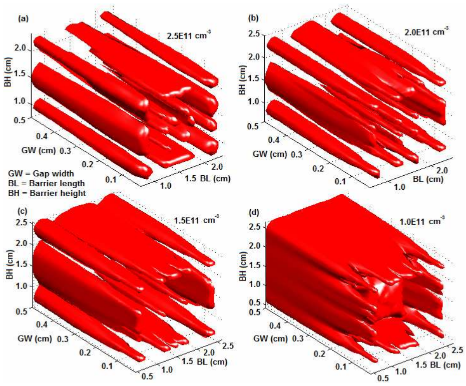

Figure 3 (a - d). Constricted filamentary distribution of electrons at 5, 10, 15 and 20 kHz and -1.6 kV.

This demonstrates that the channels for conduction of charged carriers are not uniformly distributed on the surface of dielectric barrier, indicating the random behaviour of filaments. As a result, the size of filaments increases with a rise in driving frequency and they are strongly coalesced together from 15 to 20 kHz. The elastic and inelastic electron impact energy losses are increased from higher to lower frequencies, which ultimately raise the higher probability of complex filamentary discharge plasma [4]. Moreover, the filaments join each other with an increase in driving frequency and the space between them is eradicated approximately at 20 kHz except near the region of cathodic barrier, implying an impressive influence of electrons in this particular region.

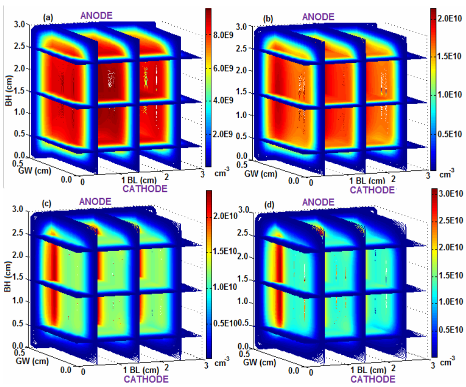

Figure 4. Slice distributions of electrons density at (a) 30, (b) 50, (c) 70 and (d) 90 kHz and V_{appl} = -1.5 kV.

The spatial snaps of electron density are extracted during the half cycle at different frequencies when the discharge current density attains its maximum value. The three-dimensional slice distributions of electrons illustrate that the maximum density is emerged near the cathode fall region at 30 kHz and it shifts near the anodic barrier at 50, 70 and 90 kHz as shown in figure 4 (a - d). A spatial volumetric gradient in the value of electron density is built up near the anodic barrier at 50 kHz, which becomes more intense and squeeze at further higher frequencies as displayed in figure 4 (c, d). These trapped electrons are responsible for the occurrence of significant residual current density during the polarity reversal of electric field from 50 to 100 kHz. In this frequency regime, the electron density keeps on increasing continuously from 30 to 90 kHz with a numerical value from ~ 8.0×10^9 to 3.5×10^{10} cm^{-3}.

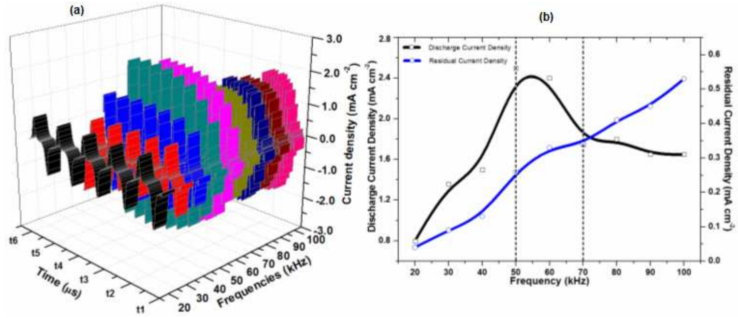

Figure 5 (a, b). Temporal profiles of discharge current density from f = 20 to 100 kHz and V_{appl} = -1.5 kV.

In addition to the above spatial distributions, the temporal profile of conduction discharge current density is investigated for several cycles from time t1 to t6 at different frequencies as shown in figure 5 (a, b) to verify the stationary state of APD. The electrons are intensively trapped after 40 kHz in the positive column at a specific location and this process becomes more prominent at further higher frequencies, violating the condition of quasi-neutrality. In particular at lower frequencies than higher, the dynamic response of ionic species density is dominant due to the collisions with the gas particles and barrier surface in the glow discharge plasma. The temporal evolution of conduction discharge current density reveals that it is directly proportional to the driving frequency from 20 to 50 kHz, falls from 50 to 70 kHz and becomes approximately constant after 70 kHz. In the range from 50 to 100 kHz, the direction of drift motion of electrons and ions are inverted before reaching the dielectric barriers of opposite polarity. This enhances a growth of electrons due to the collisions of ions between the gas particles and at the same time, the source of secondary emission of electrons is halted because the ionic species revert their path before colliding with the barrier surface. However, the value of discharge current density is partially independent of driving frequency from 70 to 100 kHz and this trend is consistent at further higher frequencies (~ 140 kHz). So, the quantitative analysis of both current densities is carried out by considering their positive maximum values of conduction discharge and residual current densities from 20 to 100 kHz as displayed in figure 5 (b). This discussion exhibits that the dynamic behaviour of electrons in the positive column is effected in different regimes of driving frequency and agrees with the previous theoretical and experimental understanding [5, 6].

References

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