Eur. Phys. J. D **19**, 89–95 (2002)
DOI: 10.1140/epjd/e20020059

THE EUROPEAN PHYSICAL JOURNAL D

EDP Sciences

Application of a ferroelectric plasma cathode as a high-current switch

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Received 5 November 2001

Abstract. In this paper the parameters of two types of high-current switches based on ferroelectric $BaTiO_3$ ignition are presented. Both types of switches showed a reliable and controllable operation with a repetition rate of several Hz. The first type is a vacuum two-electrode switch ignited by the plasma which is generated by a $BaTiO_3$ cathode. This type of switch was tested in the voltage range of 3−25 kV and switched current amplitude of 2−15 kA with either negative or positive polarity of the high-voltage electrode. The second type is a $BaTiO_3$ surface flashover strip-like switch ignited by a driving pulse which has an amplitude of several kV. It was shown that the application of the driving pulse (>10 kV) leads to the appearance of many non-complete surface discharges which transform further to a multi-channel discharge. This type of switch was tested in the voltage range of 1−25 kV and current amplitude of 0.5−15 kA. The design of the switches, their lifetime, the time jitter and the parameters of the switched current for different discharge conditions are presented.

PACS. 52.75.Kq Plasma switches (e.g., spark gaps) – 52.50.Dg Plasma sources – 77.80.Fm Switching phenomena

1 Introduction

One of the key elements in pulsed power technique is reliable and controllable operation of switches which allows fast (nanosecond time scale) switching of high current pulses (10^3−10^6 A). There are many common types of switches, the operation of which is based on a liquid (water, transformer oil), on a solid-state dielectric, or on a vacuum or pressurized gas electrical breakdown [1, 2].

Liquid and solid-state switches are usually used in the cases when it is necessary to minimize the self-inductance of the switch and to switch a pulse with a large current amplitude [1, 2]. The main disadvantages of this type of switches are large erosion of electrodes and strong shock wave formation (liquid switches) and a single-mode switch operation (solid-state switches). Vacuum switches are usually used in the case of large current switching when there are no restrictions for the rise time of the switched current and the time jitter in the beginning of the discharge.

For switching current with a moderate amplitude (10^3−10^5 A), various types of gaseous switches are the most often used. These switches can also be divided into several groups, namely with self-breakdown of the inter-electrode gap, distortion of the electric field in the inter-electrode gap and trigatron initiation (triggering) of the switching process. Self-breakdown switches only operate when the voltage drop between the switch electrodes reaches its breakdown value. Therefore, in order to operate with a different discharge voltage one has to change either the gas pressure or the inter-electrode gap length inside the switch. Thus, the most commonly used switches with a broad controllable range of discharge voltage are gaseous switches with electric field distortion and trigatron initiation. However, reliable triggering of switches with electric field distortion requires a (>10^4 V) pulse and switches with trigatron initiation have a relatively short lifetime (∼10^4 shots) and a strong polarity effect [1].

There is also another type of switches whose operation is based on a flashover along the surface of a dielectric placed between two electrodes [3–6]. Such switches have a low inductance and can be used for switching current with an amplitude in the range of 10^5−10^6 A. However, the lifetime of these switches is short and they require (∼10^5 V) triggering pulses for controllable operation.

In this paper we describe experimental results of the operation of a low-pressure triggerable two-electrode switch and a pressurized gaseous strip-like switch based on a gas discharge. This discharge is initiated by a ferroelectric plasma cathode [7] which serves as a source of charged particles. Successful applications of ferroelectric cathodes for triggering low-pressure hollow-cathode switches were reported in references [8–10]. These experiments showed that triggering by a ferroelectric cathode results in a small time jitter (<10 ns) of the hollow-cathode switch operation with a switched current amplitude up to 130 kA [8, 10].

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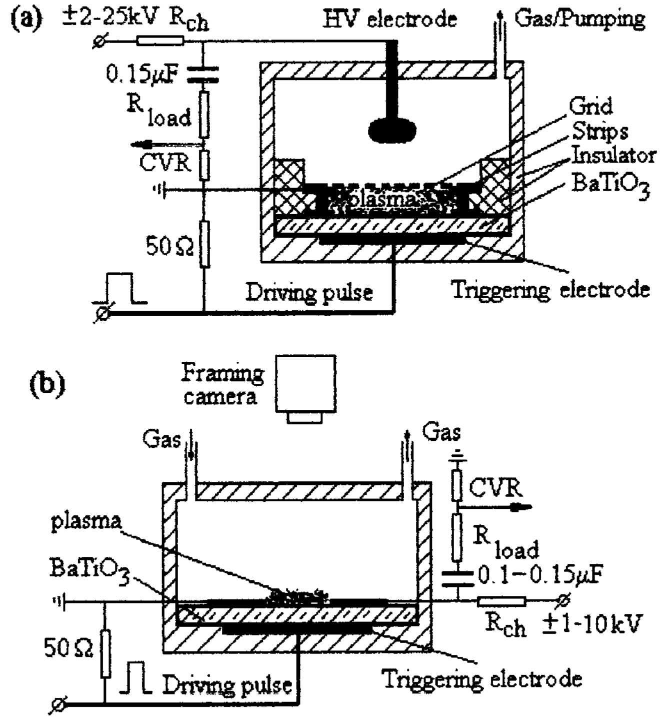

Fig. 1. Experimental setup. (a) Two-electrode gaseous switch; (b) surface flashover strip-like switch.

The intense electron emission (1−100 A/cm^2) from ferroelectric cathodes has been studied widely during the last decade since this phenomenon was reported [11]. It was shown that the electron emission follows the application of a driving pulse with an amplitude of 10^2−10^4 V and duration of 10^{-7}−10^{-6} s to a ferroelectric sample covered by a front electrode which is made of strips and a solid rear electrode. Recent investigations [12–22] showed that in the case of the existence of micro-gaps between the front electrode and the front surface of the ferroelectric, the copious electron emission occurs from a surface plasma. This plasma is formed on the front surface of the ferroelectric sample as a result of surface flashover initiated in triple points [1]. The plasma electron temperature T_e and density n_{pl} were found by different electrical and spectroscopic methods to be $T_e \leq 3$ eV and $n_{pl} \leq 10^{13}$ cm^{-3}. Results concerning the lifetime of ferroelectric cathodes were reported in references [20, 21]. It was shown that a ferroelectric cathode based on $BaTiO_3$ composition has a longer lifetime (>10^5 shots) compared with other ferroelectric ceramics, namely PZT and PLZT. The simplicity of this triggering source design and its long lifetime stimulated the present research.

2 Experimental setup and diagnostics

The setup for the two-electrode gaseous switch is shown in Figure 1a. A Tektronix power supply was used to charge a Maxwell low-inductance capacitor of 0.15 μF in the range of charging voltages of ± (2−25) kV. This high-voltage capacitor was discharged by the tested switch on a resistive load of 2−4 Ω or on the inductive load of ∼100 nH.

The switch consists of a high-voltage stainless steel electrode placed at a distance of 8 mm from a stainless steel grounded grid. The optical transparency of the grid was 75%. A metal ring having an electrical contact with the front electrode of the ferroelectric sample held this grid. The distance between this front electrode and the grid was 2 mm.

The ferroelectric sample was a $BaTiO_3$ disk (dielectric permittivity $\varepsilon \sim 1\,500$) of 44 mm diameter and 3 mm thickness. A copper electrode made of strips with 1 mm width each and 1.5 mm distance between adjacent strips was glued to the front surface of the disk. A solid copper electrode was glued to the opposite side of the disk. Both electrodes had a diameter of 20 mm. The $BaTiO_3$ sample was held by a Teflon insulator and was placed together with the grid and the high-voltage electrode inside a perspex box (see Fig. 1a) where a vacuum in the range of 10^{-1}−10^{-3} torr was kept by turbo-molecular and rotary pumps.

To produce the plasma on the front surface of the ferroelectric a pulsed generator was used. The generator produced driving pulses with an amplitude 4−12 kV, pulse duration 400 ns and repetition rate up to 50 Hz. When this driving pulse is applied to the rear electrode of the ferroelectric sample plasma formation occurs at the front surface due to incomplete surface discharge.

The experimental setup for the flashover pressurized strip-like switch is shown in Figure 1b. This switch was tested using the same electrical scheme as for the two-electrode gaseous switch. The switch was made of a ferroelectric $BaTiO_3$ disk. The discharge occurs between two copper electrodes with 2 cm width which were both glued to the front surface of the ferroelectric sample and separated by 10 mm distance. To ignite a discharge between these electrodes, a driving pulse, produced by the same pulsed generator, was applied to a solid copper electrode glued to the opposite side of the sample disk. The sample was placed inside the perspex chamber where the air pressure or SF_6 pressure was kept in the range of 7.6×10^2−3.8×10^3 torr.

The driving voltage and discharge current were measured by a Tektronix voltage divider and a current viewing resistor (0.01 Ω), respectively. The light emission from the discharge gap was observed by a 4 ps fast framing camera (frame duration ≥ 1 ns) with and without narrow band (80 Å) H_α and H_β filters. By varying the camera triggering time we obtained a set of framing photographs of the emitted light at different times of the switch operation.

3 Experimental results

3.1 Two-electrode gaseous switch with ignition by plasma charged particles generated by the ferroelectric cathode

At first we checked the operation of the switch at normal pressure. When the distance between the grid electrode and the front surface of the ferroelectric was of 5 mm we were not able to control the triggering of the switch in all the range of the tested voltages, *i.e.* $\varphi \le \varphi_{br}$. Here $\varphi_{br} = 26$ kV is the self-breakdown voltage in our experimental conditions. Decreasing the distance between the grid electrode and the front surface of the ferroelectric to 2 mm slightly improved the situation with controllable switching. It was found that in this case successful triggering of the switch could be achieved when the amplitude of the driving voltage φ_{dr} was ≥ 10 kV and the voltage drop between the switch electrodes was $\geq 0.9\varphi_{br}$. Such a narrow range of switch triggering can be explained by the fast decrease of the electron density of the surface discharge plasma while increasing the distance from the front electrode of the ferroelectric sample. In addition, this narrow range can be related to the small mean free path of the plasma ions. Indeed, the collision frequency ν_{en} of plasma electrons with neutral atom and molecules can be estimated as $\nu_{en} \approx n_n \langle V_{ep}\sigma_e \rangle \approx 10^9$ s^{-1}. Here $V_{ep} \sim 10^8$ cm/s is the velocity of plasma electrons for an electron plasma temperature of 3 eV [22], $n_n \approx 2 \times 10^{19}$ cm^{-3} is the neutral atom density at normal pressure, and $\sigma_e \sim 10^{-18}$ cm^2 is the cross-section for electron collision with neutral atoms and molecules [23]. A large electron collision frequency leads to a fast decrease of the electron plasma density due to attachment with electronegative atoms and molecules. For instance, at normal pressure the electron lifetime with respect to attachment is ~10 ns [23]. Also, one can estimate the mean free path of the plasma ions as $\lambda \approx (n_n\sigma_i)^{-1} \le 0.01$ mm, where $\sigma_i = 10^{-16}$ cm^2 is the cross-section for ion collision with neutral atoms and molecules [24]. Even for energetic dilute plasma flows [17] ($n_e \approx n_i \le 10^{11}$ cm^{-3}, energy of plasma particles $\le e\varphi_{dr}$) which are generated during the application of the driving pulse, the mean free path does not exceed 1 mm. Taking into account that the density of the surface discharge plasma and the energy of the plasma particles increases with the increase of the driving pulse amplitude [17,22], one can conclude that only when starting with $\varphi_{dr} \ge 10$ kV, a part of the plasma charged particles reaches the inter-electrode gap of the switch causing the initiation of the discharge.

It is possible that a further decrease of the distance between the grid electrode and the front surface of the ferroelectric could improve the situation with the controllable switching. However, in this case the front surface of the ferroelectric could be damaged by the part of the discharge current that penetrates through the grid electrode.

In order to achieve controllable switch operation it was necessary to increase the mean free path of plasma charged particles. Indeed, a controllable triggering in the range of 3–26 kV was achieved by decreasing the pressure inside the switch to $P = 10^{-1}$–10^{-3} torr. In this pressure range we did not obtain any change in the switch operation. However, we did obtain a significant difference in the beginning of the discharge between a negative and a positive high-voltage electrode.

In the case of a positive high-voltage electrode the switching process began with a time delay of ~ 50 ns with

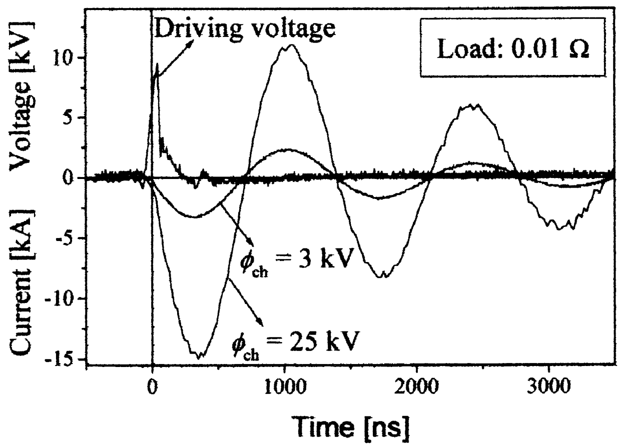

Fig. 2. Typical waveforms of the discharge current and driving voltage for different charging voltages of the storage capacitor.

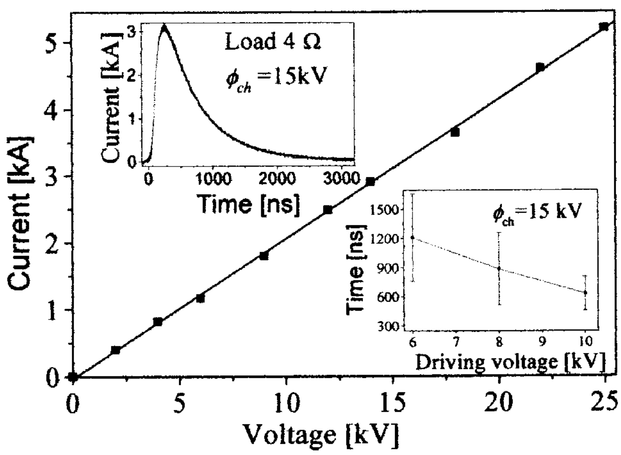

Fig. 3. Dependence of the discharge current on the charging voltage with a typical waveform of the discharge current (averaged over 20 shots, $f = 2$ Hz) and the dependence of the time jitter on the amplitude of the driving voltage.

respect to the start of the driving pulse. Also, the time jitter of the start of the switching was ~± 10 ns which is similar to the time jitter obtained in reference [8]. It was found that this time delay and time jitter did not depend on the amplitude of the driving voltage which was changed in the range of 5–10 kV. Typical waveforms of the discharge current and driving voltage for different charging voltages of the storage capacitor are shown in Figure 2. One can see that the amplitude of the discharge current reaches 15 kA at a charging voltage of $\varphi_{ch} = 25$ kV. We also tested the operation of the switch with a repetition rate up to 2 Hz for a few minutes. This test showed no changes in the switching characteristics.

Also, the same controllable switch operation was achieved in the case of a negative high-voltage electrode. In Figure 3 we present the dependence of the discharge current on the charging voltage. In the same figure we also show a typical waveform of the discharge current and the dependence of the time jitter on the amplitude of the driving voltage. As one can expect for the gas spark

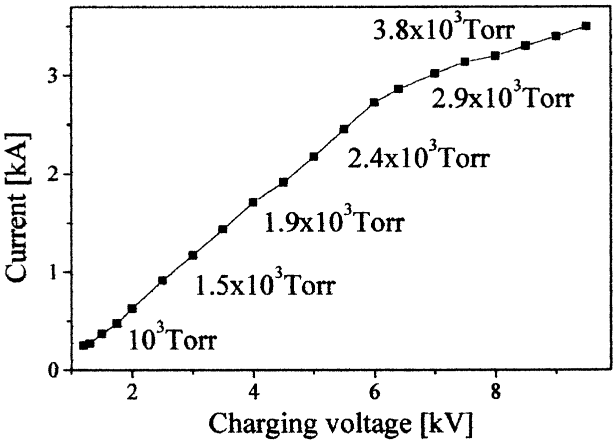

Fig. 4. Dependence of the discharge current on the charging voltage of the storage capacitor. Background medium: pressurized air.

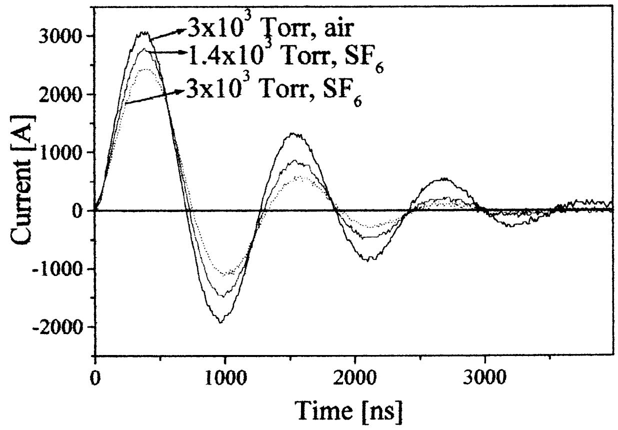

Fig. 5. Typical waveforms of the discharge current obtained for different background pressures and gases but for the same charging voltage of $\varphi_{ch} = 8$ kV of the 0.1 μF storage capacitor.

switch operation, the switched current depends linearly on the charging voltage of the storage capacitor. We also obtained good reproducibility of the switched current while the switch was operated with a repetition rate of 2 Hz.

However, in the case of the negative high-voltage electrode we obtained a significant time delay in the beginning of the switching process with respect to the start of the driving pulse and a large time jitter which depended on the amplitude of the driving voltage. The difference in the switch operation can be explained by the properties of the plasma formed on the front surface of the ferroelectric. In reference [17] it was shown that the formation of this surface plasma is accompanied by a fast electron flow. Thus, in the case of a positive high-voltage electrode, this fast electron flow initiates a discharge between the spark gap electrodes by ionization of residual gas. In the case of a negative high-voltage electrode, this ionization process is caused by plasma ions which require a certain propagation time between the front surface of the ferroelectric and the grid electrode of the switch.

3.2 Flashover pressurized two-electrode strip-like switch with ignition by plasma charged particles generated by the ferroelectric cathode

Experiments with flashover pressurized two-electrode switch were carried out with air pressure in the range of 7.6×10^2–3×10^3 torr. The application of pressurized gas was necessary in order to increase the range of charging voltages of the storage capacitor. In some experiments we used also SF_6 gas which allowed us to keep the discharge voltage at a lower pressure. The time delay in the beginning of the switching process with the respect to the start of the driving pulse was found to be 50 ± 20 ns. The increase of the amplitude of the driving voltage from 5 kV to 10 kV led to a decrease of this time delay to 30 ± 5 ns.

In Figure 4 we present the dependence of the discharge current on the charging voltage of the storage capacitor. One can see that the discharge current amplitude depends linearly on the charging voltage of the storage capacitor for background pressure $\leq 2 \times 10^3$ torr.

Similar decrease of the amplitude of the discharge current for the same charging voltage was obtained when the switch was operated with SF_6 gas. In Figure 5 we present waveforms of the discharge current obtained for different background pressures and gases but for the same charging voltage of 8 kV. One can see significant decrease of the amplitude of the discharge current when the switch is operated with SF_6 gas. Moreover, the larger was the pressure of the SF_6 gas the smaller was the amplitude of the discharge current. This phenomenon can be explained by the increase of the resistivity of the discharge channels as well as by the decrease of their number.

Similar decrease of the discharge current amplitude for the same charging voltage was obtained when the switch was operated in the self-breakdown mode (see Fig. 6). One can see that the amplitude of the discharge current decreases as much as by 20% for the self-breakdown mode compared with the current amplitude for the triggerable mode of the switch operation.

In order to understand the significant decrease of the amplitude of the discharge current we took fast framing photographs of the switch operation with and without narrow band (8 nm) H_α and H_β filters. In Figure 7 we present a set of framing photographs obtained without the discharge of the storage capacitor when only a driving pulse was applied to the rear electrode of the sample. The obtained photographs show light emission from many surface discharge channels. This light emission begins almost simultaneously with the start of the driving pulse and continues until the driving pulse reaches its maximum amplitude. Similar framing photographs were obtained in our recent research of ferroelectric cathodes which was carried out in vacuum [16]. The difference between the present photographs and those obtained in reference [16] is in the faster decay of the light emission. This difference is related to faster plasma electron disappearance due to the attachment process in the case of a high-pressure switch operation.

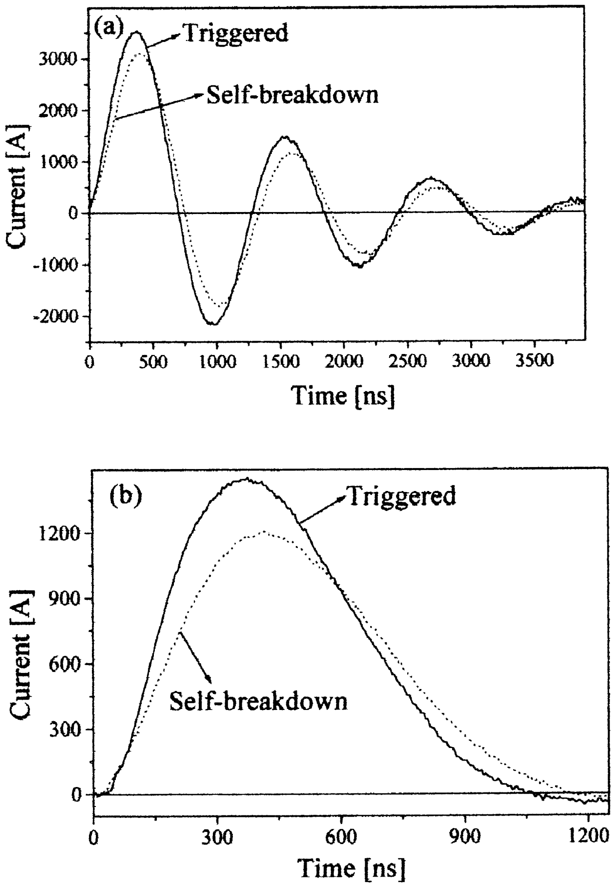

Fig. 6. Typical waveforms of the discharge current for the same charging voltage of the storage capacitor $0.1\,\mu$F obtained in self-breakdown and triggerable modes of the switch when operating with (a) $\varphi_{\mathrm{ch}} = 7.8$ kV, resistive load of 2 Ω; (b) $\varphi_{\mathrm{ch}} = 6.7$ kV, inductive load of ∼100 nH.

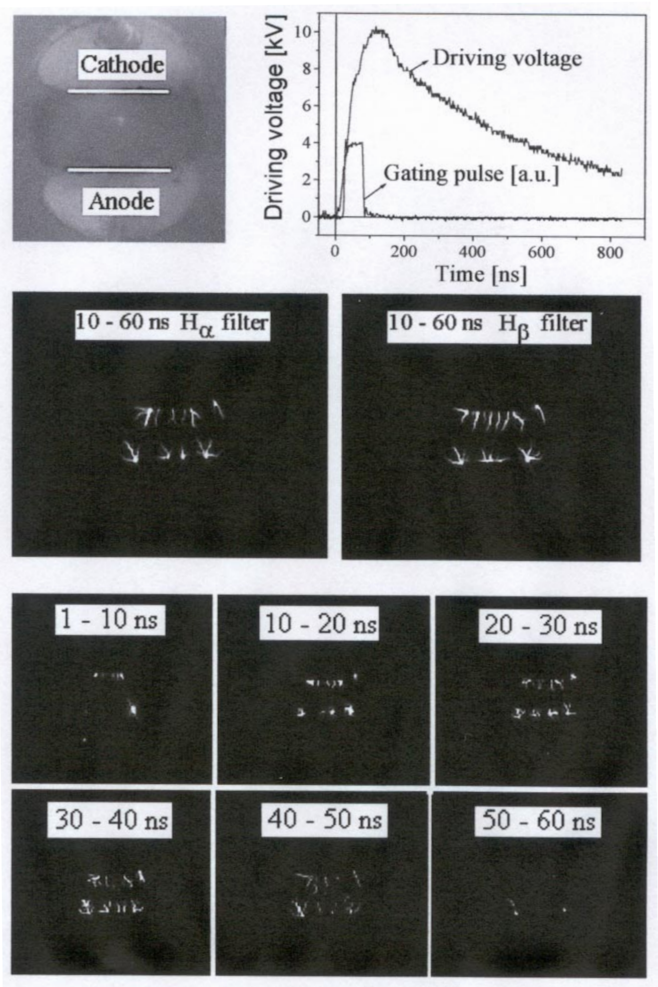

Fig. 7. Set of framing photographs obtained without storage capacitor discharge when only a driving pulse was applied to the rear electrode. Without filters: frame of 10 ns, gain voltage of 850 V. With H_α and H_β filters: frame of 50 ns, gain voltage of 950 ns. Positive driving pulse is applied to the rear electrode.

The obtained incomplete surface discharges trigger the main discharge when a dc high voltage is applied between two electrodes. We obtained a set of framing photographs which showed that the discharge occurs via many plasma channels which were initiated by a driving pulse (see Fig. 8). The number of the bright discharge channels varies from shot to shot in the range of 6−10 channels. Taking into account that the width of the electrodes is 2 cm one can conclude that there are 3−5 bright discharge channels per cm. On the contrary, in the case of self-breakdown, only 1–2 bright channels were observed. Thus we believe that the obtained decrease of the discharge current amplitude in the case of the self-breakdown discharge is related to a significant increase of the number of bright discharge channels. Indeed, a simple electrical analysis of the obtained ringing current waveforms in the cases of the triggerable and self-breakdown modes of the switch operation showed that the difference in the resistance of the corresponding discharge channels could be as high as ≈0.15 Ω. It was found that the obtained light emission of the discharge channels disappeared within 15 μs after the beginning of the discharge. This allows one to estimate the maximum repetition rate of this switch operation as <100 kHz. In addition, it was shown that the operation of this type of switch does not depend on the polarity of the high-voltage electrode.

We checked the operation of this type of switch at a repetition rate in the range of 2−10 Hz during 30−60 minutes with inductive and resistive loads (see Fig. 9). This test showed that there was no change in the switch operation and that there was no damage of the switch surface. The latter is very important for a long switch lifetime but it is in some sense in contradiction with the results obtained in reference [21] which showed significant erosion of the ferroelectric surface with an increasing number of driving pulses. We believe that this contradiction can be explained because of the different types of discharges which occur in vacuum and in a gas medium. In the case of surface discharge in vacuum, the plasma is formed by ionized atoms and molecules of the ferroelectric material and this is the reason for the surface erosion. In the case of surface discharge in the presence of gas, the plasma is

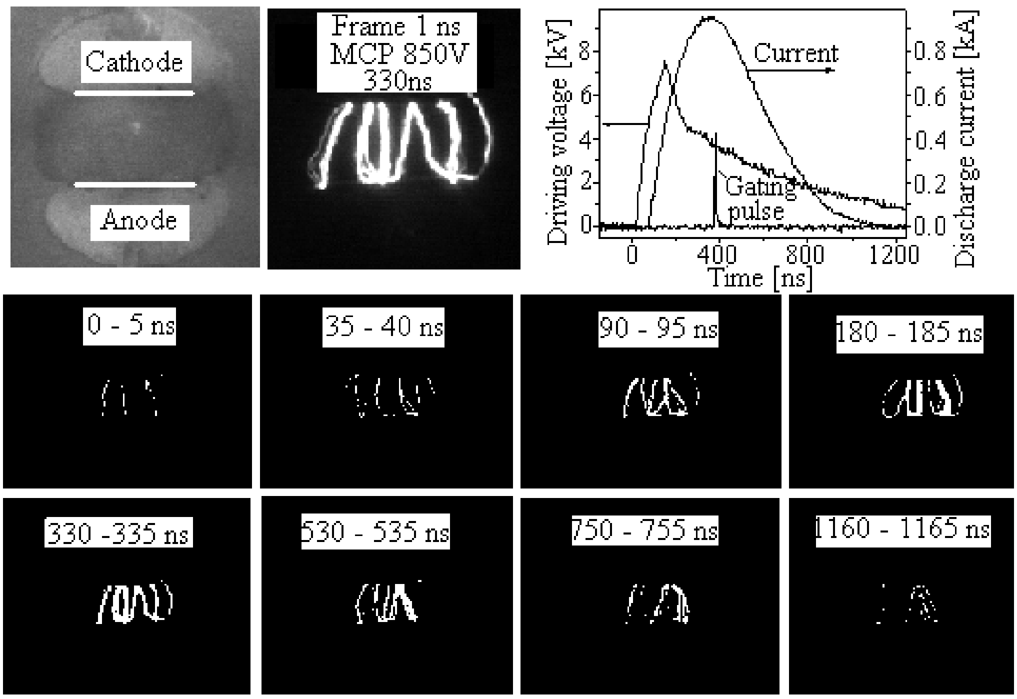

Fig. 8. Set of framing photographs obtained with the discharge of the storage capacitor. Framing photographs with 5 ns exposure were obtained with 750 V gain voltage and with H_α filter. A framing photograph with 1 ns exposure was obtained without filter and with 550 V gain voltage.

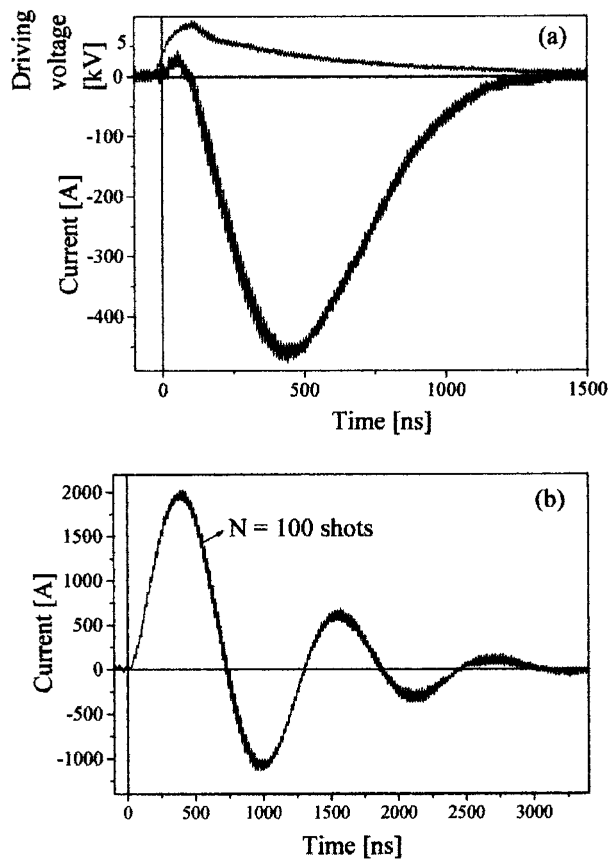

Fig. 9. Typical waveforms of the discharge current and driving pulse obtained at a repetition rate of 7 Hz with (a) resistive load of 2 Ω; (b) inductive load of ~100 nH. Charging voltage is 5 kV. Total number of shots is 10^4.

formed by the ionized atoms and molecules of the gas. Therefore, one can obtain reproducible and long lifetime switch operation without surface erosion in the presence of a gas medium.

4 Summary

We presented results of experimental investigation of two types of high-current, high-voltage switches, namely a two-electrode gaseous switch and a surface flashover strip-like switch. Controllable operation of the switches was achieved by a ferroelectric $BaTiO_3$ plasma cathode which plays the role of a trigger. The application of a driving pulse with an amplitude in the range of 5−10 kV leads to plasma formation on the front surface of the ferroelectric due to incomplete surface discharge initiated in triple points. This plasma was used as a source of charged particles which causes effective breakdown of the inter-electrode gap of the tested switches.

The main advantages of ferroelectric triggering is the relatively low amplitude of the driving pulse and the broad range of operational switch voltages (3−25 kV). It was shown that the application of the ferroelectric triggering allows to achieve a nanosecond time scale jitter in the beginning of the discharge in both types of switches. In the case of the surface flashover switch, the high dielectric permittivity of the ferroelectric allows to obtain a multi-channel discharge. This discharge is characterized by a significantly smaller resistance compared with the resistance of a one-channel discharge. In addition, it was shown that these switches have reliable, controllable and long lifetime operation with a repetition rate of several Hz and current amplitude of 2−15 kA with both polarities of the high-voltage electrode. Thus, we believe that these simple switches can be successfully used in pulsed power research as an alternative to gaseous switches with commonly used trigatron initiation or with electric field distortion.

References

1. G.A. Mesyats, *Generation of High-Power Nanosecond Pulses* (Sov. Radio, Moscow, 1974), and references therein.
2. I. Vitkovitsky, *High Power Switching* (van Nostrand Reinold, New York, 1987), and references therein.
3. H.M. von Bergman, in *Gas Discharge Closing Switches*, edited by G. Schaefer *et al.* (Plenum, New York, 1990), pp. 345−373.
4. P.M. Ranon, H. Krompholz, M. Kristiansen, L.L. Hatfield, in *Proc. 5th IEEE Intern. Pulsed Power Conf.*, edited by M.F. Rose, P.J. Turchi, Arlington VA (Publishing Services, IEEE, New York, 1985), pp. 276−279.
5. L.M. Earley, G.L. Cost, in *Proc. 8th IEEE Intern. Pulsed Power Conf.*, edited by R. White, K. Prestwich, San Diego CA (Publishing Services, IEEE, New York, 1991), pp. 340−343.
6. B. Etlitcher, L. Frescaline, H. Lamain, P. Auvray, C. Rouille, J.M. Buzzi, B. Roques, J.F. Leon, F. Lassalle, A. Morell, *10th IEEE Intern. Pulsed Power Conf.*, edited by W. Baker, J. Cooperstein, Albuqueque NM (IEEE Services Center, New Jersey, 1995), pp. 243−248.
7. G. Rosenman, D. Shur, Ya.E. Krasik, A. Dunaevsky, J. Appl. Phys. **88**, 6109 (2000), and references therein.
8. H. Gundel, H. Reige, J. Handerek, K. Zioutas, Appl. Phys. Lett. **54**, 2071 (1989).
9. H. Riege, Nucl. Instrum. Meth. Phys. Res. A **340**, 80 (1994).
10. K. Bergmann, R. Lebert, J. Kiefer, W. Neff, Appl. Phys. Lett. **71**, 1936 (1997).
11. H. Gundel, H. Reige, J. Handerek, K. Zioutas, CERN/PS/88-66 (AR), 1988.
12. V.D. Kugel, G. Rosenman, D. Shur, Ya.E. Krasik, J. Appl. Phys. **78**, 2248 (1995).
13. D. Shur, Ya.E. Krasik, G. Rosenman, Appl. Phys. Lett. **70**, 574 (1997).
14. G. Rosenman, D. Shur, Kh. Garb, R. Cohen, Ya.E. Krasik, J. Appl. Phys. **82**, 772 (1997).
15. D. Shur, Ya.E. Krasik, G. Rosenman, J. Phys. D: Appl. Phys. **31**, 1375 (1998).
16. Ya.E. Krasik, A. Dunaevsky, J. Felsteiner, J. Appl. Phys. **85**, 7946 (1999).
17. A. Dunaevsky, Ya.E. Krasik, J. Felsteiner, S. Dorfman, J. Appl. Phys. **85**, 8464 (1999).
18. A. Dunaevsky, Ya.E. Krasik, J. Felsteiner, S. Dorfman, J. Appl. Phys. **85**, 8474 (1999).
19. A. Dunaevsky, Ya.E. Krasik, J. Felsteiner, A. Krokhmal, J. Appl. Phys. **87**, 3270 (2000).
20. M. Einat, D. Shur, E. Jerby, G. Rosenman, J. Appl. Phys. **89**, 548 (2001).
21. A. Dunaevsky, Ya.E. Krasik, J. Felsteiner, S. Dorfman, A. Berner, A. Sternlieb, J. Appl. Phys. **89**, 4480 (2001).
22. A. Dunaevsky, K. Chirko, Ya.E. Krasik, J. Felsteiner, V. Bershtam, J. Appl. Phys. **90**, 4180 (2001).
23. Yu.P. Raizer, *Gas Discharge Physics* (Springer, New York, 1997).
24. A. von Engel, *Ionized Gases* (Oxford University Press, London, UK, 1965).