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ABSTRACT
Transition from a Townsend mode to a normal glow mode has been reported in the literature for uniform dielectric barrier discharge (DBD) at atmospheric pressure. In this paper, through a one-dimensional fluid model, more modes of uniform DBD in helium and transitions between them are found with varying rising time of a saw-tooth voltage. The results indicate that a positive discharge initiates at the positive-slope voltage phase, whose pulse duration decreases, while the peak value increases with decreasing rising time. During this process, a negative discharge initiating at the negative-slope voltage phase keeps weakening to almost zero current. The predominant positive discharge is then investigated through analyzing spatial distributions of electron density, ion density, and electric field at the peak current moment. In combination with the voltage-current curve, discharge modes of DBD are revealed to transit from a Townsend, a normal glow, to an abnormal glow with decreasing voltage rising time. These mode transitions are qualitatively explained by analyzing the gap voltage and electron density averaged in the gap just before discharge initiation. The results also suggest that by reducing the rising time or increasing voltage amplitude, DBD is prone to operate in the abnormal glow mode. Moreover, DBD in the abnormal glow mode has an increasing peak current and a decreasing pulse duration with increasing voltage amplitude. Finally, the critical voltage amplitude is given as a function of voltage rising time for the mode transitions from the Townsend to the normal glow and the normal glow to the abnormal glow.

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I. INTRODUCTION
Low-temperature plasma at atmospheric pressure has been extensively used in various application fields, such as thin-film deposition, surface modification, ozone generation, and waste water treatment.

As one of the most promising approaches to generating low-temperature plasma at atmospheric pressure, dielectric barrier discharge (DBD) has attracted much attention. DBD is usually excited by alternating-current sinusoidal voltages from line frequency to several tens of kilohertz. Under such excitation, uniform DBD can be obtained under proper conditions, such as the usage of inert gases and thin dielectric layers. The uniform DBD can be operated in different modes, including a glow mode and a Townsend mode. The glow mode is characterized as narrow current pulses of high current density and a spatial structure similar to that of low-pressure glow discharge. As a comparison, the Townsend mode is characterized by a relatively long-duration pulse with low current density. Due to the weak current, the electric field is hardly disturbed by space charge. In numerical simulation, the electron density of the glow mode ranges from $10^{11}$ to $10^{12}$ cm$^{-3}$, whereas it ranges $10^{8}$ to $10^{10}$ cm$^{-3}$ in the Townsend mode. Besides the difference in the electron density, no positive column composed of quasineutral plasma is formed in the Townsend mode, however, which is a characteristic region for the glow mode. For the normal glow mode, any further increase in the current will inevitably increase the electron and ion densities at the cathode, which will lead to transition to the abnormal glow mode if the electron and ion densities surpass their critical values. After transition to the abnormal glow mode, the voltage-current curve has a positive slope at the rising stage of
current.\textsuperscript{22} From the descriptions mentioned above, it can be inferred that the discharge mode is very important for DBD applications because plasma density and discharge aspect are distinct for different modes.

Golubovskii \textit{et al.} have proposed that uniform DBD in helium is prone to operate in the normal glow mode with a thin barrier and a wide gap. Otherwise, it belongs to the Townsend mode.\textsuperscript{23} With increasing voltage amplitude, argon DBD transits from the Townsend mode, subnormal glow mode, to the normal glow mode.\textsuperscript{24} Besides sinusoidal excitation, the Townsend-like mode is demonstrated in experiments at the rising phase of a saw-tooth voltage, which transits to a glowlike mode at the falling voltage phase.\textsuperscript{1} By applying a microsecond-duration pulsed voltage with nanosecond rising time, the normal glow mode is experimentally produced in a helium DBD.

In fact, the discharge mode is crucial for DBD applications because it determines key plasma parameters, such as electron density and electron temperature. Unfortunately, it is very hard to produce high-voltage excitations with variable parameters in experiments. Hence, a numerical simulation is frequently employed to shed light on the operating mode of DBD with various excitations. Excited by a low-frequency Gaussian voltage, argon DBD transits from the Townsend mode to the normal glow one with increasing voltage amplitude.\textsuperscript{25} With increasing frequency of a triangle voltage, argon DBD transits from the Townsend-like mode to the normal glow one.\textsuperscript{24} Under the same excitation, helium DBD transits from the Townsend mode to the normal glow one with increasing gap width.\textsuperscript{26} Excited by a square-wave voltage, helium DBD with a narrow gap operates in the glowlike mode.\textsuperscript{27} With increasing amplitude of a pulsed voltage, DBD transits from the subnormal glow mode to the normal glow one in argon, while it transits from the Townsend mode to the normal glow one in nitrogen.\textsuperscript{26} With increasing rising time of a pulsed voltage, DBD transits from the normal glow mode to the Townsend one in nitrogen\textsuperscript{27} or helium.\textsuperscript{28} Besides the discharge modes mentioned above, other modes, such as the abnormal glow mode, has not been revealed for nanosecond pulsed DBD.

In this paper, through a one-dimensional fluid model, atmospheric pressure helium DBD excited by a saw-tooth voltage is investigated with varying voltage rising time in a wide range. Besides the usual Townsend and normal glow modes, the results reveal that DBD can operate in the abnormal glow mode with decreasing voltage rising time.

\section{II. MODEL DESCRIPTION}

In our model, atmospheric pressure helium DBD is generated between two parallel-plate electrodes, each of which is covered by a dielectric layer with a thickness of 1.0 mm. There is a 4.0 mm separation between the electrodes, leaving a gap with 2.0 mm width between the dielectric layers. Since helium is used as the working gas, the following species are considered in the model: electrons ($e$), helium monomer ions ($He^+$), and atomic helium ($He$).\textsuperscript{29} The applied saw-tooth voltage is depicted as follows:

\begin{equation}
V_a(t) = \begin{cases} 
2V_p \frac{T_r}{T_r + T_p}, & nT - \frac{T_r}{2} \leq t \leq nT + \frac{T_r}{2}, \\
-2V_p \frac{T_r}{T_r + T_p} + \frac{TV_p}{T - T_r}, & nT + \frac{T_r}{2} \leq t \leq nT + \frac{2T - T_r}{2}.
\end{cases}
\end{equation}

Here, $V_p$ and $T$ are the amplitude and period of the saw-tooth voltage $[V_a(t)]$, respectively. $T_r$ is the rising time of $V_a(t)$, during which $V_a(t)$ increases from $-V_p$ to $+V_p$, and $n$ is an integer. Uniform DBD is assumed to be produced in the gap. Therefore, a one-dimensional fluid model is employed in our model. Electrons and ions are described by the continuity equation,

\begin{equation}
\frac{\partial n_e}{\partial t} + \frac{\partial j_e}{\partial x} = S,
\end{equation}

where $n$ and $j$ are the density and flux of a particle, respectively. Subscripts $e$ and $p$ represent the electron and ion, respectively. In the source term ($S$), direct ionization by electron impact and recombination between the electron and ion are considered as given below,

\begin{equation}
S = q\mu_e|E|n_e - \beta n_e n_p.
\end{equation}

Here, $E$ is the electric field. The Townsend ionization coefficient ($\alpha$), the electron–ion recombination coefficient ($\beta$), and the electron mobility ($\mu_e$) can be calculated from Refs. 30–32. Then, $j_{e,p}$ can be obtained from the momentum equation,

\begin{equation}
\frac{\partial \rho_e}{\partial t} + \frac{\partial \rho_j}{\partial x} = -D_e \frac{\partial n_e}{\partial x},
\end{equation}

where $\rho_e$ and $D$ are the mobility and diffusion coefficients, respectively. Rather than solving Poisson’s equation, $E$ can be obtained from the total current density ($I_T$) and the conduction current density ($I_c$) through the current conservation equation,

\begin{equation}
\varepsilon(x) \frac{\partial E(x,t)}{\partial t} + I_c(x,t) = I_T(t).
\end{equation}

Here, the permittivity $\varepsilon(x)$ is $\varepsilon_0$ in the gas gap and $\varepsilon_0\varepsilon_b$ ($\varepsilon_b = 7.5$) in the dielectric layers. $E$ and $I_c$ satisfy the following conditions, respectively:

\begin{equation}
\int_0^d E(x,t)dx = V_a(t),
\end{equation}

\begin{equation}
I_c(x,t) = c(j_e(x,t) - j_i(x,t)).
\end{equation}

The electron flux leaving the cathode is taken as $y j_{p_e}$; here, the secondary electron emission coefficient ($y$) is 0.01. Then, $I_T$ can be obtained by integrating Eq. (5) from $x = 0$ to $x = d$,

\begin{equation}
I_T(t) = \left(d_e + \frac{2d}{\varepsilon_b} \right)^{-1} \left[ \int_{x_1}^{x_2} I_c(x,t)dx + \varepsilon_0 \frac{\partial V_a(t)}{\partial t} \right].
\end{equation}

Here, $d_e$ is the gap width. The surface charge ($\sigma$) accumulated on the surface of the dielectric can be obtained from the following equation:

\begin{equation}
\sigma(x,t) = \int_0^t I_c(x,t')dt'.
\end{equation}

The set of equations listed above is solved by the semi-implicit Scharfetter–Gummel scheme.\textsuperscript{31} Uniform initial densities of electron and ion in the gap are considered with $n_e(x,0) = n_p(x,0) = 10^7$ cm$^{-3}$.

The theoretical model we established is reliable. This model has been used to investigate the influence of the discharge frequency on...
an argon DBD excited by a triangle voltage. The simulated results conform well to the experimental ones. Moreover, the model has successfully been used to simulate different DBD modes in the literature through analyzing spatial distributions of electron and ion to distinguish the Townsend mode from the glow one.

In the glow mode, the slope of the voltage-current curve at the rising stage of current is used to distinguish the normal glow mode from the abnormal one.

III. RESULTS AND DISCUSSIONS

Figure 1 presents waveforms of $V_a$ and the discharge current ($I_c$) with different rising times ($T_r$) of positive-slope voltage. Similarly, the falling time ($T_f$) corresponds to a negative-slope voltage phase, during which the applied voltage changes from $+V_p$ to $-V_p$. The applied saw-tooth voltage has a constant cycle and amplitude. We have applied a series of pulses to reach a steady state of the discharge. That is to say, amplitudes of the discharge current and the surface charge density do not vary any more from one pulse to another for a steady-state discharge. Figure 1 shows that there are a positive discharge (initiated under an applied voltage with positive slope) and a negative one (initiated under an applied voltage with negative slope) for a steady-state discharge. Moreover, the discharge is symmetric for the two voltage phases. A comparison of Fig. 1(a) with Figs. 1(b) and 1(c) shows that the current amplitude of the positive discharge increases and the pulse duration decreases with decreasing $T_r$. At the same time, the negative discharge weakens to almost zero current. With further decreasing $T_r$ to 200 ns [Fig. 1(d)], the current amplitude of the positive discharge increases to about 193 mA/cm$^2$ (peak current) and the pulse duration decreases to about 199 ns, which are identical to those of a nanosecond pulsed discharge. In a word, with decreasing $T_r$, the positive discharge turns predominant, which increases in the current amplitude, while decreases in the pulse duration.

For the positive discharges with different $T_r$, spatial distributions of electron density, ion density, and electric field at the peak moment of the positive discharge are illustrated in Fig. 2. Maximal electron density exists in the vicinity of the instantaneous anode poised at $x = 0$ mm, as shown in Figs. 2(a) and 2(b). A quasineutral plasma region is absent, and densities of the electron and ion are so low that the distortion of the electric field can be negligible. All these evidences reveal that the discharge with long $T_r$ belongs to the Townsend mode.

In Fig. 2(c), a positive column appears in the discharge region. Besides, a cathode fall region is formed in front of the instantaneous cathode ($x = 2.0$ mm). The cathode fall region verifies that the discharge belongs to the glow mode. In the glow mode, the electron density is $1.8 \times 10^{11}$ cm$^{-3}$. Similarly, the positive discharge in Fig. 2(d) also belongs to the glow mode with an electron density of $6.2 \times 10^{11}$ cm$^{-3}$, which is several times higher than that in Fig. 2(c).

Figure 3 presents the temporal evolution of surface charge density ($\sigma$). With a shorter rising time ($T_r$) of the positive-slope voltage, $\sigma$ has a sudden increment once the discharge initiates in the gas gap. Compared with it, $\sigma$ changes more slowly with a longer $T_r$. The difference in $\sigma$ should also come from the different discharge modes. As mentioned before, the normal glow discharge mode has intense electron avalanche, with results in faster accumulation of surface charge.

*FIG. 1. Temporal evolution of the discharge current ($I_c$) and applied voltage ($V_a$) with different rising times ($T_r$): (a) 50.0 $\mu$s, (b) 6.3 $\mu$s, (c) 1.0 $\mu$s, and (d) 200 ns.*
**FIG. 2.** Spatial distributions of electron density ($n_e$), ion density ($n_p$), and electric field ($E$) from the anode to the cathode with different voltage rising times: (a) 50.0 μs, (b) 6.3 μs, (c) 1.0 μs, and (d) 200 ns.

Figure 4 presents the gap voltage ($V_g$) as a function of discharge current for the glow mode in Fig. 2. The red line and the black line in Fig. 4 illustrate the rising and the falling stages of the current, respectively. Only the rising stage of the current is used to identify the discharge mode. As shown in Fig. 4(a), $V_g$ first increases and then decreases with increasing $I_c$. Compared with the voltage-current curve of a direct-current discharge, the negative differential conductivity verifies that the discharge belongs to the normal glow mode. In Fig. 4(b), there is a positive correlation between $V_g$ and $I_c$, which is identical to the abnormal glow mode. Hence, the discharge in Fig. 4(d) is indeed in the abnormal glow mode. Consequently, the positive discharge undergoes a scenario from the Townsend mode, to the normal glow mode, and finally to the abnormal glow one with decreasing $T_r$.

Due to an abrupt change in the gap voltage at initiation moment, averaged electron density can be obtained just before the positive discharge. Figure 5 presents the electron density averaged in the gap and gap voltage as functions of $T_r$ to shed light on the mechanism of mode transition. It can be found that with decreasing $T_r$, the averaged electron density just before positive discharge keeps nearly constant ($10^{8} \text{ cm}^{-3}$) for a long $T_r$, which increases sharply for a short $T_r$. Similarly, the gap voltage just before initiation (initiation voltage) keeps nearly constant for a long $T_r$, which increases sharply for a short $T_r$.

As is well known, residual charges (mainly electrons) in the discharge volume play an important role in DBD. Before initiation with a long $T_r$, net field in the gap slowly recovers with time due to the slowly increasing applied field. Hence, electron avalanche can be negligible under the fairly weak field. Under this circumstance, residual-electron density just before initiation keeps almost constant with varying $T_r$. Accordingly, the initiation voltage also keeps almost constant with varying $T_r$. Moreover, the $\alpha$ coefficient, proportional to the net field intensity, remains at a low value after initiation. This means that the positive discharge with a long $T_r$ is too weak to produce numerous ions to disturb the applied electric field. As a result, the discharge with a long $T_r$ can only be sustained in the Townsend mode. With decreasing $T_r$, the electric field recovers more quickly with time. Hence, some of residual electrons may
Figure 4. Curves of the gap voltage and discharge current in the glow discharge mode. (a) and (b) correspond to Figs. 2(c) and 2(d), respectively.

Figure 5. Electron density averaged in the gap (a) and gap voltage for initiation (b) as functions of voltage rising time.

have enough energy to induce small avalanches, which are not sufficient to give rise to breakdown of the whole gap. This causes the increase in the electron density just before initiation with decreasing $T_r$. Moreover, the steeply increasing voltage tends to initiate the discharge under an overvoltage condition (high $\alpha$ coefficient). Under mutual effects of more electrons and the overvoltage condition, a great number of large electron avalanches will develop after gap initiation. Resultantly, the current amplitude increases with decreasing $T_r$. With more ions produced in the discharge, a cathode fall region tends to be formed. Hence, the discharge transits to the glow mode with decreasing $T_r$. With further decreasing $T_r$, the discharge turns stronger and the current density becomes higher, which leads to the transition from the normal glow mode to the abnormal glow one.

As mentioned before, the peak current and pulse duration of the positive discharge vary with $T_r$. Besides, they are also influenced by voltage amplitude, as shown in Fig. 6. It can be found that the peak current increases monotonously, while the pulse duration decreases with increasing amplitude of the saw-tooth voltage. Similar to the mode transition with varying $T_r$, the increasing peak current with voltage amplitude can also induce the mode transition from the normal glow to the abnormal one (the mode transition is verified through current-voltage curves, which are not shown here).

Figure 7 presents the critical peak voltage (voltage amplitude) of mode transition as a function of $T_r$. Figure 6 shows that under a constant $T_r$, the mode transits from the Townsend to the normal glow and from the normal glow mode to the abnormal one with increasing voltage amplitude. Under a constant voltage amplitude, DBD transits from the Townsend mode to the normal glow one and from the normal glow mode to the abnormal one with decreasing $T_r$. In a word, atmospheric pressure DBD is prone to operate in the abnormal glow mode with decreasing $T_r$ or increasing voltage amplitude.
IV. CONCLUSIONS

Based on a one-dimensional fluid model, the influence of $T_r$ has been investigated on discharge modes of an atmospheric pressure helium DBD excited by a saw-tooth voltage. Results indicate that uniform DBD initiates only once during the positive voltage phase. Moreover, the current amplitude of positive discharge increases and its pulse duration decreases with decreasing $T_r$. Besides, the discharge transits from the Townsend mode, the normal glow mode to the abnormal glow mode with decreasing $T_r$. The mode transition from the normal glow to the abnormal mode is further verified by the voltage-current curve. Furthermore, it is analyzed through investigating the averaged electron density and gap voltage as functions of $T_r$. Besides $T_r$, the voltage amplitude can induce the mode transition from the normal glow to the abnormal glow one. Finally, the critical voltage amplitude as a function of $T_r$ is investigated for the transitions from the Townsend mode to the normal glow one and the normal glow mode to the abnormal glow one. As a major contribution, our results reveal that through varying voltage rise time or voltage amplitude, the DBD mode can transit from the Townsend, the normal glow, to the abnormal glow modes. In the abnormal glow mode, the current amplitude increases with increasing voltage amplitude, while the pulse duration decreases.

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