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RESEARCH ARTICLE

# Study on Output Characteristics of 20 kV/100 ns Nonlinear GaAs Photoconductive Semiconductor Switch

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**ABSTRACT** In this paper, the output electric pulse characteristics of gallium arsenide photoconductive semiconductor switch (GaAs PCSS) with bias voltage of 20 kV and pulse width of about 100 ns are studied. By designing the reflection and transmission optical paths, the absorption rate of the trigger optical of the GaAs PCSS at a wavelength of 1064 nm was measured to be 24.8%. When the bias voltage is 16 kV-20 kV, the avalanche multiplication rates of carriers are calculated respectively. The relationship between the output current waveform and the residual charge in the energy storage capacitor is analyzed when the bias voltage is 20 kV. And the trend of GaAs PCSS electric field intensity and current waveform change with time. This research will be helpful for the application design of GaAs PCSS under the nonlinear mode with special requirements, and has important significance for the application of frontier science.

**INDEX TERMS** Gallium arsenide photoconductive semiconductor switch (GaAs PCSS), nonlinear mode, output characteristics.

## I. INTRODUCTION

The gallium arsenide photoconductive semiconductor switch(GaAs PCSS) is a new type of device formed by combining ultrafast laser with photoelectric semiconductors. GaAs PCSS have drawn wide attentions in the fields of ultra-high speed electronics, ultrafast pulse power technology and THz technology due to the unique features such as the GHz repetition rate, photoelectric isolation, flexible structure [1], [2], [3]. The GaAs PCSS has linear mode and nonlinear mode. When the electric field and optical energy of GaAs PCSS meet the threshold conditions, the switch enters the nonlinear mode [4], [5]. At present, with the continuous development of ultra-wideband pulse generation, there are more precise requirements for the output electric pulse of GaAs PCSS under specific conditions. For example, munitions firing sets require a PCSS that can operate at 1 kV and 1 kA with a compact package, and electro-optic drivers require a PCSS that can switch a current of 100 A at 3 kV-6 kV with a rise time on the order of hundreds of picoseconds [6], [7]. In 1975, D.H. Auston et al. of Bell Laboratories, USA, produced the first silicon optoelectronic semiconductor photoconductive switch on a microstrip line. And a related paper on photoconductive switches triggered with picosecond laser pulses to generate electrical pulses of kilovolt and nanosecond magnitude was published [8]. In 1980, Lee and Marthur successfully used in their laboratory GaAs and CdS0.5 Se0.5 to generate electrical pulses of different widths with amplitudes up to several kV [9]. It can be seen that the output electrical pulse amplitude and pulse width of GaAs PCSS in nonlinear mode are still the key technical index to be studied. In the field of pulse power technology, achieving electrical pulse output on the order of 100 nanoseconds is of great value for ultra-wideband fields Microwave pulses research [10]. One hundred nanosecond pulse width can increase the single pulse output energy of

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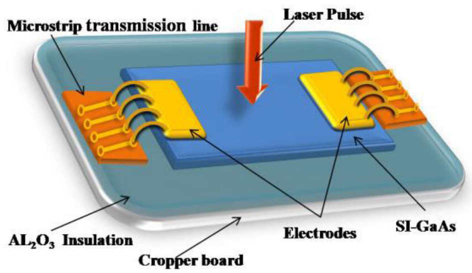


FIGURE 1. The schematic diagram of GaAs PCSS structure.

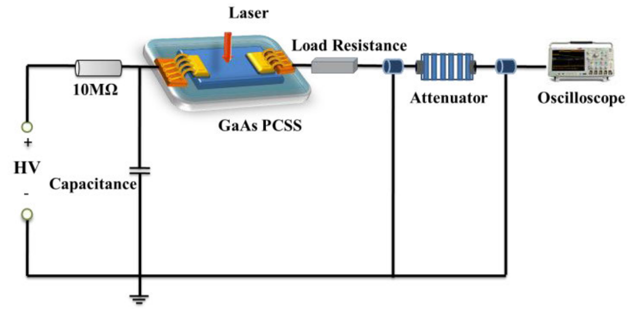


FIGURE 2. The GaAs PCSS test circuit.

the switch at a certain power and improve the switching life of the photoconductive switch, however, there is no research on the output characteristics and life of the PCSS under 100 nanoseconds conditions. In the application of frontier science, the output of 100-nanosecond pulse width is a major requirement. However, there are few reports on the output characteristics of nonlinear GaAs PCSS at tens of kilovolts and pulse widths of about 100 nanoseconds. In my previous work, the output pulse width of GaAs PCSS was controlled by energy-storage capacitance and current-limiting resistance. When triggered by a pulse laser with a width of 10 ns and single pulse energy of 200 $\mu$J, the switch can output the minimum pulse width of the 6.3 ns and the maximum pulse width of 196 ns. The results indicate that adding different current-limiting resistances and energy-storage capacitance in the circuit can control the electric field intensity, so that different pulse width can be output [11]. In this paper, we obtain the results of the output pulse width of about 100 ns at a bias voltage of 20 kV for the nonlinear GaAs PCSS. The output characteristics of GaAs PCSS, such as absorption rate, carrier avalanche multiplication rate and electric pulse width, are calculated and analyzed.

## II. EXPERIMENT

### A. GaAs PCSS

The PCSS used in the experiment is a lateral structure, as shown in Fig. 1. The photoconductive material of the PCSS is semi-insulating (SI) GaAs, with a dark resistivity of $5 \times 10^7 \Omega \cdot$ cm in total darkness and the electron mobility higher than 5000 $cm^2/(V \cdot s)$. The gap width of GaAs PCSS is 1.43 eV, the intrinsic breakdown field strength is 250 kV/cm, and the relative dielectric constant is 12.9. The overall size of the GaAs PCSS is 16 mm (length) × 6 mm (width) × 0.6 mm (thickness). The electrodes with ohmic contacts are made of Au/Ge/Ni/Au alloy. The distance between two electrodes is 8 mm. The electrode corners of GaAs PCSS are chamfered. The optimized design can effectively improve the electric field distribution inside the GaAs PCSS, avoiding the electrode corners from increasing the local electric field strength. The 900 nm $Si_3N_4$ and 4 mm silica gel, which are coated on the surface of the GaAs PCSS, is used for the insulation protection.

### B. THE TEST CIRCUIT

The details of the experimental circuit are shown in Fig. 2. In the text circuit, the GaAs PCSS is triggered by the solid state pulsed laser. The laser with a wavelength of 1064 nm, a pulse width of 10 ns and an optical energy of 4.7 mJ was used. The dominant factor in the ability of semi-insulated GaAs to absorb 1064 nm optical pulses and generate photo-generated carriers is due to its internal EL2 deep level and two-photon absorption [12], [13], [14]. The load resistance used in the experiment is 300 Ω. The highvoltage DC source charges the energy storage capacitor through a 10MΩ glass glaze current-limiting resistor. When the laser excites the GaAs PCSS, the energy storage capacitor discharges through the GaAs PCSS and the switching voltage is attenuated by a 60-dB attenuator and recorded by oscilloscope. In order to maintain the integrity of the signal, the whole test circuit uses a 50 Ω coaxial transmission line, and the impedance of the oscilloscope is also 50 Ω.

## III. RESTULTS AND DISSCUSSION

### A. ABSORPTION OF GaAs PCSS

GaAs PCSS output ultrafast electrical pulses by absorbing photons to generate carriers. In order to accurately obtain the absorption of the trigger optical source (1064 nm) by GaAs PCSS, we measured the reflectance and transmittance of GaAs PCSS. The formula of absorption rate can be expressed as,

$$A = 1 - T - R \tag{1}$$

where A is the absorption rate of the triggered optical by GaAs PCSS, T is the transmittance, and R is the reflectance.

In order to ensure the stability of the optical emitted by the laser through the fiber coupling, the beam quality meter was used to measure the divergence angle of the optical fiber as 0.2°, which met the test requirements. In the test, the GaAs PCSS was fixed on the optical fixture, the laser pulse was emitted through the optical fiber and irradiated on the surface of the GaAs PCSS, and the optical energy meter was placed on the back of the GaAs PCSS, as shown in Fig. 3. In the experiment, the laser transmittance of GaAs PCSS was tested at three different distances 4.5 mm, 8.5 mm and 25.5 mm between the optical energy meter and the back of GaAs PCSS. The test results are shown in TABLE1. It can be seen that the closer the distance between GaAs PCSS and the optical energy meter, the higher the transmittance and the closest

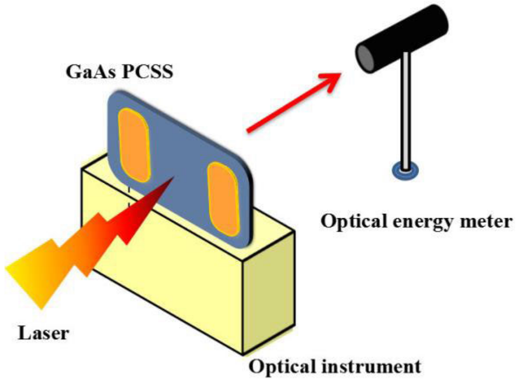


FIGURE 3. Transmittance test optical path.

TABLE 1. Transmittance of GAAs PCSSAnd light energy meter at different distances.

| GaAs PCSS and energy meter distance | Laser Energy | Transmission energy | Transmittance |
|---|---|---|---|
| 4.5 mm | 36.9 μJ | 19.6 μJ | 53.1% |
| 8.5 mm | 43.3 μJ | 20.8 μJ | 48.0% |
| 25.5 mm | 29.6 μJ | 12.0 μJ | 40.5% |

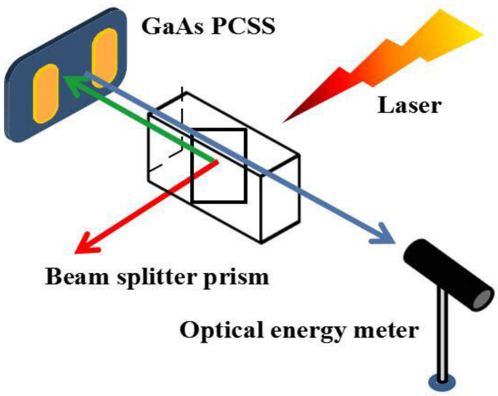


FIGURE 4. Reflectance test optical path.

the actual value. Therefore, the laser transmittance of GaAs PCSS in this paper is calculated using the closest data of the distance between the optical energy meter and the backside of GaAs PCSS.

When the laser irradiates GaAs PCSS, its surface also reflects some of the optical energy. The surface of GaAs PCSS is vertically irradiated with laser, and the reflectance test optical path is shown in Fig. 4. The laser pulse is irradiated on the 50/50 splitting prism. One beam is transmitted to the air through the prism, and the other beam is reflected on the GaAs PCSS. The surface of the GaAs PCSS is reflected back to the splitting prism, and then transmitted to the optical energy meter. The surface reflectivity of GaAs PCSS is 22.1%. Therefore, the absorption rate of GaAs PCSS was calculated to be 24.8%.

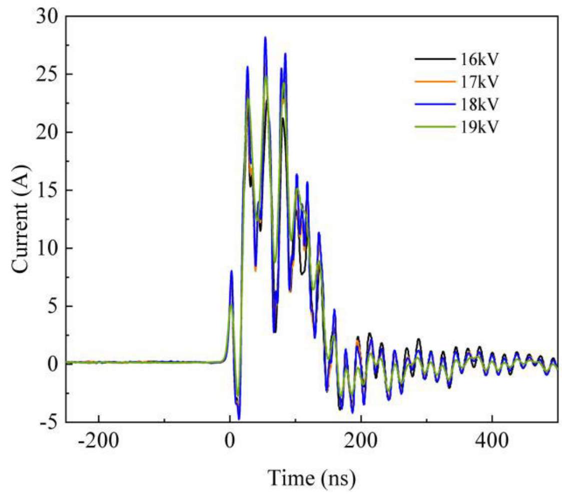


FIGURE 5. Output current waveforms of GaAs PCSS at different bias voltages.

### B. CARRIER AVALANCHE MULTIPLICATION RATE OF GAAS PCSS

When the bias voltages are 16kv, 17kv, 18kv, 19kv and 20kv, the GaAs PCSS operates in nonlinear mode, and the avalanche multiplication effect of carriers occurs. Even if the trigger laser pulse disappears, the GaAs PCSS can still be conductive, and the photo-activated charge domain (PACD) is formed in the GaAs PCSS [15], [16], [17]. In the experiment, when the bias voltage is 16 kV-19 kV, the trigger optical energy is kept at 1.17 mJ, and when the bias voltage is increased to 20kV, the trigger optical energy is decreased to 0.61 mJ. Reducing the trigger optical energy can decrease the chance of flashover along the GaAs PCSS surface. The output electrical pulse waveformsare shown in Fig. 5 and Fig. 6.

In nonlinear mode, the output characteristics are mainly determined by the avalanche multiplication of carriers. The avalanche multiplication strength of carriers is mainly determined by the material characteristics and the electric field strength. The avalanche multiplication of carriers rate (K) in nonlinear mode can be expressed as [18],

$$\mathbf{K} = N_e/N_p \tag{2}$$

$N_e$ is the number of photo-generated carriers, and $N_p$ is the number of photons absorbed by GaAs PCSS. The total amount of charge flowing in the circuit can be estimated using the output area under the GaAs PCSS current waveform. The number of photons absorbed by GaAs PCSS is only related to the optical source, can be expressed as,

$$N_p = E\lambda/hc \tag{3}$$

where E denoted the actual absorption optical energy, h ($\mathbf{6.626 \times 10^{-34}}$) is Planck constant, $\boldsymbol{\lambda}$ (1064 nm) is wavelength of laser and c ($\mathbf{3 \times 10^{-8} m/s}$) is velocity of optical.The calculation of carrier avalanche multiplication rate of GaAs PCSS with bias voltage of 16 kV-20 kV is shown in Table 2. With the bias voltage increases, the carrier avalanche multiplication rate also increases.

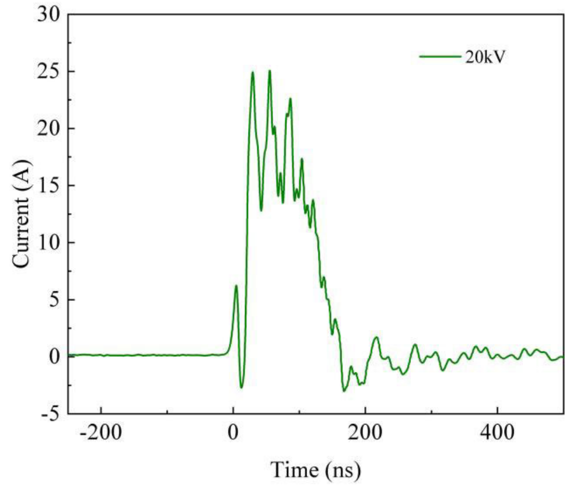


**FIGURE 6.** Output current waveforms of GaAs PCSS at 20 kV bias voltage.

**TABLE 2.** Avalanche multiplication rates of carriers of GaAs PCSS at different bias voltages.

| Bias voltage(kV) | Trigger light energy(mJ) | Avalanche multiplication rate of carriers |
|---|---|---|
| 16 | 1.17 | 27.8 |
| 17 | 1.17 | 29.5 |
| 18 | 1.17 | 30.8 |
| 19 | 1.17 | 31.6 |
| 20 | 0.61 | 43.5 |

### C. HUNDRED-NANOSECOND PULSE OUTPUT

After the gaas pcss was triggered, the charge in the energy storage capacitor discharge on the load resistor through the switch. The amount of charge within the energy storage capacitor affects the carrier drift motion by influencing the electric field strength of the gaas pcss. The directional drift of photo-generated carriers within the gaas pcss forms a conduction current within the pcss, and the separation of electrons and holes creates a built-in electric field within the gaas pcss that changes rapidly with carrier drift. With the rapid reduction of the charge in the capacitor, when the electric field at both ends of the gaas pcss is less than the sustain electric field of the lock-on mode, the gaas pcss exits the nonlinear mode. The remaining charge of the energy storage capacitor in the discharge process can be expressed as,

$$Q(t) = Q - \Delta Q = CU - \int_0^t I(t)dt \tag{4}$$

where C is the energy storage capacitor, U is the bias voltage and $I(t)$ is the current in the circuit.

When the bias voltage is 20 kV, the curve of the output current of GaAs PCSS and the residual charge of the energy storage capacitor with time is shown in Fig.7. The output pulse width is about 100 ns at a bias voltage of 20 kV. The area enclosed by the output current curve of GaAs PCSS is the charge released by the energy storage capacitor during the switching process. As can be seen from Fig.7, the curve area of GaAs PCSS is small when it is just turned on, and the residual charge of the energy storage capacitor is large. With the continuous conduction of the switch, the output current waveform area increases continuously, and the residual charge in the energy storage capacitor decreases. Moreover, there is still residual charge in the energy storage capacitor after the switch is turned off. The remaining charge in the capacitor after the switch is turned off is $0.2 \times 10^{-6}$ C, and the capacitance discharge rate is 91.07%.

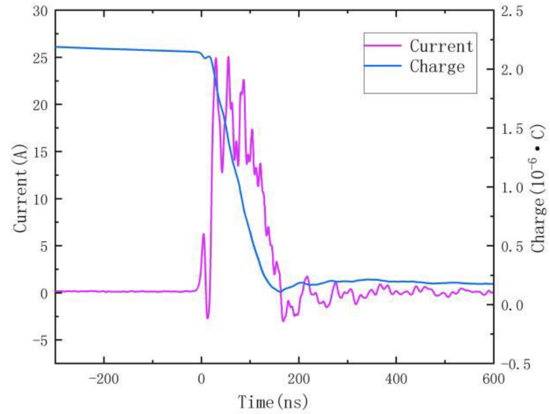


**FIGURE 7.** Output current and residual charge curve of GaAs PCSS under 20 kV bias voltage.

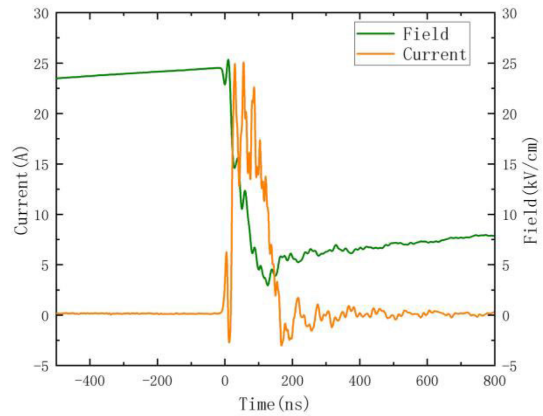


**FIGURE 8.** Electric field and current change curve of GaAs PCSS at 20 kV bias voltage.

The bias electric field of GaAs PCSS in the circuit is calculated as follows,

$$\mathrm{E(t)} = \frac{1}{d}\left(\frac{Q(t)}{C} - i(t)R\right) \tag{5}$$

where d is the electrode gap of GaAs PCSS, and R is the load resistance in the discharge circuit.

The curve of the electric field intensity of GaAs PCSS with the output current waveform is shown in Fig.8. At the moment when the optical pulse is triggered, the carrier concentration increases instantaneously. GaAs PCSS operate in a nonlinear mode with a bias electric field above the threshold electric field. The carriers accumulate to form PACD and become steady-state domains moving toward the anode in a very short time. The built-in electric field of the PACD increases with carrier impact ionization, and carrier avalanche multiplication corresponds to the maintenance phase of the output electric pulse. During the conduction process of GaAs PCSS, the energy storage capacitor discharges continuously, and the field intensity of the GaAs PCSS also changes with time. When the voltage across the energy storage capacitor is lower than the maintenance voltage of the pacd, the built-in electric field of the PACD decreases. The electron-hole pair is compounded off and the carrier drift rate decreases. The domains are burst before they reach the anode, and the GaAs PCSS turn off rapidly. Since the electric field strength of the GaAs PCSS is no longer able to maintain the conditions of the nonlinear mode, the GaAs PCSS then exits the Lock-on stage and the carriers in the switch will recombine. The output pulse shows a fast falling edge, this was the desired result.

## IV. CONCLUSION

In this paper, the characteristic of GaAs PCSS outputting about 100-nanosecond electrical pulse under the nonlinear mode is studied when the bias voltage is 20 kV. The transmittance and reflectance of GaAs PCSS to 1064 nm laser pulse were measured, and the laser absorption rate of GaAs PCSS was 24.8%. In addition, the avalanche multiplication rate of carriers under bias voltage of 16 kV-20 kV were calculated. The current waveform output by GaAs PCSS is compared with the change of residual charge in the energy storage capacitor and the change of electric field intensity of GaAs PCSS, respectively. The results show that the rapid falling edge of the output pulse of the nonlinear switch is due to the fact that the remaining charge of the energy storage capacitor cannot maintain the nonlinear mode.

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