Research on Characteristics of GaAs PCSS Triggered by 905nm Laser Diode array

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***Abstract*—Photoconductive semiconductor switches (PCSSs), especially GaAs PCSS, have an excellent performance in the field of pulse power. Since PCSSs can operate in non-linear mode, laser diodes, which are small in size, low-cost, driven easily compared to traditional laser devices, can be used to trigger them at low power. In former literatures, energy is generally considered as an important factor of influences on the characteristics of PCSSs, but power density is rarely studied. In this paper, an array of laser diodes which emit laser pulse with a dominant wavelength of 905 nm and an optical fiber with 5 branches are used to trigger a semi-insulating GaAs PCSS. By adjusting the driving current and the quantity of LDs in series, power density of laser pulse is in a range of 525.2~2347.5 W/mm^2. It's found that the output characteristics of PCSS are strongly influenced by power density of laser pulse. The related experiment results and further discussions are presented in this following paper.**

Keywords*—*PCSS; LD; optical fiber; power density;

I. INTRODUCTION

In the field of pulse power, there are many kinds of switches, and photoconductive semiconductor switches (PCSSs) have a significant status. As is known to all, PCSS can be operated in two modes, linear mode and non-linear mode. After absorbing a triggering photon, PCSS generates one electron-hole pair in linear mode, whereas it generates more than one pair in nonlinear mode [1]. Therefore, nonlinear mode needs relatively lower laser energy for PCSS to output high voltage or conduct high current compared with linear mode. Due to this feature, PCSSs no longer need to rely on the traditional laser devices, which are expensive in price, huge in volume, and high in power (usually MW or GW). Since laser diode (LD) was firstly used as the trigger source of PCSSs [2], LDs have been subminiature, structure-simple, fast response, pulse width adjustable, high efficiency, inexpensive and driven easily, resulting in a miniaturized and integrated triggering system [3]. Many research results have shown that this lower power laser diode can be a good choice as the PCSS trigger source [4-6].

The power of LD is relatively low, and its flare is huge, scattered and non-uniformed, which has adverse effects on the synchronization of PCSSs. Meanwhile, previous literature [7] has explored to increase the impact of laser energy on the properties of PCSS. But the study was based on a high power laser device, whose power is far more than LD's (at least five orders of magnitude). And Zhang, et.al [8] also studied the effects of different illuminating power of a single laser diode on the performance of the PCSS. However, when the trigger source is LD, the laser pulse is still emitting energy when the output high voltage pulse is over. So talking about influences of energy is not reasonable compared with the influences of radiant power. Meanwhile, the initial carriers, generated by the laser pulse, function as the "seed" source of the avalanche, which directly affects the breakover process of the switch. Even the same radiant power has a different spot area combined with different shapes. Former literatures exhibited the derivation of the initial carrier concentration. In those papers, the volume was equal to the thickness multiplied by the whole surface area, resulting in an average carrier concentration. Thus, it is not reasonable to ignore the size of spot and the distribution of carriers. Actually, the initial carrier concentration is related to the spot area. If the laser power is constant, a bigger spot area would cause a smaller carrier density, which may lead to break-over failure of PCSS. In the same way, when the spot area is the same, the bigger the power is, the greater the carrier density is. To study the influence of laser power density on the characteristics of PCSS can better balance the influence of power, spot area and width of the trigger laser pulse, achieving a better performance of PCSS.

In this paper, power density is defined as the value of laser power per unit illuminating area on the surface of PCSS. An optical fiber with five branches is used to converge the power from five laser diodes to trigger a GaAs PCSS. By varying the quantity of LDs in series, the laser power density can range from 525 W/mm^2 to 2347 W/mm^2. What's more, the output voltage, delay time and jitter of PCSS are investigated and discussed, respectively.

II. EXPERIMENTAL SETUP

The PCSS, which is made of semi-insulating GaAs, selected in our experiment is vertical structure. Its metallic cathode and anode are parallel stripes at the opposite sample edges. The resistivity is larger than $5\times10^7\,\Omega\cdot\text{cm}$ in darkness and the mobility of carriers is about 8000 cm^2/(V·s). The electrodes which are Ge/Au/Ni/Au metallization from inside to outside orderly are deposited on the surface of GaAs, and ohmic contacts are formed by annealing. The schematic is shown in Fig. 1. The length is 9 mm, the width is 7 mm, and the thickness is 0.6 mm, the longest horizontal distance between the two electrodes is 3 mm.

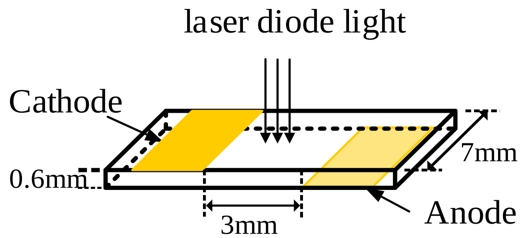


Fig. 1. Schematic of the PCSS selected in the experiment

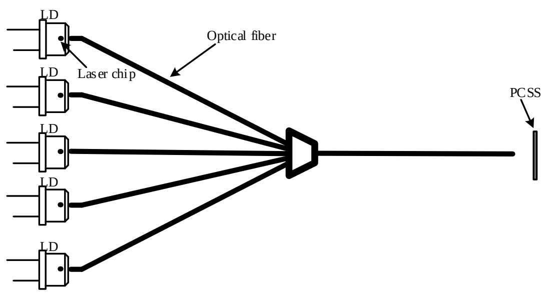
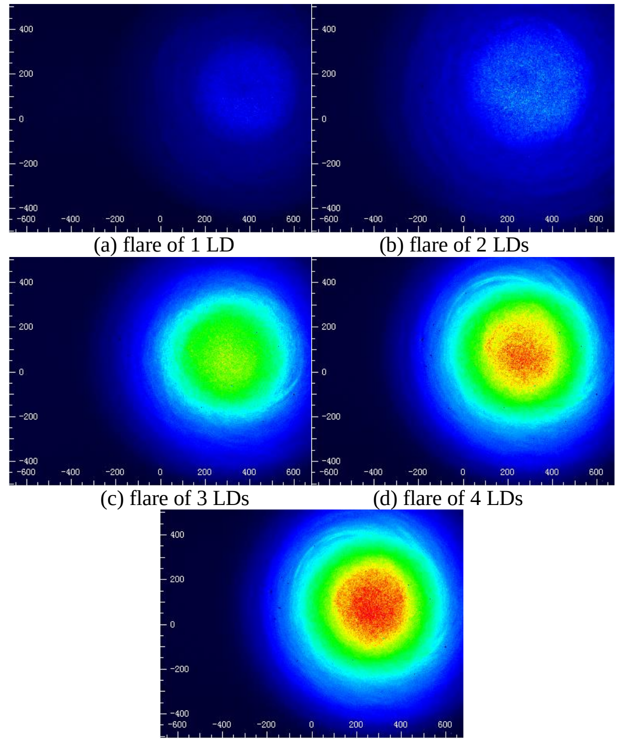


Fig. 2. Optical model of the fiber combined with laser diode

Five OSRAM SPL PL90-3 LDs are used to emit 905 nm laser to trigger the PCSS. The LDs are driven by current pulse in its driving circuit, and the amplitudes can be adjusted by changing voltage of the DC voltage source. The width of the laser pulse is also adjustable under the control of an external electric circuit. In our study, the width of the laser pulse is fixed to 120 ns and the current is fixed to 34 A. So by changing the quantity of LDs in the access circuit through short-circuiting the LDs as well as adjusting the voltage to ensure that the driving current keeps the same, it is able to change the total illuminating power from one LD to five LDs.

The optical fiber used in the experiment has a diameter of 400 μm. The external diameter of the LD is 4.9 mm and the fiber is 3 mm. Fig. 2 shows the coupling schematic of the LDs and the fiber. Since the laser chip is in the middle of the radiating surface of LD, each LD can connect with the fiber by using a 3D-printed model with a high precision to ensure that most energy is transmitted via the fiber. The laser transmission loss of the fiber is less than 1%. However, both the diameter of the optical fiber and the size of the light emitting chip are very small. Moreover, there exists a mismatched tolerance between the LDs and the fibers. So, the coupling rate of different LDs is not the same.

Fig. 3 shows the laser flares obtained from the output end of the fiber. They are emitted by 1~5 LDs and shaped by the fiber. All of them are detected by using a Thorlabs Beam BC106-VIS with a combination of four absorptive neutral density filters (NDFs). As mentioned in section I, the flare of LD is not uniform, and even for the same laser diode, it is slightly different of the spot between triggers. In previous research, it is found that different shapes of the flare exhibits influence to PCSS [9]. So after shaping the flare to one as Fig.3 shows, it would be more precise for the experiment. As is shown, they share the same illuminating area, which has a circular form with a diameter of 400 μm, so the area can be calculated to be 0.1257 mm^2 and it is listed in TABLE I.



(a) flare of 1 LD (b) flare of 2 LDs

(c) flare of 3 LDs (d) flare of 4 LDs

(e) flare of 5 LDs

Fig. 3. Shapes of the flares emitted by LDs of different quantities.

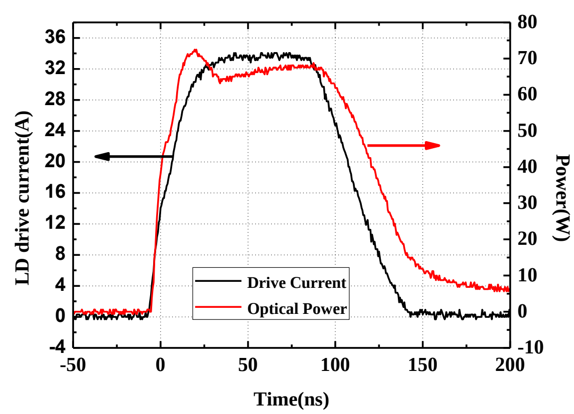


Fig. 4. Temporal profile of the driving current and the LD output power

TABLE I. PERFORMANCE DETAIL OF LASER PULSE

Number of LDs	1	2	3	4	5
Laser energy(uJ)	7.92	18.56	27.74	30.80	35.38
FWHM(ns)	120	120	120	120	120
Laser power(W)	66	155	231	256.7	295
Size(mm^2)	0.1257	0.1257	0.1257	0.1257	0.1257
Power density (W/mm^2)	525.2	1233.5	1838.2	2042.8	2347.5

A typical output waveform of the LD power is shown in Fig. 4. The temporal profile of the laser pulse is monitored by using a high-speed photodiode (ET-2030, <300ps rise/fall time) combining with NDFs. It shows that the drive current is 34 A, which is fixed, while the quantity of LDs is changing, and the FWHM of the laser pulse is 120 ns. The laser energy is measured by Coherent Energy Max sensor (J-10MT-10kHz, <10 nJ noise equivalent energy). Thus the power is calculated by using the energy to divide the FWHM of the laser pulse, the power density of the laser pulse is calculated by using the power to divide the area of the flares. All of them are listed in TABLE I.

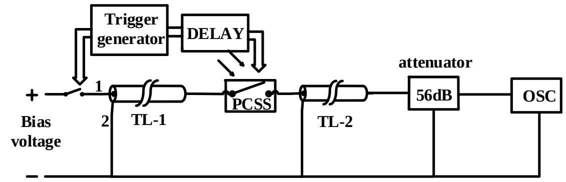
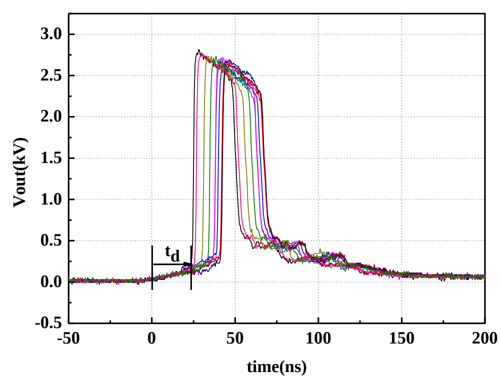


Fig. 5. Experiment test circuit

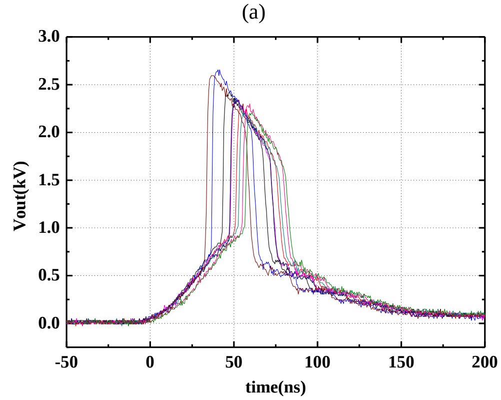
The experiment test circuit is shown in Fig. 5. The PCSS is immersed in the transformer oil to improve the PCSS's insulation strength, and two transmission lines are connected to the electrodes respectively, soldered on a printed circuit board (PCB). They share the same impedance of 50 Ω. Among them, TL-1 is used to store the discharge energy, the propagation delay and length is 5 ns/m and 2m, respectively. TL-2 is used as an ordinary wire. The load is a series of attenuators, named as NMFP-26B and DTS50G. Their attenuation ratio is 26 dB and 30 dB respectively, a total of 56 dB. All of the waveforms are monitored by an oscilloscope of Agilent DSO7104B.

III. Experimental Results

With the change of the illuminating power density of the laser pulse, the output voltage, the delay-time and the time jitter differ in a specific rule. In order to discuss the topic in a convenient way, several concepts should be explained in advance. For the accuracy of the data, each dot is the average value of 10 shots under the same condition (optical, electrical and positional).



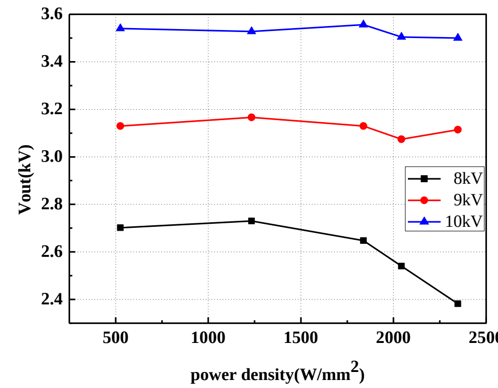
(a)



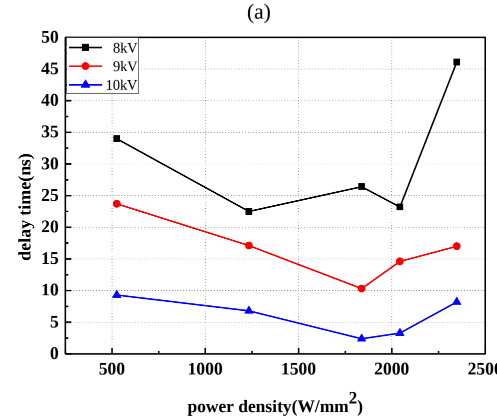
(b)

Fig.6. Typical output waveforms of 10 shots under the condition of 8kV and (a) 525.2W/mm² laser power density, (b) 2347.5W/mm² laser power density

Fig. 6 shows the typical output voltage waveforms of 10 shots measured from the attenuators under the power density condition of 525.2 W/mm² and 2347.5 W/mm² with the same bias voltage of 8 kV. The delay-time is defined as the time interval between the beginning of optical illumination and the onset of switching [10]. The beginning of laser pulse is set at the time axis of 0 point, so the time interval of the sudden increase of each waveform to 0 point is the delay time, t_d shown in Fig.6(a). The time jitter is RMS time of ten delay times [11].



(a)



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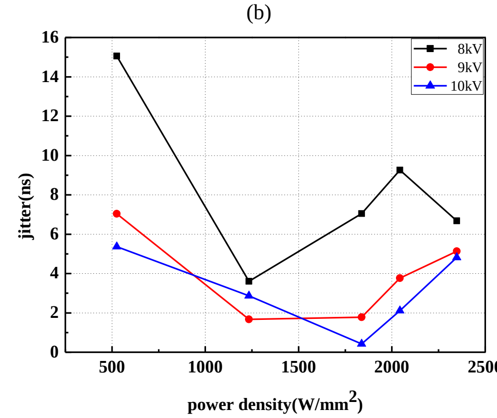

Fig.7. (a) each dot is the average output voltage of 10 shots under a certain bias voltage and laser power density. (b) is the comparison of delay time when triggered by different laser power density. (c) is the relevant jitter of each output waveform under different condition

As shown in Fig. 6, when the bias voltage is fixed, the delay time and the output voltage are strongly influenced by the illuminating power density. In order to reduce the error of measurement, the results are displayed in a statistical manner and plotted in figure. They are shown in Fig. 7

It is obviously seen that an increase in bias voltage causes a rise in output voltage and a decrease in delay time and time jitter, which is also shown in many former literatures.

From Fig. 7(a), it can be seen that with the increase of laser power density in a range of 525.2~1838.2 W/mm^2, the output voltage is increasing. However, when the laser power density continues to increase, the output voltage contrarily decreases.

Delay time is directly related to the response speed of a switch. Fig. 7(b) shows the trend that the delay time decreases firstly when the power density is up to 1838~2042 W/mm^2 and then increases with the laser power density continuing to increase. The trend of jitter is similar, as shown in Fig. 7(c). What should be mentioned is the jitter under the condition of 8 kV and 2347.5 W/mm^2. Compared with the former dots, when the power density is increased from 2042.8 W/mm^2 to 2347.5 W/mm^2, the jitter is getting smaller, though the delay time is getting larger. The results will be discussed in detail in the following section.

IV. Discussion

Based on the formation of high-electric-field domain [12], PCSSs generate large amounts of excess electrons and depleted electrons, forming a dipole in the PCSS. As the dipole grows, it eventually transfers into a mature domain which then transits to anode and quenches to make the switch break-over. In the progress that the dipole grows into domain, there exists a higher electric field in the dipole than outside it. This higher electric field slows down the electrons in the dipole. Consequently, the tailing electrons accumulate at the excess electrons region of the dipole and the faster leave of heading electrons form the accumulation of the depletion electrons region [13]. Under this process, the electric field in the dipole increase with the decrease of that outside the dipole. According to the velocity-field characteristics of GaAs [14], the electric field outside the dipole can decrease to a certain value, which makes the velocities of electrons inside and outside the dipole get to the same. At that time, a mature domain is formed.

At that domain forming progress, the density of initial carriers activated by laser pulse plays a significant role. It can be calculated by

$$n_0 = \frac{N}{V} = \frac{\beta E_0}{h\upsilon s d} \quad (1)$$

where N is the amount of carriers, β is absorption coefficient of the trigger light, E_0 is the total trigger energy, h is the plank constant, υ is the frequency, s is the area of laser spot, V and d is the effective volume and thickness of PCSS, respectively. Since the width of laser pulse is always lager than the breakover time of PCSS, not all of the laser energy is effective. Therefore, E_0 can be expressed as

$$E_0 = \int P(t)dt = P_{avg} t \quad (2)$$

where $P(t)$ is the instant laser power, and P_{avg} is the average laser power, t is the effective time. So equation (1) can be changed into

$$n_0 = \frac{\beta t}{h\upsilon d} \cdot \frac{P_{avg}}{s} \quad (3)$$

So, the initial carrier density is not only related to the laser power, but also related to the illuminating area. The spot area is rarely talked about when the topic involves the power or energy of laser pulse. Actually, the area differs when the laser device type is different. What's more, even with the same device, like LD, the area varies when the distance between the laser device and PCSS changes because of the existence of beam divergence. Thus discussing the power density is more reasonable.

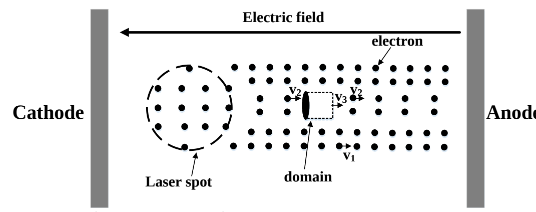

Fig. 8. Model of distribution of laser spot, domain and carriers

Fig. 8. shows the model of distribution of laser spot, domain and photon-generated carriers. Since the width of the domain (also named the accumulation layer which is ~10-100 μm) is much shorter than the length of the optical spot [15] which in our experiment is 400 μm, the effective energy of forming domain is less than 1/4. What's more, the domain should be mature before arriving to the anode, so the ratio of the effective carriers should be lower. Within the progress that the carriers are accumulated to form the domain and the domain drifts to the anode, the carriers around the domain move to the anode quickly. According to the transferred-electron effect, the velocity (v_1) of the carriers around the channel, where the domain drifts, is the largest, followed is that (v_2) of carriers in the channel, and the domain is the slowest (v_3). Thus, though the switch does not break over, a small voltage can still be measured from the attenuator, as shown in Fig. 6(a) in 0~t_d.

With the increase of laser power density, the carrier density increases with the same illuminating time. It is assumed that the threshold of the trigger energy is fixed for a bias voltage of 10 kV. When the laser power density is lower than 2042 W/mm^2, increasing laser power density, the carrier density will be increased. It would shorten the time of domain forming and becoming mature, make the domain more stable, leading to a lower delay time and a smaller jitter in this range of power density. The effect on the output caused by the carriers outside the domain can still be ignored. This can explain the trend that increasing the laser power density can lead to higher output voltage, lower delay time and smaller jitter as shown in Fig. 7.

However, if the laser power density is larger than 2042 W/mm^2, with the increasing of laser power density, the ratio of effective carriers is getting lower, and more carriers will move to anode before the domain arriving to the anode, leading to the probability of linear-alike outputting [16] which can largely extend the delay time as shown in Fig.6(b) getting larger. So we can see that the type of output waveform is more likely to change from Fig. 6(a) to Fig. 6(b). Thus the delay time and jitter is getting lager with the laser power density continuing increasing in Fig. 7(b) and Fig. 7(c). When the probability for PCSS to operate in linear-alike mode gets to 100%, and the laser power density is still increasing, the delay time is larger but the jitter is becoming lower centrally, such as the dot under the condition of 8 kV and 2347.5 W/mm^2 shown in Fig. 7(b) and Fig. 7(c). Moreover, since the velocity (v_2) of carriers in the channel is larger than that (v_3) of the domain, when the domain has matured, the stream of carriers will shock the domain and lower the stability of the domain. And the influence will be stronger when the power density increases.

In this experiment, the energy storage device is the transmission line TL-1 in Fig. 5, the capacity is only tens of Pico-farads, thus the energy stored in TL-1 is very small. When the output voltage of the waveform is suddenly increasing, the bias electric field has largely decreased. Especially in linear-alike mode shown in Fig. 6(b), a large part of the energy stored in TL-1 has lost when the PCSS turns on, causing the output voltage greatly reduced shown in Fig. 7(a).

It is found that the output characteristics of PCSS are not only related to the laser power, but also related to the power density, and the optimal value should be about 1800 W/mm^2 under a bias voltage of 10 kV. Because the width of domain becomes lager with the increasing of bias voltage, the optimal value should change with the change of bias voltage, namely a bigger bias voltage causes a larger optimal power density. It is reckoned that when power density is up to the optimal value, increasing the laser power with the same illuminating area or decreasing the illuminating area with the same laser power should get the better performance of the PCSSs.

V. Conclussion

A series of experiments are demonstrated on a semi-insulating GaAs PCSS, and within the laser power density of LD array changing from 525.2 W/mm^2 to 2347.5 W/mm^2, characteristics of output voltage, delay time and time jitter are investigated and discussed. For a certain bias voltage, increase in laser power density will make promotion in properties especially in jitter and delay time of the PCSS in a different range, but it is not always better for the performance of PCSS to increase the laser power density. Meanwhile, the idea of using optical fiber to shape the laser flare and converge the energy of several LDs is feasible. It is reckoned that the law of the optimum beam intensity is only suitable for the second-generation PCSSs which can work in non-linear mode, and the geometry of PCSSs do not affect the law. For the first-generation PCSS (Si PCSS) and the third-generation PCSSs (like SiC PCSS), they can only work in linear mode, laser power density should be as high as possible.

Acknowledgment

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References

[1] G. M. Loubriel, M. Omalley, and F. J. Zutavern, “Towards pulse power uses for photoconductive semiconductor switches: closing switches”, IEEE Pulsed Power Conf., Albuquerque, NM (USA), Jan. 1987, pp.145-148.

[2] S. J. Davis, “Bulk semiconductor switch”, US patent, US4438331, 1984.

[3] M. Pocha, and R. Druce, “35-kV GaAs subnano-second photoconductive switches”, IEEE Trans. Electr. Dev., vol.37, no.12, pp.2486-2492, 1990.

[4] W. Wei, L. Xia, Y. Chen, Y. Liu, C. Yang, M. Ye, and J. Deng, “Research on synchronization of 15 parallel high gain photoconductive semiconductor switches triggered by high power pulse laser diodes”, Appl. Phys. Lett., vol. 106, no. 2, pp. 022108-1-4, 2015.

[5] L. Ragle and S. Davis, “Bulk avalanche semiconductor switch using partial light penetration and inducing field compression”, US patent, US4782222, 1987.

[6] F. J. Zutavern, S. F. Glover, K. W. Reed, M. J. Cich, A. Mar, M. E. Swalby, T. A. Saiz, M. L. Horry, F. R. Gruner, F. E. White. “Fiber-Optically Controlled Pulsed Power Switches”, IEEE Trans. Plasma Sci., vol.36, no.5, pp. 2533-2540, 2008.

[7] J. Yuan, W. Xie, H. Liu, H. Li, X. Wang, W. Jiang, “High-power GaAs photoconductive semiconductor switch triggered with picosecond laser pulse”, IEEE Pulsed Power Conf., 2009 Iet European, pp. 1-3, 2009.

[8] T. Zhang, B. Wang, J. Qiu and K. Liu, “Investigation of GaAs PCSS triggered by laser pulse with different parameters”, IEEE Trans. Plasma Sci., vol. 42, no. 10, pp. 2981-2985, 2014。

[9] T. Zhang, K. Liu, S Gao and Y. Shi, “Characteristics of GaAs PCSS triggered by 1 μJ laser diode”, IEEE Trans. Dielectr. Insul., vol. 22, no. 4, pp. 1991-1996. 2015.

[10] Z. Du, K. Gong, F. Meng, and Z. Yang, “Delay time in GaAs high-power photoconductive switches”, IEEE Phot. Tech. Lett., vol. 11, no. 3, pp. 337-339, 1999.

[11] J. Lehr, M. Abdalla, J. Schoenberg, et al. “Progress toward a compact, high power ultra-wideband array using gallium arsenide photoconductive semiconductor switches”, 23rd IEEE Power Modulator Symposium Conf., pp. 156-159, 1998.

[12] A. Neumann, “Slow domains in semi-insulating GaAs”, J. Appl. Phys., vol. 90, no. 1, pp. 1-26, 2001.

[13] S. M. Sze and K. K. Ng, “Transferred-Electron and Real-Space-Transfer Devices”, Physics of Semiconductor Devices, 3rd ed. Hoboken, New Jersey: John Wiley & Sons. Inc, ch. 10, sec. 2, pp. 511-512, 2007.

[14] J. G. Ruch and G. S. Kino, “Measurement of the velocity-field characteristic of gallium arsenide”, Appl. Phys. Lett., vol. 10, no. 2, pp. 40-42, 1967.

[15] B. Wang, T. Zhang, K. Liu, and J. Qiu, “Characteristics of the GaAs photoconductive semiconductor switch operated in linear-alike mode”, IEEE Trans. Electr. Dev., vol.60, no. 8, pp. 2580-2585, 2013.