

ORIGINAL RESEARCH

Positive and negative streamers in air and nitrogen in a sharply inhomogeneous electric field under conditions of runaway electron generation

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Abstract

The development of positive and negative streamers in a point-to-plane gap filled with air and nitrogen at various pressures (50–200 kPa) and voltages (8–25 kV) was studied. A four-channel intensified charge-coupled device (ICCD) and a streak-camera were used. Electrical parameters were measured with high resolution (10 GHz). An original method of measuring a displacement current caused by a streamer was applied. As was expected, positive streamer branches in nitrogen at low voltages and/or elevated pressures while a large-diameter streamer is formed in air. However, at high voltages or negative polarity, the large-diameter streamer is formed both in nitrogen and air in the entire pressure range. It was found that runaway electrons (REs) are generated in the very first picoseconds of gas ionisation near the pointed cathode. It was assumed that REs can be generated near the pointed anode and produce bremsstrahlung radiation due to a sharply inhomogeneous distribution of electrical potential. It was found that in the final stage of negative streamer development in air and nitrogen, the gas between the streamer front and the opposite electrode is ionised almost simultaneously in the entire volume when the streamer diameter is almost equal to the interelectrode gap.

1 | INTRODUCTION

Streamer discharges have been studied for a very long time, the physics of which is presented in papers [1–5] and monographs [6–10]. They are formed at high gas pressures, in particular at atmospheric pressure. Due to the prospects of using atmospheric pressure discharges in a wide variety of fields of science and technology, significant success has been achieved both in the modelling of streamer discharges using particle-in-cell methods [11–13], fluid models [14–17] including nanosecond atmospheric discharges [18–20], experimental studies [21–24], and their combinations [25–29]. Special attention has been paid to nanosecond discharges in gases of atmospheric pressure in an inhomogeneous electric field, as a fairly simple method for

producing a low-temperature non-equilibrium plasma. Under conditions of an inhomogeneous distribution of the electric field strength and nanosecond duration of voltage pulses, providing high overvoltages, a diffuse discharge is formed, the plasma of which is cold. Studies of the initial stage of the diffuse discharge by high-speed imaging methods have shown that a streamer develops in the discharge gap, and its diameter is comparable to the distance between the electrodes. Researchers are still trying to understand what processes are responsible for the formation of such a streamer. On the one hand, the large diameter of the streamer is a consequence of the inhomogeneous distribution of the electric field strength. On the other hand, it is not completely clear why a continuous plasma front develops rather than separate small-diameter channels (filaments). This indicates a

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sufficiently high level of preliminary ionisation of gas ahead of ionisation front, which ensures the overlap of avalanches. The existing models describe well the formation of such streamers in air, where the gas preionisation is provided due to the ionisation of oxygen molecules by the radiation of nitrogen molecules [30–34]. However, difficulties arise in pure gases [35].

It has long been known that runaway electrons (REs) [36–38] and x-rays [39–43] are generated in the prebreakdown stage of such discharges [44–48]. They are able to provide a sufficient level of preliminary gas ionisation, which was shown in the work comparing the action of two mechanisms: photoionisation and REs [49, 50]. It is shown that the streamer develops along the ‘tracks’ of REs.

When studying the dynamics of streamer formation in a sharply inhomogeneous electric field, it was shown that the streamer velocity changes as it develops and is associated with a change in its diameter and a reduction in the distance to the opposite electrode [51]. It was found that in the final stage, the streamer velocity increases dramatically. This fact in itself is not new and is already known [52–55]. However, under some conditions, the streamer velocity (or at least the velocity of the light front propagation) can reach practically the light speed [56]. This article is devoted to the study of this effect from different angles using a streak camera and measuring a displacement current caused by the redistribution of the electric field during the formation of a streamer [57, 58]. The displacement current caused by the streamer is called a dynamic displacement current (DDC) in order to separate it from the displacement current caused by the voltage change over time.

The purpose of the study is to shed light on the features of the development of gas ionisation at the final stage of the formation of a large-diameter streamer in a sharply inhomogeneous electric field under conditions of generation of REs.

2 | EXPERIMENTAL SETUPS AND MEASURING TECHNIQUES

The experimental setup consisted of a gas discharge chamber combined with a 2-m long transmission line (wave impedance of 75 Ω), high-voltage nanosecond generators, four-channel intensified charge-coupled device (ICCD), streak camera, and oscilloscope is shown in Figure 1.

Antares high-voltage nanosecond generators based on the fast ionisation device (FID) technology [59] were used in the experiments. A GIN-50-1 generator produces positive voltage pulses, U_0 , (8–25 kV at a matched load) with a rise time of 2.2 ns and full width at half maximum (FWHM) of 13 ns. A GIN-100-1 generator produces negative voltage pulses with amplitudes of 15–27 kV at a matched load with the rise time of 1.7 ns and FWHM of 4.5 ns.

A capacitive voltage divider (CVD) was built into the input of the 2-m long transmission line. This made it possible to measure separately the incident, U_0 , and reflected, U_{ref} , voltage pulses. The gap voltage was determined as the sum of $U_0 + U_{\text{ref}}$.

The high-voltage electrode was made of a sewing needle (stainless steel) 5 mm long. The needle tip curvature radius was

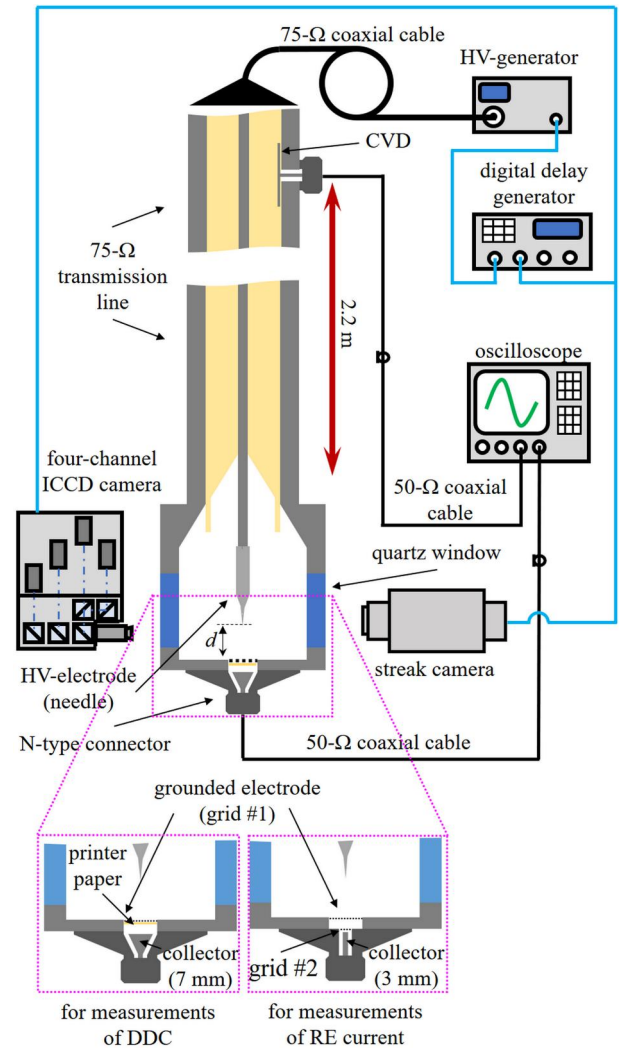


FIGURE 1 Block diagram of experimental setup. CVD, capacitive voltage divider; DDC, dynamic displacement current; RE, runaway electron

0.075 mm. The grounded electrode was made of a perforated plate (grid #1 in Figure 1). Its light transmittance was 0.75. The interelectrode distance was $d = 8.5$ mm.

The streamer dynamics was studied with a HSFC-PRO four-channel ICCD camera and a Hamamatsu C10910-05 streak camera as shown in Figure 1. The minimal exposure duration of the ICCD camera was 3 ns. However, delay between the channels could be varied in the range of 0.2–3 ns under experimental conditions. The slit of the streak camera was oriented along the gap axis. The slit width was 0.02 mm, which ensured the temporal resolution in the order of magnitude of tens of picoseconds. The ICCD camera and streak camera operated simultaneously and were switched on by a signal from a digital delay generator. Every image presented below was recorded per one shot. High-voltage generators were operated in single-pulse mode.

Streamer development was studied also by analysing the DDC caused by the redistribution of the electric field during the streamer formation. DDC shows when a streamer appears and when it reaches the opposite electrode [57, 58]. It provides

accurate synchronisation of ICCD and streak images with the waveforms of voltage and current. DDC was measured with a collector 7 mm in diameter placed behind the grounded grid electrode (see Figure 1). The electric field penetrates the grid with high attenuation ($\sim 10^3$ [60]), and the collector registers the displacement current as the electric field begins to change when a streamer appears in the discharge gap. Printer paper with a thickness of ≈ 0.1 mm was placed on the back of the grounded electrode close to it to absorb REs generated during a pre-breakdown stage at negative polarity of the pointed electrode. Under the experimental conditions, the RE current amplitude is quite small (tens to hundreds of mA). Therefore, one layer of paper was enough. Thus, they did not contribute to a signal.

To measure the current of REs in experiments with negative polarity, a collector 3 mm in diameter was used (see Figure 1). Grid #2 served as an additional barrier for the electric field to exclude DDC. It has a cell size of 1×1 mm and a wire thickness is 0.4 mm. Both grids (#1 and #2) attenuate the electric field by $\sim 10^3$ times [60].

Signals from CVD and collectors were fed to a Tektronix MSO64B oscilloscope (8 GHz, 20 GS/s) via RadioLab 5D-FB PEEG coaxial cables (50 Ω) with a bandwidth up to 30 GHz.

The discharge chamber was pumped out with a fore vacuum pump and then filled with air or nitrogen. The pressure was varied in the range of 50–200 kPa.

3 | RESULTS AND DISCUSSIONS

3.1 | Positive streamers in air and nitrogen at various pressures and voltages

The development of positive streamers in air, as well as in nitrogen with oxygen admixture at various percentages, has been well studied both experimentally and theoretically. A decrease in the proportion of oxygen in the mixture leads to the fact that the ionisation front loses its stability and the streamer begins to branch. If the reduced electric field is low, the streamers can stop.

Figure 2 shows the difference in the streamer development in air and nitrogen at atmospheric pressure at a relatively low voltage ($U_{\max} = 16$ kV, $U_{\max}/d \approx 19$ kV/cm). ICCD images taken during discharge in air (Figure 2a) show that a large diameter streamer [51, 56, 61] develops in the gap. The same streamers were observed in Refs. [12, 18, 19, 22, 25, 26, 38, 44, 46, 49–51, 62–66]. It is seen that the streamer diameter can reach the order of the length of the interelectrode distance d . Figure 2c shows that the streamer front moves in the direction of the grounded electrode at different velocities as in our previous studies [51, 67]. Near the pointed electrode, the streamer develops very quickly, since in this zone the electric field strength is maximum. The streamer sharply slows down with an increase in its diameter, which is due to a decrease in the electric field strength at the front. At a distance of 5–6 mm (Figure 2c), the streamer almost stops. The streamer covers a distance of 1 mm in 2 ns (0.05 cm/ns). However, then there is a ‘jump’; the streamer travels the last 2.5 mm in 0.5 ns (0.5 cm/

ns) and bridges the gap. The peculiarity of gas ionisation at the final stage of streamer development is that the electric field between the streamer front and the grounded electrode should be distributed almost uniformly. Figure 2a (frame C2) shows that the front of the large diameter streamer and the grounded electrode form something resembling a ball-to-plane gap. As a result, a small-diameter streamer is formed, as can be seen in Figure 2a, frame C3. The high velocity of such a streamer is due to the high electric field strength at its front, since the radius of the streamer head is orders of magnitude smaller than the radius of the streamer that developed at the beginning.

The conductivity of the plasma channel depends on the electric field strength at which a streamer was formed because the one determines the ionisation rate and the electron concentration in the plasma channel. For this reason, there is no voltage drop at minimum voltage under the study (Figure 2e,f); the current through the gap is small. If the voltage pulse had a longer duration (hundreds of nanoseconds), then the channel conductivity could be increased due to secondary ionisation waves.

Figure 2g shows the results of measurements of a displacement current ($C_{\text{gap}}dU_{\text{gap}}/dt + \text{DDC}$) with the 7-mm collector placed downstream the grounded grid electrode (see Figure 1). The electric field strength near the surface of the grounded electrode, $E_{\text{gr. el.}}$, is calculated from the displacement current ($C_{\text{gap}}dU_{\text{gap}}/dt + \text{DDC}$) by the method described in Refs. [57, 58]. The start of ionisation processes near the pointed electrode and the subsequent appearance of a streamer lead to the appearance of a displacement current caused by the redistribution of the electric field in the gap by dense plasma. Thus, we know with high accuracy when the streamer appears relative to the voltage pulse, we see how long it propagates towards the opposite electrode, and when it arrives at it. One can see the exact correlation between the DDC waveforms (Figure 2g) and the streak images (Figure 2c).

Under the same conditions, breakdown in nitrogen was markedly different (Figure 2b,d,f,h). It can be seen that at the very beginning, a streamer is formed near the pointed electrode, as in air, but then it branches: several streamers fan out from a common origin. Some of them move in the direction of the grounded electrode. They arrive at it at different times. This follows from the DDC waveform. One can see a sequence of peaks with a sharp front in the time interval 11–16 ns in Figure 2h.

As in the case of breakdown in air, in the vicinity of the pointed electrode, the propagation velocity of the ionisation front in the axial direction is high, but rapidly decreases as the central streamer develops (Figure 2d). However, unlike the streamer in the air, it can be seen that at a distance of 4–8.5 mm, streamers in nitrogen accelerate smoothly, and not abruptly. Such dynamics of the streamer is reflected in DDC (Figure 2f), the value of which gradually increases as the streamer approaches the opposite grounded electrode.

The absence of effective preliminary gas ionisation ahead of the streamer front in nitrogen leads to the fact that the concentration of seeded electrons is low and insufficient to maintain a continuous ionisation front. Therefore, branching occurs.

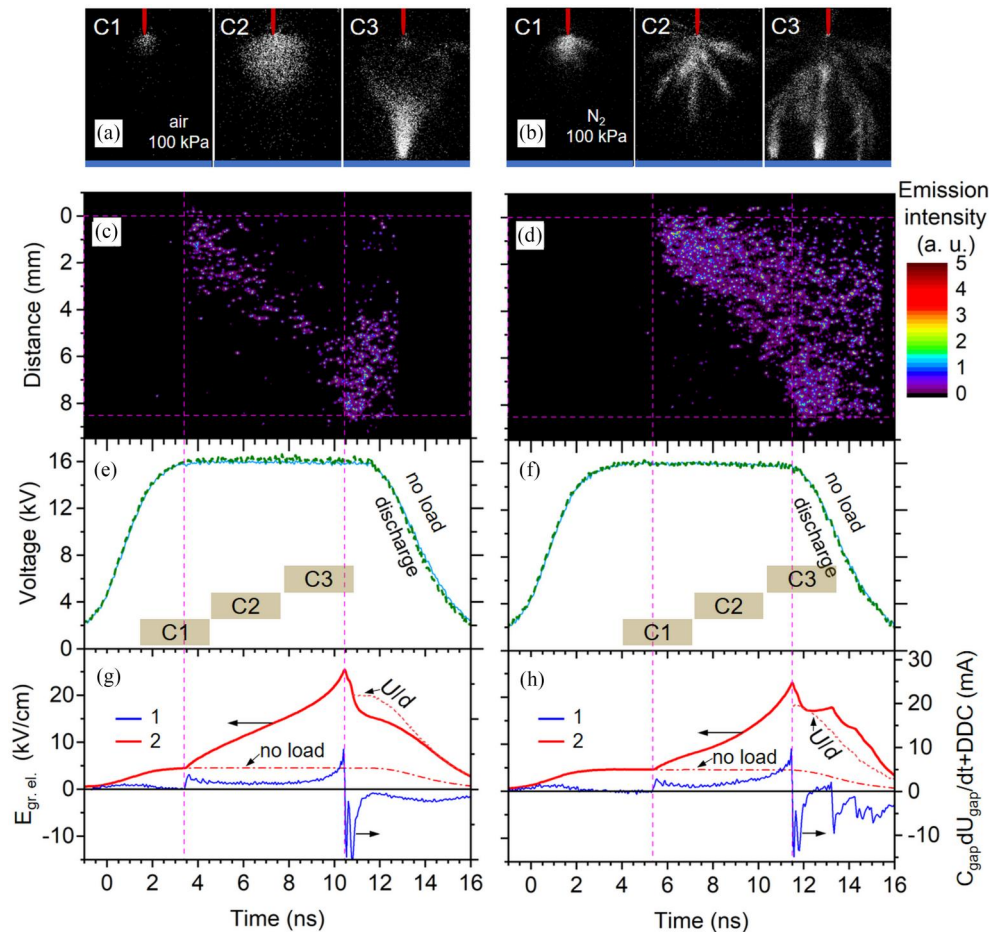


FIGURE 2 Development of positive streamers in air and nitrogen at a pressure of 100 kPa. (a), (b) Intensified charge-coupled device (ICCD) images for air and nitrogen, respectively, (c), (d) Streak images of discharge emission along the gap axis in air and nitrogen, respectively, (e), (f) Voltage waveforms during the discharge and in no-load mode in air and nitrogen, respectively, (g), (h) displacement current (1) waveforms and time-dependence of the electric field strength (2) near the grounded electrode recorded during the discharge in air and nitrogen, respectively. Rectangles C1–C3 show the operation of the ICCD camera channels; their width corresponds to the exposure duration

Figure 3 shows the development of a positive streamer in nitrogen at a pressure of 100 kPa at various voltages of 30, 40, and 50 kV ($U_{\max}/d \approx 35, 47, \text{ and } 59 \text{ kV/cm}$). It can be seen that at these voltage pulse amplitudes, the large-diameter streamer is formed. The ionisation front remains continuous and there is no branching. This may indicate that at high voltages, some processes provide a sufficient concentration of seeded electrons, at which the ionisation front remains continuous. These can be REs and the X-rays generated by them. The critical electric field strength E_{cr} for electron runaway in nitrogen at atmospheric pressure is $\approx 450 \text{ kV/cm}$ [10, 43]. For the discharge gap under the study, the electric field strength reaches $\sim 1 \text{ MV/cm}$ near the point electrode at a voltage of only 15 kV [57]. Due to the sharply inhomogeneous potential distribution, an electron is able to gain an energy of 100–1000 eV after passing a distance of 1–10 μm on its way to the pointed electrode (anode). When electrons with such energies decelerate by the anode, X-ray bremsstrahlung can occur. With increasing voltage, not only the electric field strength near the anode increases, but also the area of space in which the electric field strength exceeds E_{cr}

increases too. The probability of the transition of electrons to the continuous acceleration mode (runaway mode) and their number are increased. As a result, their influence on ionisation processes grows and becomes decisive.

The streak images (Figure 3d–f) show that the streamer velocity is still non-monotonic: high velocity at the beginning, deceleration in the middle, and acceleration at the end when approaching the grounded electrode. In addition, when the streamer is approaching to the grounded electrode, a backward ionisation wave (BIW) starts in the direction of the pointed electrode. Its velocity is also non-monotonic. After some time, the secondary streamer starts towards the BIW. These processes promote an increase in the conductivity of the plasma channel and, accordingly, an increase in current and a decrease in voltage.

Figure 4 shows the pressure dependence of positive streamer formation dynamics at the same voltage (50 kV). The large-diameter streamer develops at a nitrogen pressure of 50 kPa as expected (Figure 4a). A twofold decrease in pressure led to an increase in the velocities of the primary streamer, the BIW, and the secondary streamer. There is also a noticeable

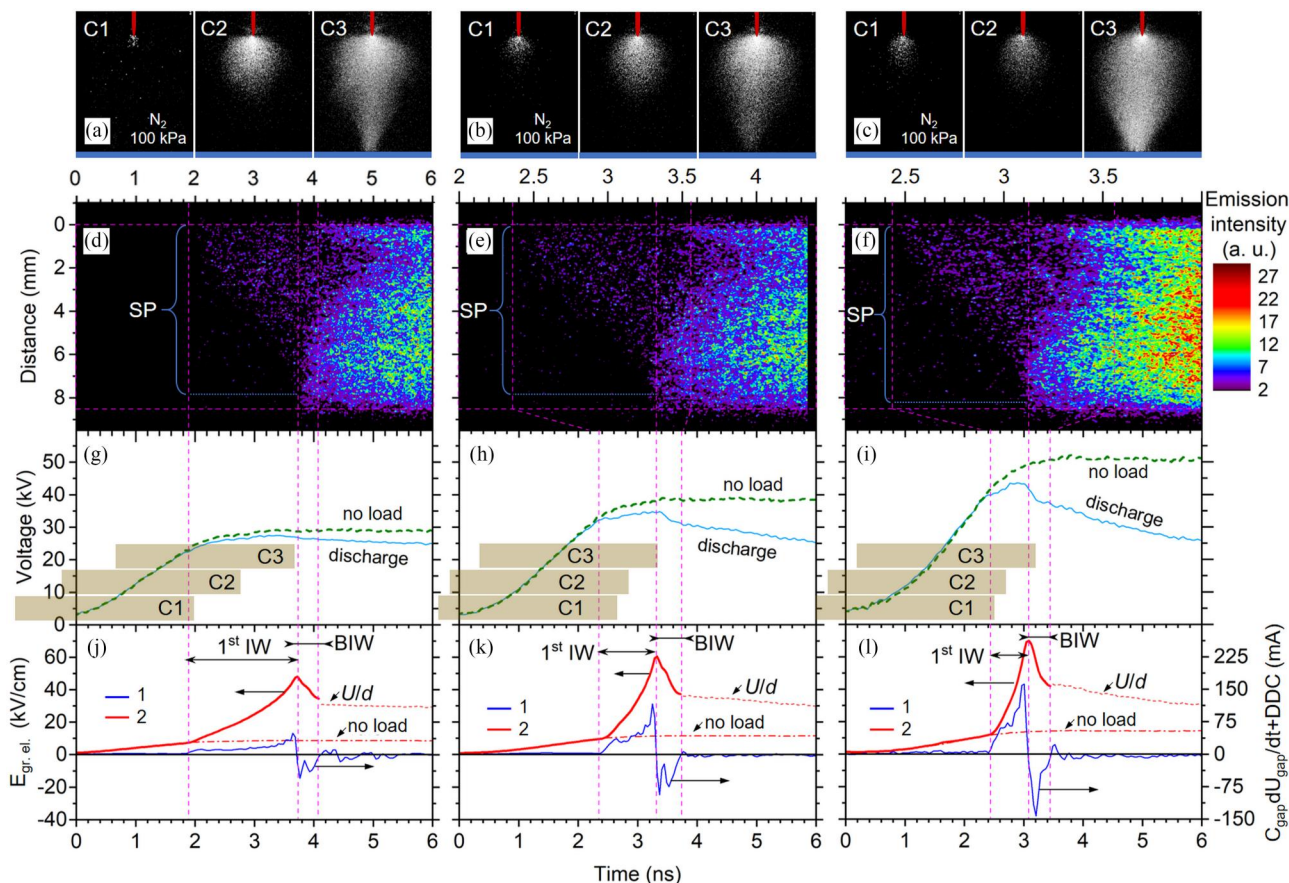


FIGURE 3 Development of positive streamers in nitrogen at a pressure of 100 kPa at various voltage pulse amplitudes. (a–c) Intensified charge-coupled device (ICCD) images of streamer development, (d–f) streak images of discharge emission along the gap axis, (g–i) voltage waveforms during the discharge and in no-load mode, (j–l) displacement current (1) waveforms and time-dependence of the electric field strength (2) near the grounded electrode recorded during the discharge and no-load mode. Rectangles C1–C3 show the operation of the ICCD camera channels; their width corresponds to the exposure duration. 1st IW, first ionisation wave (streamer); BIW, backward ionisation wave; SP, streamer propagation

voltage drop across the gap after breakdown. Unfortunately, the attempt to measure DDC failed.

At a nitrogen pressure of 200 kPa, branching is observed (Figure 4c). From a comparison of Figure 4k,l, it follows that the electric field strength near the grounded electrode at the moment the streamer arrives is the same. However, the pressure and, consequently, the reduced electric field strength differ by a factor of two. Probably, at a nitrogen pressure of 200 kPa, the reduced electric field strength is insufficient for electron run away in the initial stage of discharge formation.

The streak images demonstrate that the streamer velocity is non-monotonic (Figure 4d–f). At a nitrogen pressure of 50 and 100 kPa, a sharp acceleration of the streamer is observed when approaching the opposite grounded electrode, but this is not observed at a pressure of 200 kPa.

3.2 | Negative streamers in air and nitrogen at various pressures and voltages

Figure 5 shows streak images of streamer development in air at a pressure of 100 kPa at relatively low voltages. Due to the fact

that a negative polarity voltage pulse does not have a plateau, like a positive polarity pulse, a streamer can either cross the gap (Figure 5a,d) or stop somewhere in the gap (Figure 5b,c,e,f) depending on when it appears. However, REs are generated in all cases what is very important from the point of view of understanding the origin of REs. This proves that they are generated at the very beginning of the ionisation processes in the vicinity of the pointed electrode. A similar and more accurate result was obtained using another method in Ref. [60]. The formation of the discharge in such conditions was studied in work [12] but in pressurised hydrogen. The authors showed that the duration of the field emission from the cathode can affect whether the streamer stops in the gap or not. Under more extreme conditions, when the voltage pulses with an amplitude of half a megavolt are applied across a gap, a beam of REs generated near the cathode leads to the runaway breakdown [68].

FWHM of the RE current pulse is about 68 ps. However, this value corresponds to the pulse response of the oscilloscope. Measurements carried out using an oscilloscope with a bandwidth of 50 GHz showed that, under similar experimental conditions, FWHM of the one is 16–28 ps depending on the

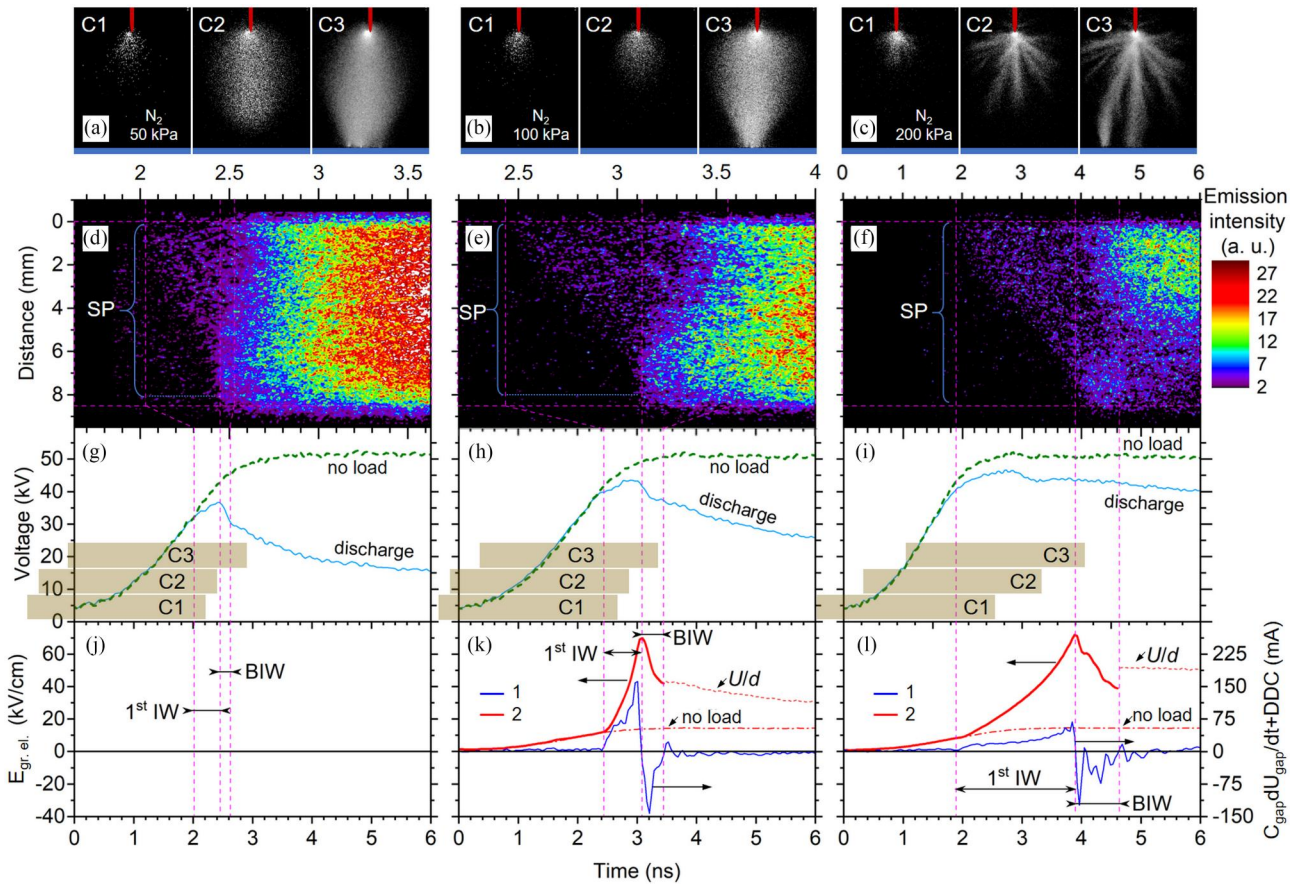


FIGURE 4 Development of positive streamers in nitrogen at various pressure and maximum voltage pulse amplitude. (a–c) Intensified charge-coupled device (ICCD) images of streamer development, (d–f) streak images of discharge emission along the gap axis, (g–i) voltage waveforms during the discharge and in no-load mode, (j–l) displacement current (1) waveforms and time-dependence of the electric field strength (2) near the grounded electrode recorded during the discharge and no-load mode. Rectangles C1–C3 show the operation of the ICCD camera channels; their width corresponds to the exposure duration. 1st IW, first ionisation wave (streamer); BIW, backward ionisation wave; SP, streamer propagation

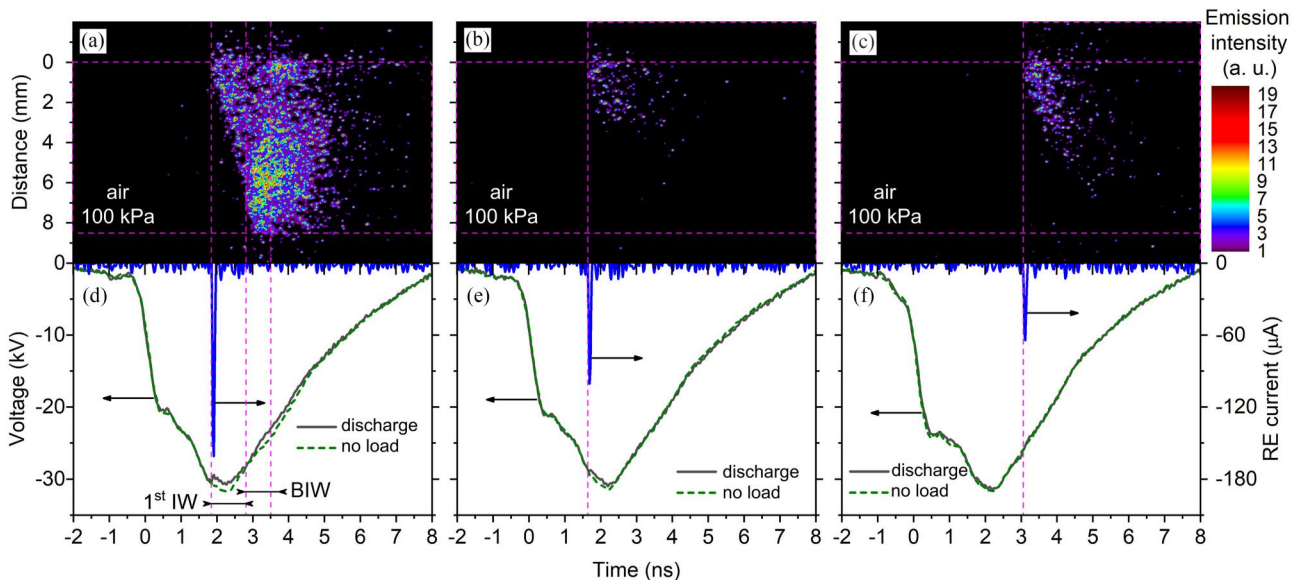


FIGURE 5 Development of negative streamers in air at a pressure of 100 kPa and minimum voltage pulse amplitude. (a–c) Intensified charge-coupled device (ICCD) images of streamer development, (d–f) voltage and runaway electron (RE) current waveforms during the discharge and in no-load mode. 1st IW, first ionisation wave (streamer); BIW, backward ionisation wave

gas pressure and the shape of a cathode [69]. According to the data of other measurements carried out using an oscilloscope with a bandwidth of 59 GHz, FWHM of the RE current pulse can be shorter than 11 ps at voltages higher by almost an order of magnitude [47].

The energy spectrum of REs is wide [44, 46]. There are electrons with energies of unity and tens of keV. At breakdown voltages of 100 kV and higher, the electron energy can reach hundreds of keV. Being generated in the vicinity of the pointed electrode at the very beginning of the ionisation processes, they fly through the gap and leave behind a weakly ionised gas. Simulation results show the high efficiency of this process [12, 49, 50]. REs are also capable of producing characteristic X-rays [70].

3.3 | Features of gas ionisation in the final stage of the development of negative streamer at high voltages

Figure 6 shows ICCD and streak images of the discharge formation in nitrogen at a pressure of 100 kPa as well as corresponding waveforms of voltage, RE current, and displacement

current. The electric field strength near the grounded electrode surface, $E_{gr. el.}$, is also shown.

Note that the measurement of RE current was performed in an individual experiment since different configurations of collectors were used (see Figure 1). Over 30 discharge implementations were recorded in both experiments. Then, for comparison, the implementations with the same breakdown delay were selected. It is seen that in a point-to-plane gap, the dynamics of the discharge formation is reproduced if the ionisation processes start under the same voltage. Figures 6g,h,i and 7g,h,i show that the voltage waveforms are reproduced.

Nitrogen was chosen in order to eliminate the effect of photoionisation that occurs in air and to demonstrate the role of REs in fast breakdown. The images taken with the four-channel ICCD camera shows that the large diameter streamer develops in the gap at different voltages of negative polarity. REs are generated at the initial stage of the streamer development. The streak images demonstrate that the streamer velocity is non-monotonic. In addition, in the final stage of the breakdown, the streamer rushes forward abruptly towards the opposite electrode. Streamer velocity reaches sublight value. Thus, the final stage of breakdown, when the streamer diameter exceeds the distance from the streamer front to the plane electrode, the

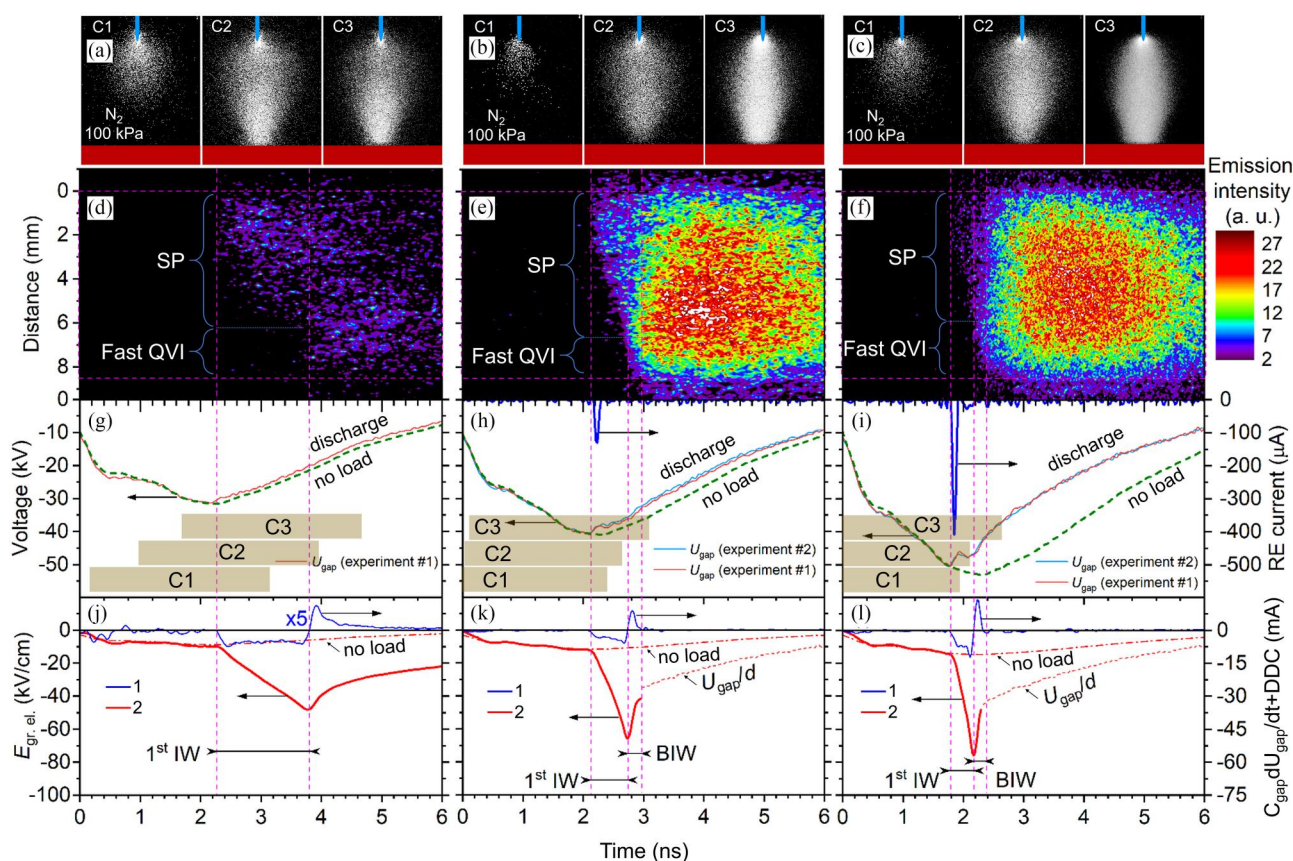


FIGURE 6 Development of negative streamers in nitrogen at a pressure of 100 kPa and various voltage pulse amplitudes. (a–c) Intensified charge-coupled device (ICCD) images of streamer development, (d–f) streak images of discharge emission along the gap axis, (g–i) voltage and runaway electron (RE) current waveforms during the discharge and in no-load mode, (j–l) displacement current (1) waveforms and time-dependence of the electric field strength (2) near the grounded electrode recorded during the discharge and no-load mode. Rectangles C1–C3 show the operation of the ICCD camera channels; their width corresponds to the exposure duration. 1st IW, first ionisation wave (streamer); BIW, backward ionisation wave; QVI, quasi-volume ionisation; SP, streamer propagation

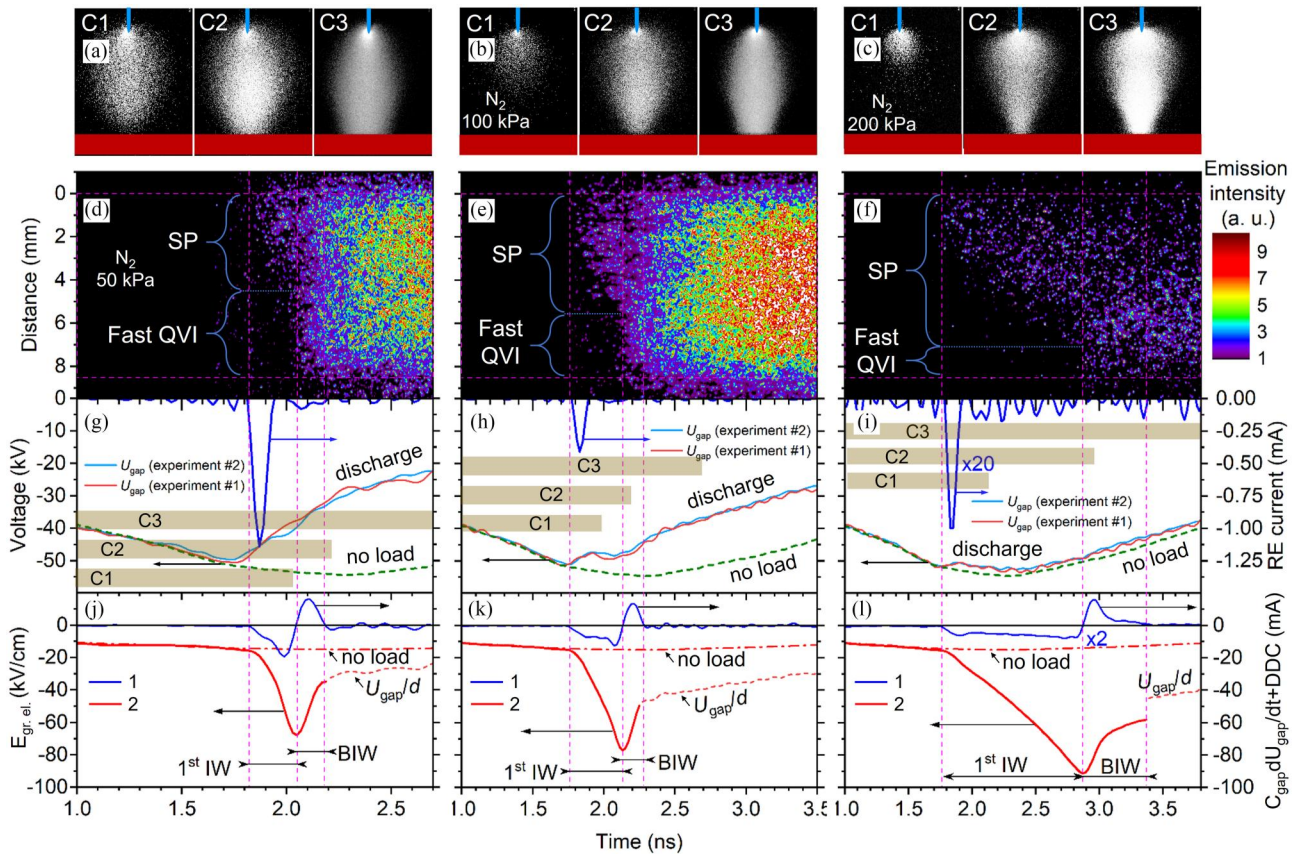


FIGURE 7 Development of negative streamers in nitrogen at various pressure and maximum voltage pulse amplitude. (a–c) Intensified charge-coupled device (ICCD) images of streamer development, (d–f) streak images of discharge emission along the gap axis, (g–i) voltage and runaway electron (RE) current waveforms during the discharge and in no-load mode, (j–l) displacement current (1) waveforms and time-dependence of the electric field strength (2) near the grounded electrode recorded during the discharge and no-load mode. Rectangles C1–C3 show the operation of the ICCD camera channels; their width corresponds to the exposure duration. 1st IW, first ionisation wave (streamer); BIW, backward ionisation wave; QVI, quasi-volume ionisation; SP, streamer propagation

ionisation conditions change radically: the distribution of the electric field strength becomes close to uniform, the gas is already partially ionised under the action of REs. Under these conditions, a quasi-volume ionisation (QVI) of gas is observed (Figure 6d–f).

The boundary between the stage of the streamer propagation (SP) and QVI is especially clearly visible at a minimum voltage across the gap (Figure 6d). Under these conditions, the streamer formation time is quite long (≈ 1.6 ns). DDC (blue curve in Figure 6j) shows when the streamer appears and when it approaches the opposite electrode. We see a strict correspondence of the DDC time dependence to the streak image. The streamer velocity decreases rapidly as the streamer develops due to, as noted above, an increase in the streamer diameter and, accordingly, a decrease in the electric field strength at its front. At the same time, the electric field strength increases with a decrease in distance between the streamer front and the grounded electrode. A high electric field strength in the still non-ionised part of the gap and a high concentration of seeded electrons can create conditions for almost instantaneous gas ionisation in the remaining gas volume. Thus, the streamer breakdown is transformed into a qualitatively different process.

The transition to QVI is also indicated by a sharp ‘jump’ in the DDC value before the onset of the decay of $E_{gr. el.}$ (blue

curve in Figure 6l, time interval 2–2.2 ns). Such a ‘jump’ can only be caused by a sharp acceleration of the ionisation rate, which causes a large displacement current to flow. The duration of the observed spike corresponds to the duration of the pulse response of the oscilloscope (≈ 68 ps). This means that the transition to QVI occurs probably in tens of picoseconds.

QVI leads to the appearance of a BIW. In fact, the redistribution of the electric field caused by the appearance of a dense plasma near the grounded electrode initiates BIW. In this sense, BIW is inevitable, in contrast to a secondary streamer, which is not observed under experimental conditions. BIW moves several times faster than the streamer. The stage of its propagation corresponds to a decrease in $E_{gr. el.}$ or a change in the DDC polarity (Figure 6j–l).

Figure 7 shows the ICCD and streak images of discharge formation in nitrogen at various pressures (50, 100, and 200 kPa) as well as corresponding waveforms of voltage, RE current, displacement current, and the electric field strength near the surface of the grounded electrode. The figure demonstrates the effect of nitrogen pressure on the size of the QVI region. In contrast to the previous data, they were obtained at a higher resolution (2-ns time range vs. 5-ns one).

It is clearly seen that the size of the QVI region increases with decreasing pressure. Numerous factors are likely to

contribute to this. First, the streamer diameter should increase with an increase in the reduced electric field strength. As a result, the distribution of the electric field between the streamer front and the grounded electrode (anode) becomes quasi-uniform at a larger distance to the opposite electrode. Second, the number of REs, which provide preliminary ionisation of the gas, increases (Figure 7g–i). Third, the reduced electric field strength increases in the region of quasi-uniform electric field distribution (53, 120, and 285 $\text{V}\cdot\text{cm}^{-1}\cdot\text{Torr}^{-1}$ at 200, 100, and 50 kPa, respectively), despite a decrease in the electric field strength at the streamer front, $E_{\text{gr. el.}}$ (91, 77, 68 kV/cm at 200, 100, and 50 kPa, respectively) before the transition to QVI (Figure 7j–l).

In general, a decrease in $E_{\text{gr. el.}}$ with decreasing pressure is interesting in itself. There are several reasons for this: an increase in the streamer diameter, an increase in the size of the QVI region, and a decrease in the voltage across the gap due to the flow of a significant current in the external circuit due to the high rate of streamer formation causes significant displacement currents. The decrease in the z-component of the electric field as a consequence of the SP at high velocities is described theoretically [71, 72].

A short spike on the DDC signal, indicating a transition to QVI, is also seen at 100 and 50 kPa (blue curve in Figure 7j,k, time interval 2–2.2 ns). However, it is absent at 200 kPa, although QVI is visible in Figure 7a. This can be explained by the fact that at low pressures, rapid ionisation occurs in a much larger volume of the discharge gap than at high pressures. This, in turn, causes a rapid and, what is important, significant change in the capacity of the discharge gap, which causes a large displacement current.

4 | CONCLUSIONS

The development dynamics of positive streamers in a gap with a sharply inhomogeneous electric field strength distribution filled with air and nitrogen at various pressures as well as at various amplitudes of positive voltage pulses was compared. At low voltages, a positive streamer in nitrogen branches, but a large-diameter streamer occurs in air. At high voltages or low pressures, the large-diameter streamer occurs in both air and nitrogen. It means that some processes provide a sufficient concentration of seeded electrons ahead the positive streamer front allowing to maintain stability of the ionisation front at a high reduced electric field strength. We assume that electrons can go into a runaway mode in the vicinity of the pointed electrode (anode), where the electric field strength reaches $\sim 10^6$ V/cm, at a short stage of electron avalanche multiplication. A sharp inhomogeneous distribution of potential makes it possible for electrons to gain high energy ($\sim 10^2$ – 10^3 eV and higher at higher voltages) while travelling a distance of ~ 1 – 10 μm to the anode and, consequently, to produce bremsstrahlung radiation. The duration of the RE generation stage is usually limited by the rate of occupation of space near the pointed electrode with plasma. A sharp decrease in the electric field strength on its front terminates the generation of REs.

Can a short flash of bremsstrahlung radiation pre-ionise the entire gap? This question requires a neat theoretical study.

The development dynamics of negative streamers in the same discharge gap and at various amplitudes of negative voltage pulses was studied. Large-diameter streamers develop in the gap both at low voltages and at elevated pressures of air and nitrogen. We believe that a ‘shot’ of REs generated in the vicinity of the pointed electrode (cathode) at the very beginning of ionisation processes (stage of electron avalanche multiplication) provides a sufficient level of preliminary gas ionisation in the gap, so that the ionisation front remains continuous. In this case, there is an interesting feature.

A transition from the streamer breakdown to a quasi-volume gas ionisation occurs both in air and nitrogen with negative polarity. The transition is possible due to the action of various factors. The main ones: the large diameter of a streamer and the preliminary ionisation of gas by the flow of REs. The first factor makes the distribution of the electric field between the plasma front and the grounded electrode more homogeneous. The second factor creates seed electrons in this volume.

The results obtained again testify to the fundamental role of REs in the formation of discharges. Therefore, to adequately simulate the formation of nanosecond discharges, it is important to take into account the effect of running away of electrons. From a practical point of view, the QVI effect can be used in fast switches.

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CONFLICT OF INTEREST


The authors declare no potential conflict of interests.


DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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