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Research Article

Photoconductive semiconductor switch-based triggering with 1 ns jitter for trigatron

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Abstract

Synchronization for multiple-pulse at nanosecond range shows a great value on the power multiplication and synchronous electric fields applications. Nanosecond or sub-ns jitter synchronization is essential for the improved working efficiency of the large amounts of pulse modules and accurate requirements for the power coherent combining applications. This paper presents a trigger generator based on a laser diode-triggered GaAs photoconductive semiconductor switch (PCSS) with low jitter and compact size characteristics. It avoids the high currents that are harmful to high-gain mode PCSSs. In the trigger circuit, a 200 pF capacitor is charged by a microsecond-scale 18 kV pulse and then discharged via the high-gain mode GaAs PCSS to trigger the high-power trigatron switch. When triggered by the ~10 ns pulse generated by the PCSS, the DC-charged trigatron can operate in the 20–35 kV range with 10 ns rise time and 1 ns delay-time jitter.

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Keywords: Pulsed power; High power switches; Synchronization; Trigger generator; Photoconductive semiconductor switch

1. Introduction

Photoconductive semiconductor switch (PCSS) is high-speed, low-jitter, and compact switches and are promising for applications in the high-power and ultrafast electronics technology fields [1–3]. For example, in the ultra-wideband microwave radiation field, a PCSS array is needed to produce the high-power radiation, which requires all PCSSes in that array to have high synchronism [4,5]. The GaAs PCSS can operate in a high-gain mode, which means that a single incident photon will ultimately induce the formation of electron–hole pairs. The optical energy of the trigger laser for GaAs PCSS can therefore be reduced from the order of mJ to the order of μJ and a compact pulsed laser diode (LD) can then replace the more complex tabletop laser source [6,7]. The cost of the PCSS and the trigger source size could thus be significantly reduced [8]. However, the high-gain PCSS conducts its current through current filaments, and these current filaments imply high current densities. A previous PCSS lifetime testing study [9] demonstrated lifetimes of 10^8 pulses at 20 A/filament (20 ns pulse width), 10^5 pulses at 40–80 A/filament, and 1 pulse at 1000 A/filament or more, while there were specific output current amplitude and duration requirements for individual applications [10].

Power modules require ns or sub-ns synchronization for certain important applications, including X-ray radiography and Z-pinch devices [11–13]. The conventional way to achieve synchronization with jitter of 1 ns or less is to use direct laser triggering with mJ-level laser energy to trigger a high-power spark gap switch [14]. The trigatron switch, which is a type of power switch, has relatively modest trigger pulse

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magnitude requirements (typically 10−30 kV), and is nearly independent of the switched voltage [15,16]. These switches are used in many systems, however, without additional development effort, trigatrons would have difficulty in meeting the reliability and jitter requirements for some of these applications [15,17].

Because their current filaments are influential in high current applications and the low-jitter and compact size characteristics of the high-gain mode GaAs PCSS are highly attractive, PCSSs are promising for trigger switch applications [18]. The researchers mainly showed the detailed triggering results for a PCSS-triggered HCEI switch, the types of field distortion midplane switches produced by the High Current Electronics Institute [18]. In this paper, we will present a DC-charged trigatron that is triggered by a GaAs PCSS with LD triggering. It allows us to take the advantage of the characteristics of PCSS, including low jitter, fast rise time, compact size, and reduced current requirements. In the trigger circuit, the current that passes through the PCSS can be limited to protect the PCSS itself. Test results show that jitter of 1 ns or less can be obtained with output voltages up to 30 kV.

2. Experimental setup

The PCSS has a 5 mm switching gap, and is fabricated on a 600-μm-thick substrate with dimensions of 14 mm × 6 mm. The photoconductive material of the PCSS is semi-insulating GaAs, and the resistivity in darkness is more than 5×10^7 Ω·cm. The PCSSs are manufactured by General Research Institute for Nonferrous Metals (Beijing, China). Two Au/Ge/Ni (200 nm/100 nm/100 nm) metallization electrodes have been deposited on the same surface of the GaAs PCSS through electron beam evaporation, and ohmic contacts were formed by rapid annealing-type heat treatment. The PCSS is illuminated by a 905 nm wavelength light from an LD trigger with a laser energy of hundreds of μJ and full width at half maximum (FWHM) output pulse length of 20 ns.

The trigatron switch used has an outer diameter of 100 mm and length of 114 mm, and is constructed as shown in Fig. 1. The switch is filled with N_2 gas at a set pressure and the gap between the two electrodes is 3 mm. The setup for the DC trigatron triggering tests based on the PCSS is shown schematically in Fig. 1, and Table 1 lists the circuit parameters.

In this circuit, C_1 is initially DC charged to a specific value up to tens of kilovolts. C_0 is pulse-charged and the pulse rise time is several microseconds. The PCSS is optically triggered near the peak of the voltage pulse on C_0, and sends a pulse to the trigger electrode of the trigatron switch. Resistor R_1 is used to limit the current through the PCSS. Because the trigger pulse initiates a discharge streamer in the gas, which the main gap subsequently closes, C_1 is then discharged through the load resistance and the current-view-resistance (CVR) in series. The trigger pulse voltage is measured using a resistive voltage divider. The current through the trigatron is then measured using the CVR.

3. Experimental results

In the tests, a Stanford DG535 timing pulse delay generator is used to generate three independent command signals. The first signal enters the pulse charger system to control the conduction of the thyristor, allowing the pulse charger to output a pulse to C_0 with μs-scale rise time due to the effects of the transformer. The second signal is used to trigger the LD driver to produce the laser pulse that triggers the PCSS. Using a fixed delay between the two signals, the PCSS is then optically triggered near the peak of the voltage pulse on C_0. The third signal is directly input into a 600 MHz bandwidth

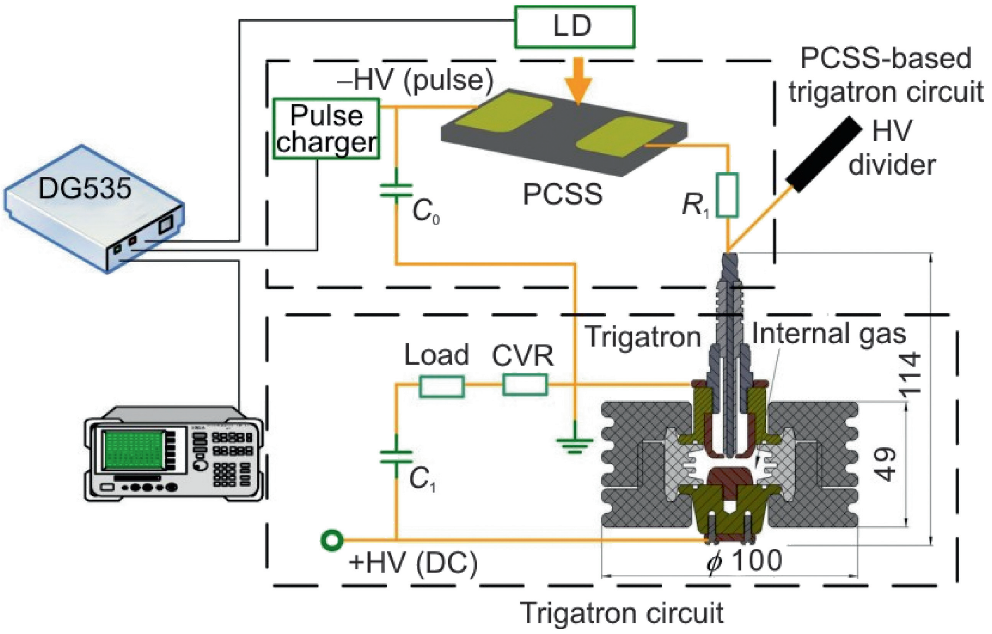

Fig. 1. Schematic of triggering setup for DC trigatron tests based on PCSS.

Table 1
Circuit component parameters.

Symbol	C_0	C_1	R_1	CVR	Load
Value	223 pF	2 nF	100 Ω	1 Ω	120 Ω

oscilloscope as a standard reference signal. The typical waveforms, including the monitored signals, are shown in Fig. 2.

In Fig. 2, the current waveforms show overdamping of the discharge form. The triggering pulse is characterized by a fast rise time of ~10 ns. To measure the total system capability for future multi-pulse synchronization applications, repeated tests must be performed and the jitter characteristics must be determined. Using the Stanford DG535 timing pulse delay generator, the time between the standard reference signal and the triggering signal for the LD driver is fixed. We define the delay time as the interval between the trigger pulse and the standard reference signal produced by the signal source.

In fact, for future multi-pulse synchronization applications, in which each PCSS will be triggered independently using a pulsed LD, linking the delay time directly to the standard reference signal produced by the signal source seems to be the most reliable process. In addition, to measure the system synchronization accurately, it is equally important that the current rise time statistics are also determined. In this case, the time jitter can be given by

$$T_j = \sqrt{\frac{\sum_{i=1}^{n}(T_i - T_{\mathrm{mean}})^2}{n}} \tag{1}$$

where T_i is the delay time (or the rise time), n is the number of identical experiments, and T_{mean} is the average value of T_i. Under various gas pressures (0.2, 0.3 and 0.4 MPa) and with various percentage values of the self-breakdown voltage (V_{bs}) across the trigatron (approximately 94%, 80%, and 64%), nine group tests are performed to calculate the jitter parameters of the system. With the exception of the case where the tests were only repeated five times under the conditions of 0.3 MPa and 62% of V_{bs}, each group of the other eight group tests was repeated 20 times. The test results are shown in Fig. 3 and are summarized in Table 2.

Fig. 3 shows the triggering results under different gas pressures and each subfigure shows the results under different applied voltages. From the figures, we can conclude that the effect of increasing the voltage on the trigatron can reduce both the delay time and the delay-time jitter. When the voltage on the trigatron is set at 94% of V_{bs}, the delay-time jitter is 2.22 ns at 0.2 MPa, 1.07 ns at 0.3 MPa and 0.976 at 0.4 MPa. The rise time of the test is approximately 21 ns and the statistical results for the rise-time jitter are in the sub-ns range. To show these results in detail, Table 2 gives some of the triggering results. The trigger jitter is defined as the jitter of the delay between the trigger pulses relative to the standard signal. The rise time and delay time in Table 2 are the mean value in the group tests. Delay range is defined as the time range from the minimum to the maximum delay time in one group tests. The low percentages of V_{bs} that are imposed on the trigatron not only increase the delay time but also enhance the delay-time jitter.

Note that the peak voltages of any trigger pulses (trigger voltage in Table 2) delivered to the switch are less than the

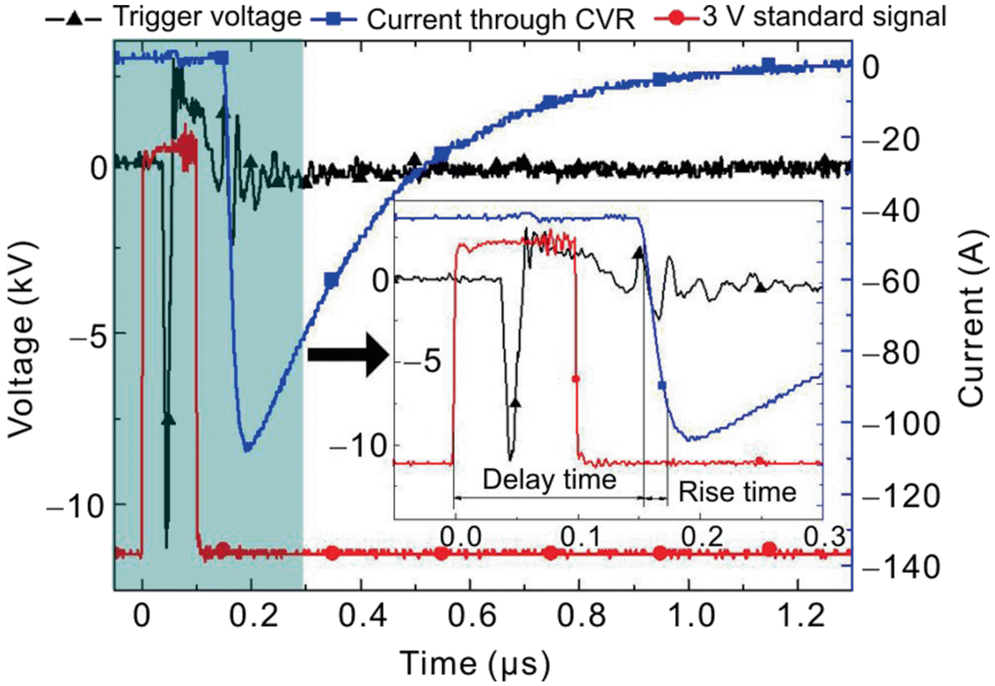

Fig. 2. Typical waveforms of the tests, where the inset shows a partially enlarged view; the charging voltage of C_1 is approximately 13.3 kV and the pressure in the trigatron is around 0.2 MPa.

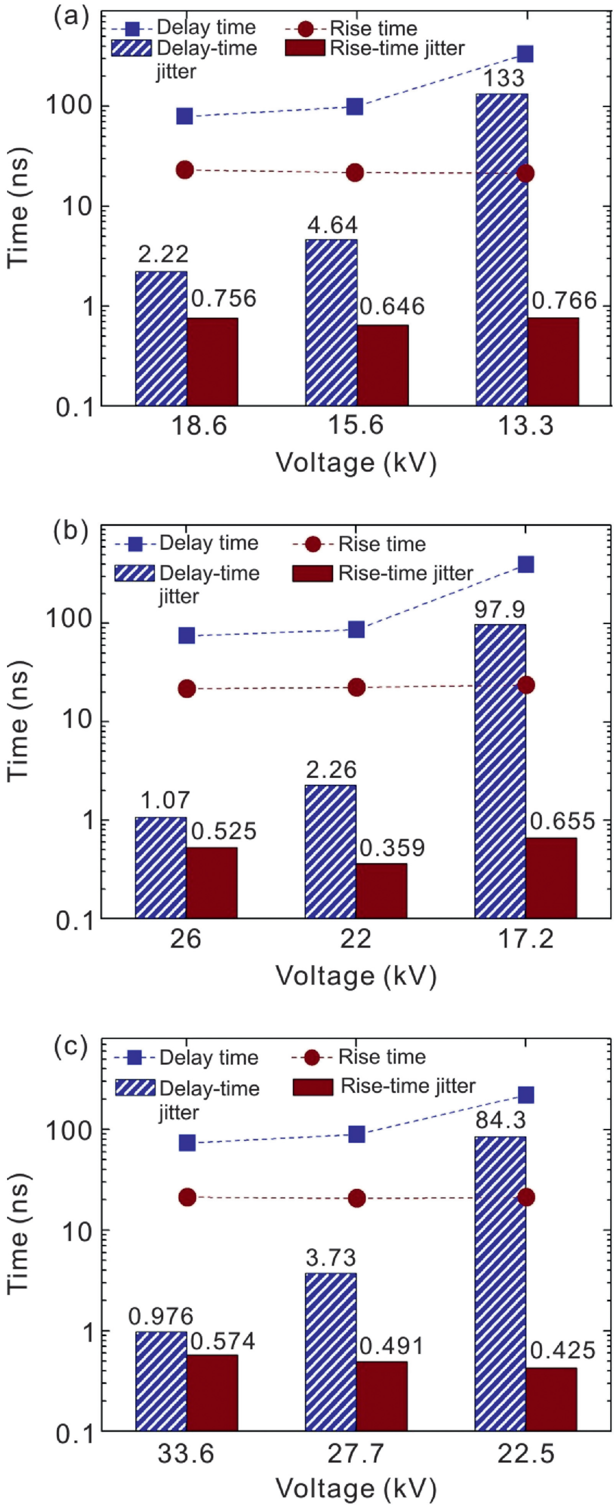

Fig. 3. Statistical results for the delay time and rise time under different switch pressures: (a) 0.2 MPa, (b) 0.3 MPa and (c) 0.4 MPa.

charging voltage of C_0 (18 kV). This is because approximately a voltage of 2–6 kV is dropped across the PCSS and the current limit resistor R_1. This current has therefore been limited to values no larger than 60 A, calculated by dividing dropped voltage by the resistance of R_1. After testing, there is no indication of damage to the PCSS. The test results show an agreement to a previous PCSS lifetime testing study [9] that demonstrated lifetimes of 10^8 pulses at 20 A/filament (20 ns pulse width), 10^5 pulses at 40–80 A/filament, and 1 pulse at 1000 A/filament or more.

To reduce the rise time, the circuit is optimized to be more compact and thus reduces the inductance. Fig. 4 shows 40 consecutive current pulse waveforms with ~10 ns rise times overlaid after optimization. In this case, the delay-time jitter can be calculated to be 1.5 ns by using the same method as Equation (1).

The PCSS-based trigger generator shows numerous characteristic advantages, including low jitter, fast rise time, compact size, controllability and optical insulation to high voltages, compared with other switches that have been used in the trigger generator to deliver synchronous high voltage pulses. Spark gaps are widely used to control the synchronization of multiple output pulses, and the jitter of a single spark gap can be controlled to 1.5 ns with considerable effort [19]. However, the voltage pulse trigger systems are required to be both large and complex, especially when multiple triggering and repetitive operation is required [20,21]. Magnetic switches are also available. While the jitter of multiple pulses generated using magnetic switches can be controlled to the nanosecond level and magnetic switches can work in repetitive operation mode, the typical trigger pulse rise time is several tens of nanoseconds and is difficult to reduce [21,22]. As a result, it is difficult to trigger power gap switches with a jitter of 1 ns or less because of statistical characteristics of gas breakdown.

If GaAs PCSSes need to be applied with a large on-state current and longer life time, we should design our PCSS more carefully. We can use the opposed contacts [23], fabricating the AlGaAs/GaAs quantum well structure and adjusting laser parameter (such as spot location and shape on the PCSS) [24,25] and the bulk GaAs PCSS structure [26] to promote the performance of the high-gain GaAs PCSS. In the future, we will also focus on improving the current capability and increase the lifetime of PCSS with the basis of previous work.

4. Conclusion

Accurate timing conduction of a DC trigatron has been achieved using GaAs PCSS-based triggering. The PCSS trigger source is a high-power pulsed LD, which means that the entire trigger generator assembly can be both compact and practical. When a voltage higher than 90% of the self-breakdown voltage (V_{bs}) was imposed on the trigatron, high-voltage pulses of 20–35 kV with a rise time of 10 ns and delay-time jitter of 1 ns were produced. The results show that a higher ratio of the bias voltage to V_{bs} across the trigatron helps to reduce the delay time, and also helps to improve the synchronization. PCSSes therefore have a bright future in ns or sub-ns synchronization applications.

Table 2
Statistics of selected experimental results.

Gas (N_2) pressure (MPa)	Number of shots	C_1 voltage (kV)	% of V_{bs}	C_0 voltage (kV)	Trigger voltage (kV)	Trigger jitter (ns)	Rise time (ns)	Delay time (ns)	Delay range (ns)
0.2	20	18.6	94	18	12.5	0.199	23.2	79.6	8.72
0.2	20	15.6	79	18	12.2	0.229	21.8	99.5	15.5
0.2	20	13.3	67	18	12.1	0.282	21.5	334	430
0.3	20	26	94	18	13.6	0.325	21.7	75	3.83
0.3	20	22	80	18	13.5	0.758	22.5	86.8	9.52
0.3	5	17.2	62	18	13.4	0.575	23.7	397	259
0.4	20	33.6	94	18	15.9	0.234	21.2	73.5	3.44
0.4	20	27.7	78	18	15.7	0.224	20.8	89.4	13.9
0.4	20	22.5	63	18	16.1	0.193	21.2	220	369

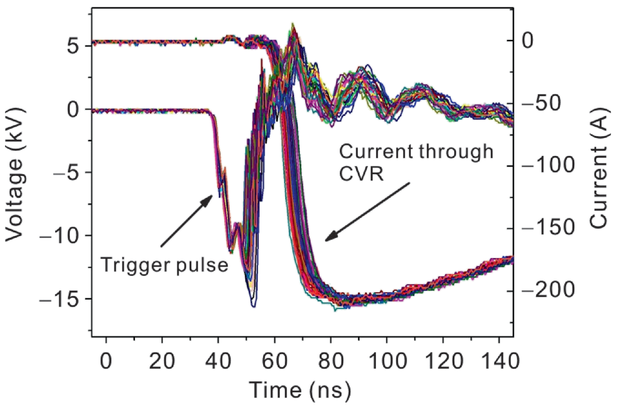

Fig. 4. 40 consecutive current and trigger-pulse voltage waveforms, when C_1 is charged to 24 kV (i.e., 90% of V_{bs} at 0.28 MPa).

Conflict of interest

There is no conflict of interest about this paper.

Acknowledgments

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References

[1] W.C. Nunnally, R.B. Hammond, 80 MW photoconductor power switch, Appl. Phys. Lett. 44 (10) (1984) 980−982.

[2] W. Shi, C. Ma, M. Li, Research on the failure mechanism of high-power GaAs PCSS, IEEE Trans. Power Electron. 30 (5) (2015) 2427−2434.

[3] F.J. Zutavern, G.M. Loubriel, M.W. O'Malley, L.P. Shanwald, W.D. Helgeson, et al., Photoconductive semiconductor switch experiments for pulsed power applications, IEEE Trans. Electron. Dev. 37 (12) (1990) 2472−2477.

[4] S. Ajram, G. Salmer, Ultrahigh frequency DC-to-DC converters using GaAs power switches, IEEE Trans. Power Electron. 16 (5) (2001) 594−601.

[5] J.S.H. Schoenberg, J.W. Burger, J.S. Tyo, M.D. Abdalla, M.C. Skipper, et al., Ultra-wideband source using gallium arsenide photoconductive semiconductor switches, IEEE Trans. Plasma Sci. 25 (2) (1997) 327−334.

[6] W. Shi, L. Tian, Z. Liu, L. Zhang, Z. Zhang, et al., 30 kV and 30 kA semi-insulating GaAs photoconductive semiconductor switch, Appl. Phys. Lett. 92 (4) (2008) 043511−043513.

[7] W. Wang, L. Xia, Y. Chen, Y. Liu, C. Yang, et al., Research on synchronization of 15 parallel high gain photoconductive semiconductor switches triggered by high power pulse laser diodes, Appl. Phys. Lett. 106 (2015) 022108.

[8] F.J. Zutavern, S.F. Glover, K.W. Reed, M.J. Cich, A. Mar, et al., Fiber-optically controlled pulsed power switches, IEEE Trans. Plasma Sci. 36 (5) (2008) 2533−2540 pt. 3.

[9] A. Mar, G.M. Loubriel, F.J. Zutavern, M.W. O'Malley, W.D. Helgeson, et al., Doped contacts for high-longevity optically activated, high-gain GaAs photoconductive semiconductor switches, IEEE Trans. Plasma Sci. 28 (5) (2000) 1507−1511.

[10] Z. Jiang, W. Shi, L. Hou, H. Gui, W. Ji, et al., Effect of current filament characteristics on the output current of high-gain photoconductive semiconductor switch, Appl. Phys. Lett. 101 (2012) 192104.

[11] J. Liu, Y. Zhang, Z. Chen, J. Feng, A compact 100-pps high-voltage trigger pulse generator, IEEE Trans. Electron. Dev. 57 (7) (2010) 1680−1686.

[12] W.A. Stygar, M.E. Cuneo, D.I. Headley, H.C. Ives, R.J. Leeper, et al., Architecture of petawatt-class Z-pinch accelerators, Phys. Rev. Spec. Top., Accel. Beams 10 (3) (2007) 030401.

[13] J.S. Green, S.N. Bland, M. Collett, A.E. Dangor, K. Krushelnick, et al., Effect of wire number on x-pinch discharges, Appl. Phys. Lett. 88 (26) (2006) 261501-1−261501-3.

[14] D.E. Bliss, R.T. Collins, D.G. Dalton, A new laser trigger system for current pulse shaping and jitter reduction on Z, in: Proc. IEEE Int. Pulsed Power Conf, 2003, pp. 179−182.

[15] M.E. Savage, B.S. Stoltzfus, High reliability low jitter 80 kV pulse generator, Phys. Rev. Spec. Top., Accel. Beams 12 (2009) 080401.

[16] L. Cai, L. Li, Y. Liu, B. Yu, C. Bao, et al., Analysis of breakdown mechanism in trigatron switches, IEEE Trans. Dielectr. Electr. Insul. 20 (4) (2013) 1069−1075.

[17] R.E. Beverly, R.N. Campbell, Transverse-flow 50-kV trigatron switch for 100pps burst-mode operation, Rev. Sci. Instrum. 67 (4) (1996) 1593−1597.

[18] S.F. Glover, F.J. Zutavern, M.E. Swalby, M.J. Cich, G.M. Loubriel, et al., Pulsed- and DC-charged PCSS-based trigger generators, IEEE Trans. Plasma Sci. 38 (10) (2010) 2701−2707.

[19] D.D. Bloomquist, R.W. Stionett, D.H. McDaniel, Saturn: a large area X-ray simulation accelerator, in: Proc. IEEE Int. Pulsed Power Conf, 1987, pp. 310−317.

[20] S.K. Lam, J. Banister, B. Christensen, Improvement on double-eagle machine synchronization in both negative and positive modes of operation, in: Proc. IEEE Int. Pulsed Power Conf, 1999, pp. 1453−1455.

[21] Y. Zhang, J. Liu, Nanosecond-range multiple-pulse synchronization controlled by magnetic switches based on a communal magnetic core, IEEE Trans. Plasma Sci. 41 (2) (2013) 371−379.

[22] X. Fan, J. Liu, An LC generator based on accurate synchronization controlling of multisecondary windings saturable pulse transformer, IEEE Trans. Plasma Sci. 42 (1) (2014) 149−153.

[23] R.P. Joshi, P. Kayasit, N. Islam, E. Schamiloglu, C.B. Fleddermann, et al., Simulation studies of persistent photoconductivity and filamentary conduction in opposed contact semi-insulating GaAs high power switches, J. Appl. Phys. 86 (1999) 3833−3843.

[24] C. Luan, Y. Feng, Y. Huang, H. Li, X. Li, Research on a novel high-power semi-insulting GaAs photoconductive semiconductor switch, IEEE Trans. Plasma Sci. 44 (2016) 839−841.

[25] C. Luan, B. Wang, Y. Huang, X. Li, H. L, et al., Study on the high-power semi-insulating GaAs PCSS with quantum well structure, AIP Adv. 6 (2016) 055216.

[26] A. Mar, F.J. Zutavern, G.A. Vawter, H.P. Hjalmarson, R.J. Gallegos, et al., Electrical Breakdown Physics in Photoconductive Semiconductor Switches (PCSS), Sandia National Laboratory, 2016. SAND2016−0109.