Title	Breakdown Process between Parallel Plates in Nitrogen, Air and Sulphur Hexafluoride : Observation of the Streamer Propagation by use of a Time Resolved high Speed Camera
Author(s)	Sato, Nobuyasu; Sawada, Sadao; Tagashira, Hiroaki
Citation	北海道大學工學部研究報告, 105, 47-54
Issue Date	1981-07-31
Doc URL	https://hdl.handle.net/2115/41684
Type	departmental bulletin paper
File Information	105_47-54.pdf

北海道大学工学部研究報告
第105号（昭和56年）

Bulletin of the Faculty of Engineering,
Hokkaido University, No. 105 (1981)

Breakdown Process between Parallel Plates in Nitrogen, Air and Sulphur Hexafluoride.

—Observation of the Streamer Propagation by use of a Time Resolved high Speed Camera—

Nobuyasu SATO[*], Sadao SAWADA[*] and Hiroaki TAGASHIRA[*]

(Received March 31, 1981)

Abstract

An image converter and image intensifier were used to investigate the streamer propagation mechanism of transient discharges that are started at undervoltages by supplying a large number of initial electrons at the cathode of parallel plates in nitrogen, air and sulphur hexafluoride. The streak photographs and corresponding current growth curves obtained in nitrogen and air for undervoltages up to 8% at pressures in a range from 20 to 400 Torr demonstrate that the pre-breakdown stage of development was first observed in the mid gap after the accumulation of the space charge caused by the generation mechanism of the avalanches and the development of the glow discharge consists of the cathode-and anode-directed luminous fronts. Transition of the glow discharge to the arc channel was recognized in nitrogen and air at a pressure of more than 300 Torr and only a filamentary arc discharge was observed in SF_6 at a pressure of 150 Torr. The mechanism of the luminous front propagation and of the arc initiation are discussed with an account for the space charge effect and dissociation of the sample gas.

1. Introduction

Transient discharges in nitrogen, air and sulphur hexafluoride that are induced at undervoltages by a large number of initial electrons released at the cathode of a parallel-plane gap have been previously studied at various pressures experimentally and theoretically.(1),(2),(3) It was shown in these studies that the undervoltage breakdown process generally consists of three stages; the first one is the formation of the space charge distribution due to the ionization amplification of the first avalanche, the second is the space charge accumulation caused by the secondary effects and the third is the rapid streamer propagation which arises from the space charge distortion of the applied field. At the first and second stages in the breakdown process, the discharge

---

[*] Applied Electricity

currents were measured, and factors affecting the development of the current such as photoelectric emission from the cathode, electron detachment from negative ions and photo-ionization effect were investigated by comparing the experimental current with a computer-simulated current.

In the present paper, attention will be paid to the mechanism of the luminous front propagation and to the initiation of the filamentary discharge which appears at the last stage in the breakdown process. A rapid, space-charge-accelerated propagation of luminosity and the corresponding current growth at this stage were observed by use of an image converter, image intensifier and storage oscilloscope at pressures in a range of 20 to 400 Torr in nitrogen and air, and at a pressure of 150 Torr in sulphur hexafluoride.

The streak photographs obtained in different gases are compared with each other to investigate the contribution of the negative ion formation to the development of the discharge at the last stage.

This work is performed as a part of the research to investigate the streamer propagation mechanism by a comparison between the experimental current growth and luminosity propagation, and the theoretical values obtained by computer simulation.

2. Experimental arrangement and procedure

The experimental arrangement is shown schematically in Figure 1. A parallel-plane gap was used with a gap length d = 10 mm. The electrodes were made of aluminium to the Harrison profile with an overall diameter of 50 mm. The anode was provided with 300 holes, each 0.5 mm in diameter, spreading over a central area of 16 mm diameter so that the cathode could be irradiated through them by ultraviolet rays.

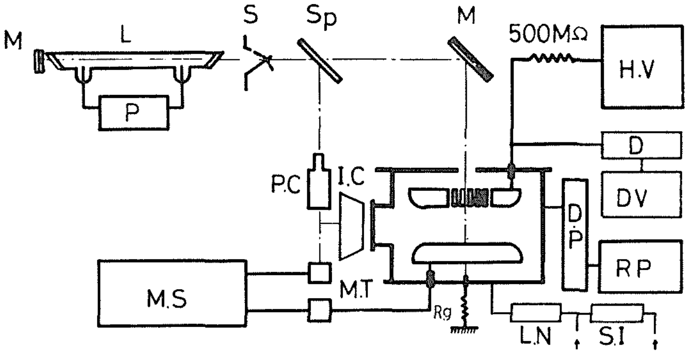


Figure 1 Experimental arrangement.

L ; N_2 laser, S ; shutter, S_p ; beam splitter, M ; mirror, H. V ; high voltage, P ; power supply, P. C ; photocell, D ; divider, D. V ; digital voltmeter, D. P ; diffusion pump, R. P ; rotary pump, R_g ; registance, L. N ; liquid nitrogen trap, S. I ; sillica-gel, M. T ; matching transformer, I. C ; image converter camera, M. S ; memory synchroscope.

The electrodes were set in a stainless steel vacuum chamber of a diameter of 150 mm. The chamber was evacuated to 10^{-6} Torr and flushed with a sample gas until the pressure of the gas reached the required value. The purity of the nitrogen gas used was 99.99% and the purity of SF_6 was 99.5%. Laboratory air used was dried passing through a silica-gel and a liquid nitrogen trap.

A static potential was applied to the anode from a regulated and stabilized voltage supply (YEC SHP-30) and measured by means of a resistance divider and a digital voltmeter (Takeda TR-6515). The measurements of the static breakdown voltage V_S were made several times to an accuracy of 0.2%, then the voltage which was lower than V_S by the value appropriate to the value of undervoltage was applied to the anode. The percentage undervoltage Δv is given by $(V_S - V_a)/V_S \times 100\%$ where V_a is the applied voltage. Under a static potential of V_a, breakdown was initiated by irradiation of an ultraviolet flash onto the cathode surface. An ultraviolet flash of 10 ns duration is produced by a nitrogen laser.

The discharge current was recorded by a storage oscilloscope (Tektronix 7623A). The light emission from avalanches and streamers was observed by means of an image converter and a 3-stage intensifier (John-Hadland Imacon 700). The converter, which employed an S 20 photo-cathode, has a lower and higher limit cut off of about 380 nm and 800 nm, respectively. To obtain time-resolved photographs, the image displayed on the converter screen could be streaked at speeds of up to 1 mm/ns. Operation of the converter camera was controlled by a pulse generated by a standard delay generator which was triggered with a pulse from a photo-cell. The experiments were carried out over a range of Δv from 1 % to 8 % in nitrogen and 1 % to 6 % in air, and at 1 % undervoltage in SF_6.

3. Results and discussion

3. 1 Transient glow discharge at 20 Torr in nitrogen

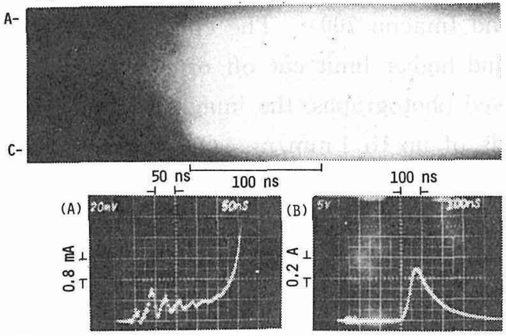
Typical streak photographs of the formation of the transient diffuse glow discharge at a pressure of 20 Torr in nitrogen are presented is Figure 2, along with the oscillograms of the corresponding discharge currents. The first peak of the discharge currents shown in Figure 2(oscillogram (A)) results from the initial avalanche started by a large number of supplied electrons, which results in the formation of the space charge distribution in the gap (the first stage). The oscillatory character of the current arises from the presence of the avalanches in the subsequent generations due to the photo-electric effect at the cathode, which results in the accumulation of the space charge with consequent increase in the field distortion (the second stage). No streak photograph of these early stages was observed because of low intensity of light emission from the avalanches.

At the final stage, however, a luminous front is first observed in the mid gap moving towards the cathode with a velocity v_{sc} of about 2×10^7 cm/sec. Shortly after the arrival of the luminous front at the cathode, a diffuse glow is seen to be established. The glow discharge at this stage exhibits a uniform column almost across the gap and a thin dark space in front of the cathode. This appearance of the discharge resembles that of a normal glow discharge. The discharge current at this stage increases rapidly up to 0.5 A and decreases gradually because of the influence of the outer circuit composed by a high resistance R and a small capacity C that are used to avoid the damage of the electrodes. The brightness of the glow discharge decreases with the reducing current. No variations of the appearance of the glow discharge were observed when Δv is increased to 8 %, although the brightness of the discharge channel and the current decrease. In SF_6 and air, no streak photographs were observed at a pressure of 20 Torr due to the limitation of the sensitivity of the converter camera.

3. 2 Transient glow discharge at 200 Torr in nitrogen and air

Figure 3 shows the streak photographs and corresponding current growths in nitrogen at Δv=1 % and 4 %. In this case, the brightness of the discharge channel

(i) N_2 20 Torr, Δv=1 %



(ii) N_2 20 Torr, Δv=8 %

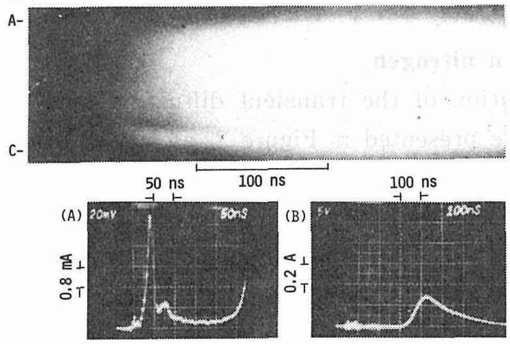
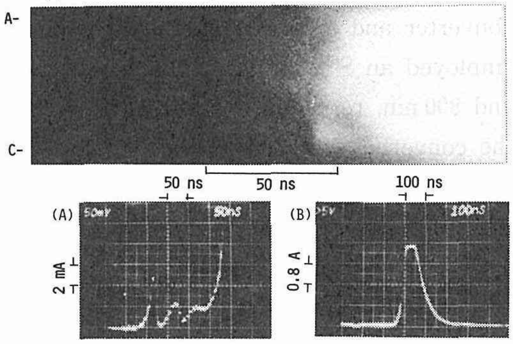


Figure 2 Development of the diffuse glow discharge in nitrogen at 20 Torr at (i) Δv=1 % and (ii)8 %. C and A represent the position of the cathode and anode, respectively. The current oscillogram (A) corresponds to the early part of (B) at increased sensitivity.

(i) N_2 200 Torr, Δv=1 %



(ii) N_2 200 Torr, Δv=4 %

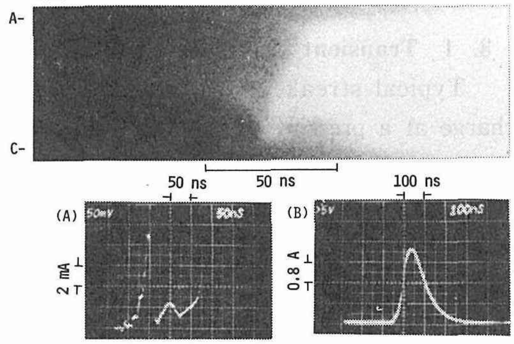


Figure 3 Development of the glow discharge in nitrogen at 200 Torr at (i) Δv=1% and (ii)4 %.

increases so that the space charge accumulation process is observed as a luminous front moving slowly towards the cathode at a velocity v_{sc} of about 2.5×10^6 cm/sec. This luminous front is followed by an accelerated cathode-directed luminous front with a velocity of about $v_{scl}=5\times10^7$ cm/sec. After its arrival at the cathode, a luminous front immediately propagates from the cathode to the anode which is followed by the second cathode-directed luminosity. The average velocity of the cathode- and anode-directed fronts was in the same order of magnitude and was found to decrease with the decreasing Δv. After the passage of the anode- and cathode-directed fronts, a diffuse glow is now seen to be established.

Figure 4 shows a series of streak photographs and discharge current oscillograms at 1-6 % undervoltages in air. The propagation pattern of luminous fronts in air is almost similar to that in nitrogen, but a few differences are evident. The discharge current is smaller than that in nitrogen so that the luminous intensity is lower. The luminous tracks are narrow and are more clearly seen than in nitrogen. It is considered that these differences of the streak pattern result from the effect of electron attachment and the negative ion formation on the development of the glow discharge.

No transition of the glow discharge to a filamentary one was observed in nitrogen and air at 200 Torr.

Figure 5 shows an idealized diagram of the discharge development in nitrogen at a pressure of 200 Torr. The observed phenomena in nitrogen may be explained quali-

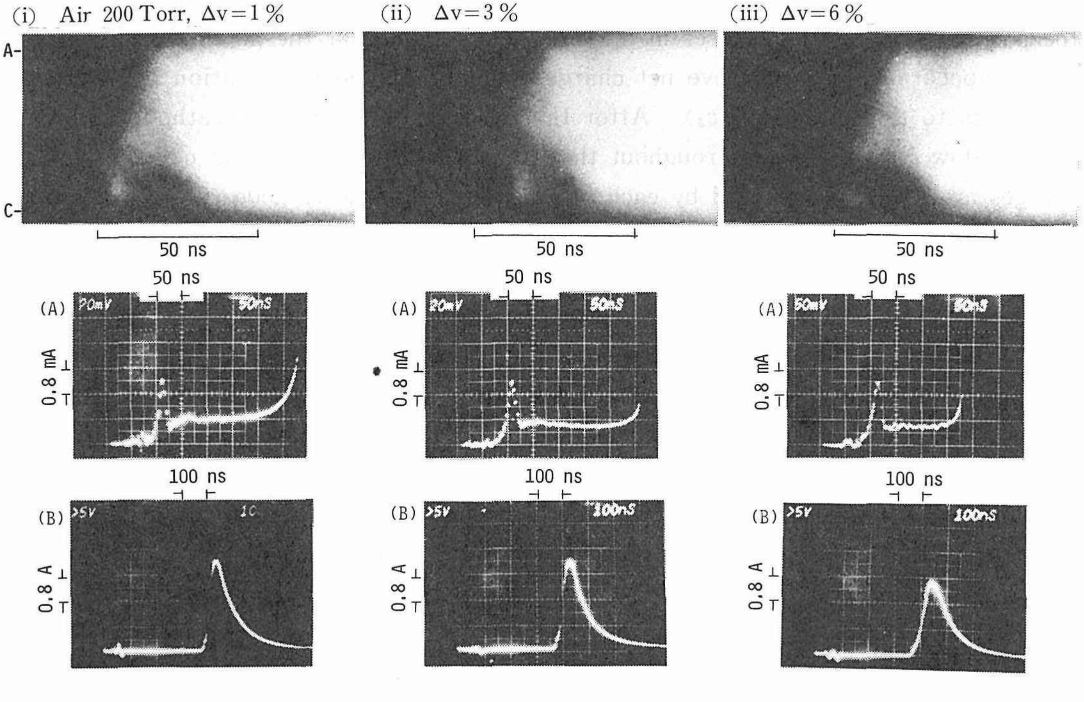

(i) Air 200 Torr, $\Delta v=1\,\%$
(ii) $\Delta v=3\,\%$
(iii) $\Delta v=6\,\%$

Figure 4 Development of the glow discharge in air at 200 Torr at (i) $\Delta v=1\,\%$, (ii) 3 % and (iii) 6 %.

tatively as follows.

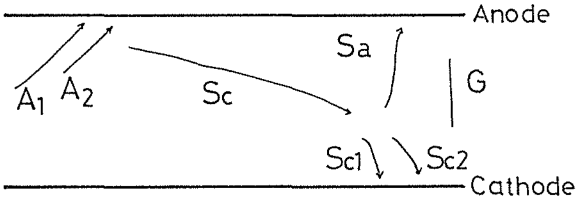


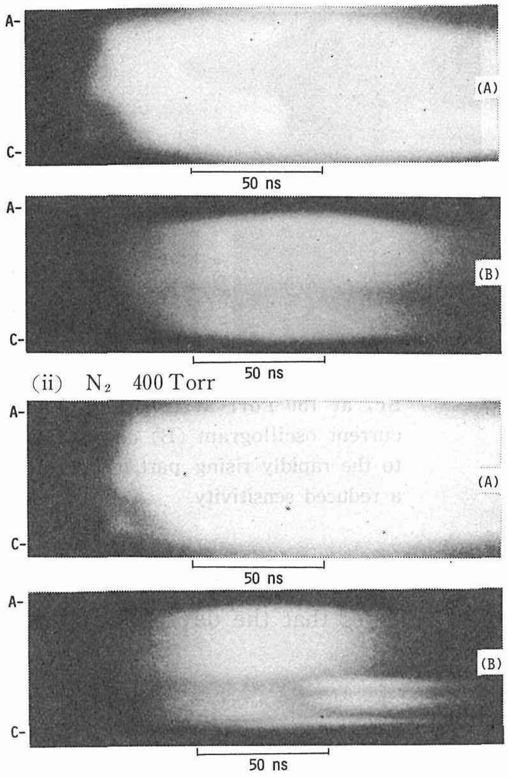
Figure 5 Idealized diagram of development of glow discharge. A_1 and A_2 are the first and second avalanches, respectively. Sc, Sc_1 and Sc_2 are the cathode-directed luminous fronts. Sa is the anode-directed luminosity. G. represents the glow discharge column.

At the second stage of the discharge process, following a few generations of avalanches, a positive space charge is accumulated near the anode which increases the field on the cathode side of the positive space charge cloud and decreases the field in front of the anode. The resulting field distortion enhances the rates of ionization and excitation on the cathode side of the positive ion cloud, which results in a shift of the positive ion distribution peak, and hence the field maximum, from anode to mid gap (Sc in Figure 5). The positive ion cloud is spread almost over the gap with a consequent increase in the field distortion near the cathode and the rate of propagation towards the cathode (Sc_1). When the first front reaches the cathode, the resulting intense space charge field near the cathode amplifies the secondary electrons from the cathode, which supplies a large number of electrons in the low field region of the mid gap. This gives rise to a neutralization of the positive ion charges and the appearance of a negative net charge distribution in the mid gap, which decreases the field in front of the cathode with a shift of the field maximum from cathode to anode (Sa). Then the positive ion density increases in the high field region near the anode which results in a reappearance of a positive net charge distribution and propagation of the field maximum to the cathode (Sc_2). After the passage of the second cathode front, a diffuse glow is established throughout the gap where the positive and negative space charges are almost neutralized by each other except near the cathode (G in figure 5).

In air, it is considered that the mechanism of the luminosity propagation is similar to that in nitrogen, although negative ion charges may play an important role on the neutralization of positive ion charges, as well as electron charges.

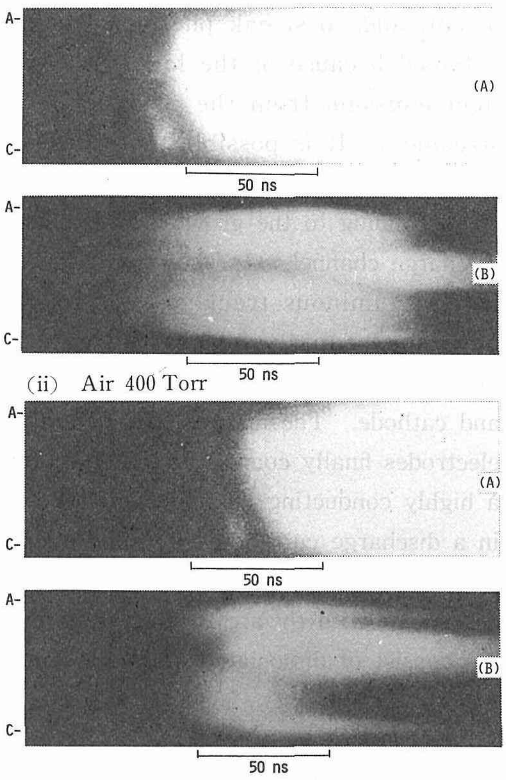
3. 3 Transition to the arc discharge in nitrogen, air and SF_6

Figures 6 and 7 show the streak photographs at $\Delta v = 1\%$ in nitrogen and air, respectively, at pressures from 300 to 400 Torr. In these cases, the propagation pattern of the luminous fronts before the establishment of the glow discharge is similar to that at 200 Torr which indicates that the essential mechanism of the glow discharge does not change at 300 or 400 Torr. In contrast to the case at 200 Torr, however, a dark space appears in the mid gap after the establishment of the glow discharge at higher pressures. In nitrogen, the dark space is seen slightly in the column of the glow discharge at 300 Torr and thin luminous regions appear in the dark space at 400 Torr. In air, a highly luminous region appears in the dark space at 300 Torr and proceeds to propagate as a continuous filament towards both electrodes.


(i) N_2 300 Torr

(ii) N_2 400 Torr

Figure 6 Development of the breakdown in nitrogen at $\Delta v=1\%$ The streak photograph (B) was obtained with a reduced sensitivity.


(i) Air 300 Torr

(ii) Air 400 Torr

Figure 7 Development of the breakdown in air at $\Delta v=1\%$

This phenomenon is more clearly seen and develops more rapidly at 400 Torr. The velocity of the propagation is about 5×10^6 cm/sec as seen in Figure 7. Chalmers et al[(4)] indicated from the observation of the discharge in nitrogen at high overvoltages that the bright filamentary phase which appeared in the glow discharge column results from thermal dissociation of molecular gases. The observed velocity of the propagation in the present experiment is in good agreement with the one calculated on the assumption that the luminous filamentary phase of the discharge development is brought about by molecular dissociation of the gas.

It is considered that the arc discharge is established at the instance that the luminous region which consists of dissociated molecular gases bridges the gap. In the present experiment, however, the arc channel is not established because the gap voltage has collapsed rapidly before the arrival of the luminous region at the electrodes.

Figure 8 shows the streak photograph and the corresponding current oscillograms in SF_6 at a pressure of 150 Torr. The discharge current during the pre-breakdown stages of the discharge development in SF_6 is restricted within smaller value than in nitrogen by the strong electron attachment, and no streak photographs were obtained because of the low intensity of light emission from the avalanches and streamers. It is possible to record only the more intense stages of development corresponding to the growth of filamentary discharge channel. As shown in Figure 8, a faint luminous track is seen to have developed rapidly across the gap and filaments propagate from both the anode and cathode. The filaments from both the electrodes finally connect together to form a highly conducting channel, which results in a discharge current peak. The average velocity of propagation of the filaments (5×10^6 cm/sec) is of the same order as that associated with the arc-forming stage in air, which indicates that the developing filaments consist of dissociated molecular gas.

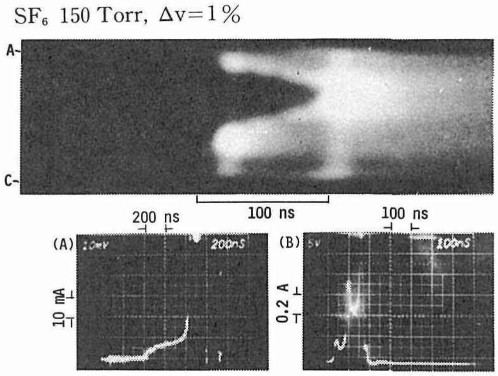

SF_6 150 Torr, Δv=1%

Figure 8 Development of the breakdown in SF_6 at 150 Torr at Δv=1 %. The current oscillogram (B) coresponds to the rapidly rising part of (A) at a reduced sensitivity.

4. Conclusions

The development of transient glow discharges at undervoltages was observed as the propagation of the cathode- and anode-directed luminous fronts in nitrogen and air at pressures in the range of 20 to 400 Torr. It is shown that the propagation of the luminosity can be explained qualitatively by the variation of the net charge distribution and the resulting field distortion. Transition of the glow discharge to the arc channel was recognized in nitrogen and air at a pressure of more than 300 Torr after the establishment of the glow discharge. Only a filamentary arc discharge was observed in SF_6 at a pressure of 150 Torr. It is indicated that the bright filamentary phase which appears before the establishment of an arc channel may be brought about by the molecular dissociation of the sample gas.

The authors are greatly indebted to Professor S. Sakamoto of Department of Electrical Engineering, Akita University, and Messrs Y. Kaneko and M. Shimozuma for their valuable discussions.

References

(1) N. Sato and S. Sakamoto; J. Phys. D: Appl. Phys. **12,** 875 (1979)
(2) N. Sato, T. Takei and S. Sakamoto; J. IEE, Japan **99 A,** 511 (1979)
(3) N. Sato and S. Sakamoto; Papers of Tech. Gr. Electrical Discharges (IEE, Japan) No. ED-78-85 (1978)
(4) I. D. Chalmers, H. Duffy and D. J. Tedford; Proc. R. Soc. **A329,** 171 (1972)