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998 Multiplication Rate of GaAs Avalanche Semiconductor Switch Triggered by 0.567 nJ

CHENG MA, WEI SHI, CHENGANG DONG, LEI YANG, ZHIQUAN WANG, MEILIN WU, HAIQING WANG, CHUANHUI ZHONG, AND CHAOFAN LI

Key Laboratory of Ultrafast Photoelectric Technology and Terahertz Science in Shaanxi, Xi'an University of Technology, Xi'an 710048, China

Corresponding author: Wei Shi (swshi@mail.xaut.edu.cn)

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ABSTRACT In this paper, the results show that the avalanche mode of GaAs photoconductive semiconductor switches (PCSS) requires only a low trigger optical energy of 0.567 nJ to achieve. At the bias electric field is 94 kV/cm, a trigger optical energy with sub-Nano Joule is used to trigger the PCSS, and the multiplication rate can be as high as 988. We have presented avalanche delay characteristics under the different bias electric voltage, and the physical mechanism of the avalanche delay time is analyzed. This article shows a high multiplication rate ultrafast pulse source with low-energy triggering.

INDEX TERMS Low energy triggering, photoconductive semiconductor switches (PCSS), multiplication, avalanche mode.

I. INTRODUCTION

Avalanche photoconductive semiconductor switches (PCSSs) is widely applied in beam accelerators, ultra-wide band microwave pulses, and in many electrical and optical short pulse applications [1]–[3]. The avalanche PCSS operating mode relies on the photon-induced carrier multiplication process in GaAs materials. Triggering the PCSS into avalanche mode with lower light energy is important for developing compact pulsed power systems [4]–[5]. In order to make the pulse source system smaller and easier to integrate, a laser source with trigger optical energy in the (nJ) range needs to be used. Alan Mar, D. K. Serkland, and others demonstrated the multi-channeling in PCSS devices using a 120 nJ vertical-cavity surface-emitting lasers to approximate line generation [6]. In 1997, avalanche operation of GaAs PCSS with the trigger optical energy of 2 nJ was reported by Zutavern *et al.* [7]. When the laser energy is in the range of nJ and the electric field intensity is in the about of 78 kV/cm, the multiplication rate is less than 100. For instance, when trigger energies of 24.5 nJ and 8 nJ were used to trigger the switch into avalanche mode, the required bias electric fields are as high as 76 kV/cm and 78 kV/cm [8]–[9]. But the multiplication rates are only 3.14 and 73.4. Therefore, obtaining a high multiplication rate and a short pulse simultaneously at low trigger optical energy represents a challenging task.

In this paper, a high multiplication rate of 998 of the GaAs PCSS at the trigger optical energy of 0.567 nJ is demonstrated. The avalanche delay effect triggered by low optical energy was also studied. The structure of this paper is arranged as follows., The experimental setup is presented in Section II. The results are presented and discussed in Section III. In Section IV, the conclusions are given.

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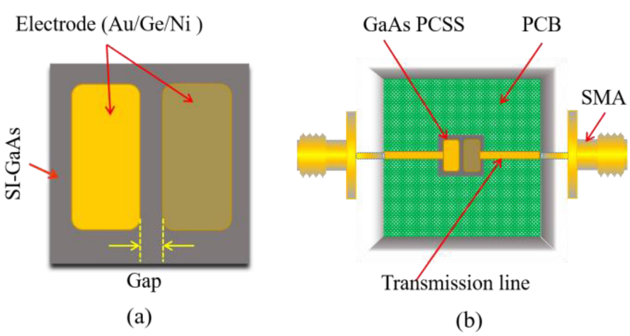

FIGURE 1. **(a) The SI-GaAs chip (b) The layout of the SI-GaAs PCSS.**

II. GAAS AVALANCHE SEMICONDUCTOR SWITHCH

The SI-GaAs chip configuration featured an opposed contact geometry, as shown in Fig. 1(a). The substrate material of the switch was SI-GaAs, and its structure is 10.0 mm (length) × 10.0 mm (width) × 0.6 mm (thickness). The average dark resistivity and the electron mobility of SI-GaAs were higher than 5×10^7 Ω·cm and 5000 $cm^2/(V \cdot s)$, respectively. The gap of 0.532-mm denoted a horizontal distance between the two electrodes. The ohmic contact of the SI-GaAs chip electrode mainly deposits Au/Ge/Ni on the surface by the electron beam evaporation method. Moreover, a 900-nm Si_3N_4 film was used to coat the surface of SI-GaAs chip in order to ensure sufficient insulation.

The layout of the SI-GaAs PCSS is shown in Fig. 1(b). The SI-GaAs chip was placed onto an epoxy-laminate printed circuit board (PCB) substrate with planar microstrip transmission lines. The impedance of the planar microstrip transmission line was 50 Ω. The planar microstrip transmission line was connected to the coaxial transmission line via the SMA connector.

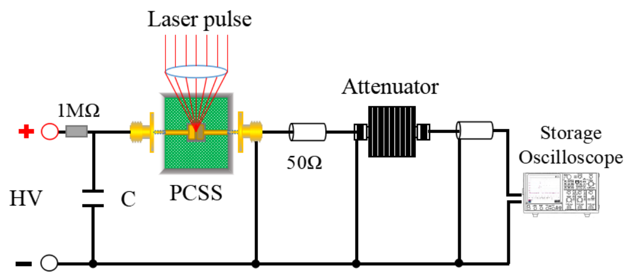

FIGURE 2. GaAs PCSS test circuit.

The test circuit is shown in Fig. 2. In the test circuit, a regenerative amplified mode-locked femtosecond titanium sapphire laser was used as the trigger optical source for GaAs PCSS. The laser parameters were 100 fs pulse width and 800 nm wavelength. The laser beam was divided into two paths by a beam splitter. One path was used to trigger the GaAs PCSS, and the other path was measured with a light energy meter with a range of 200 pJ-400 pJ. A high voltage (HV) DC source charged the capacitor via a 1-MΩ current limiting resistor. The SI-GaAs PCSS was charged via a 10-pF capacitor. Once the switch was triggered, the capacitor discharged. The generated electrical pulse was first 60-dB attenuated (Impedance 50-Ω) and then recorded using an oscilloscope with a bandwidth of 13 GHz.

III. RESULTS AND DISCUSSION

A. CHARACTERISTICS OF AVALANCHE DELAY

When the electric field is lower than the avalanche threshold electric field (7.5 kV/cm) [10], this electric field strength is the minimum electric field threshold required to enter avalanche mode. Below this electric field strength, the GaAs PCSS works in a linear mode, each photon generates a pair of electron-hole pairs, and the conductivity of the conducting material has a linear relationship with the trigger optical energy. Therefore, the output waveform is similar to the laser pulse waveform. Fig. 3 shows that when the trigger optical energy is 103 nJ and the bias voltage is 3.1 kV, the GaAs PCSS operated in the linear mode (black line).

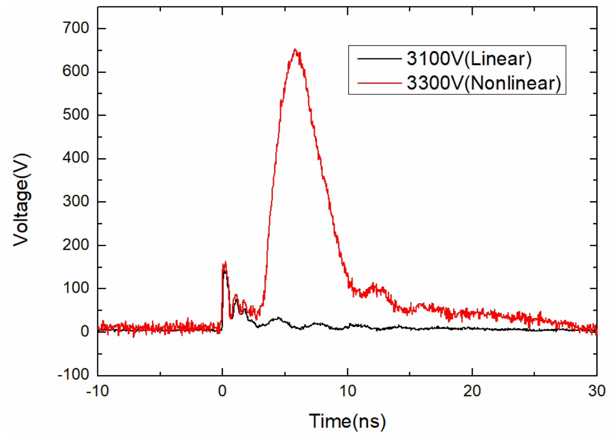

FIGURE 3. At capacitance 10-pF, the corresponding bias voltages of linear waveform and avalanche waveform are 3.1 kV and 3.3 kV, respectively.

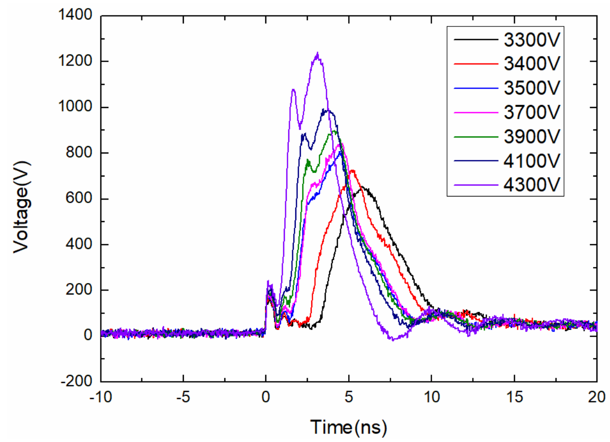

FIGURE 4. Avalanche waveforms at a different bias voltage and trigger optical energy of 103 nJ.

The trigger optical energy remains unchanged. When the bias voltage rises to 3.3 kV, the electric pulse waveform appears as two electric pulses (red line). The first electrical pulse was the same as the linear pulse at 3.1 kV. The second electrical pulse exhibited avalanche multiplication, and PCSS remained conductive even when the trigger optical energy was removed. The first electric pulse is mainly caused by photo-generated carriers, and the second electric pulse is caused by the avalanche multiplication of carriers. As can be seen in Fig. 4, the linear and avalanche pulses had a delay of 3.2 ns, and the delay decreased with the increase in the bias voltage. When the bias electric field was stronger than the threshold electric field of the avalanche mode, the GaAs PCSS operated in the avalanche mode. The photon-activated carriers formed a photon-activated charge domain (PACD) in the GaAs PCSS [10]. The PACD was composed of the excess electron regions and electron depletion regions, as shown in Fig 5(a). E_r is the electric field outside PACD, E_d is the electric field inside PACD, and E_0 is the bias electric field. The PACD created a high electric field inside the GaAs, and reduced the electron velocity inside the PACD. As a result, the excess electron region increased because the electrons behind the PACD arrived at a higher speed. Similarly,

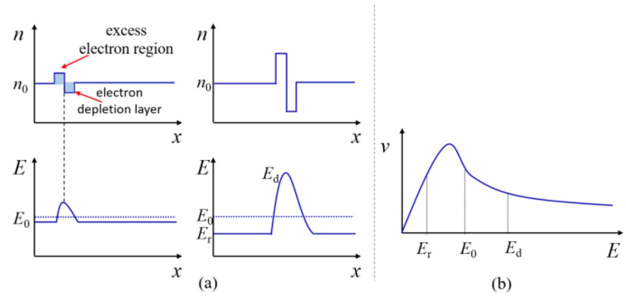

FIGURE 5. (a) Changes in the carrier concentration and electric field strength during the PACD growth. (b) Characteristic curve of the relationship between the electron drift speed and bias electric field of GaAs.

because the electrons in front of the PACD left at a higher speed [11], the electron depletion layer also increased. As the PACD growth, the electric field in this area also increased, as shown in Fig 5(a). When the electric field strength (E_d) exceeded the avalanche strength in the PACD, the avalanche phenomenon appeared. The carrier drift speed in the GaAs is 10^7cm/s, the gap in the GaAs PCSS was 0.532 mm, the PACD transit time was about 5.3 ns. According to all mentioned, the avalanche phenomenon occurred during the transit of the PACD, so the longest delay time of the avalanche should be less than 5.3 ns. In the experiment, the maximum avalanche delay time was 3.2 ns. As the bias voltage increased, the time for the maximum electric field needed to reach the avalanche field decreases. As can be seen in Fig. 4, the avalanche delay time shortened with the increase in the bias voltage. According to the results presented in Fig 5(b), the high electric field reduced the electron velocity[12]. As the bias electric field increased, the electrons behind the PACD arrived at a higher speed, and the electrons in front of the PACD left at a lower speed. So the excess electron region grows faster, the internal electric field will reach the avalanche electric field faster, and the avalanche delay time will become shorter.

B. AVALANCHE LIGHT ENERGY THRESHOLD AND MULTIPLICATION RATE

According to the previous analysis, forming a strong space charge region requires sufficient charge, that is, the device should be long enough to establish the necessary amount of space charge within the electron transit time. In theory, the formation of a PACD must meet the following condition:

$$n_0 L > \frac{\varepsilon_s v_d}{q\,|\mu_d|} \approx 10^{12} cm^{-2}. \quad (1)$$

Here, n_0 represents the carrier concentration generated by the light trigger PCSS, L denotes the gap of the PCSS, ε_s denotes the dielectric constant, μ_d denotes the negative differential mobility and q is electron charge. Therefore, the threshold trigger optical energy for GaAs PCSS to work in avalanche mode under the 800 nm laser with a diameter of 2 mm can be expressed as:

$$E_{min} = \frac{n_0 S d h c}{\lambda}, \quad (2)$$

where h represents Planck constant, c denotes the speed of light, S represents the actual absorption area and λ is the laser wavelength, d is absorption depth. The absorption depth of 800 nm is 1 μm. The diameter of the trigger light is 2 mm, because the spot area is larger than the PCSS gap, the actual absorption area is about 2 mm $\times$ 0.532 mm. Considering that the PCSS surface reflectance is 8%, the theoretical avalanche light energy threshold is about 5.87 pJ.

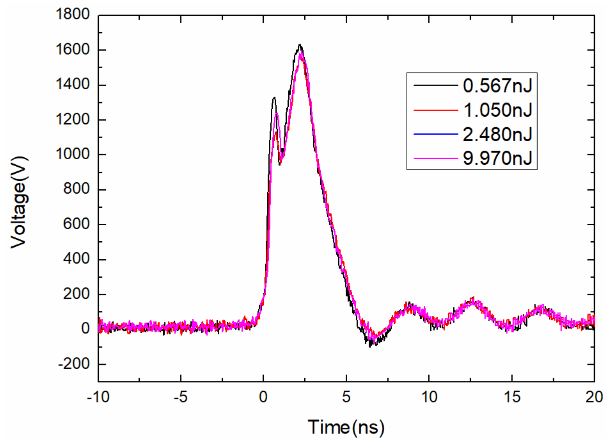

FIGURE 6. Under the bias electric field of 94 kV/cm, avalanche waveforms at a different trigger optical energy.

In the avalanche mode, trigger light only acts as an avalanche trigger. The output characteristics are mainly determined by the avalanche characteristics, and the avalanche intensity is mainly determined by the material characteristics and the electric field strength. In the experiment, in order to obtain smaller trigger optical energy and higher avalanche multiplication rate, the bias voltage was increased to 5.0 kV, and the electric field strength was higher as 94 kV/cm. First, the laser energy of 9.97 nJ was used to trigger GaAs PCSS, and then the laser energy was gradually reduce. As shown in Fig. 6, when the trigger optical energy gradually decreases from 9.97 nJ to 0.567 nJ, the GaAs PCSS can achieve avalanche operation. The minimum trigger optical energy needed for the avalanche operation was even lower than that of 100 kV at 2 nJ used by Fred J.Zutavern et. al [7].

The number of avalanche carriers (N_e) expression is:

$$N_e = \frac{S_p}{Rq} \quad (3)$$

where S_p(6.335 $\times$ 10^{-6} Vs)denoted the area of the output waveform at 0.567 nJ, q (1.6 $\times$ 10^{-19} C) is electron charge, and R was impedance of 50 Ω. The number of avalanche carriers is calculated as 7.918×10^{11}. The numbers of photons absorbed (N_0) expression is:

$$N_0 = \frac{E_p \lambda}{hc} \quad (4)$$

where E_p(0.567 $\times$ 10^{-9} J) denoted the actual absorption optical energy, λ (800 nm) is wavelength of laser, h (6.626 $\times$ 10^{-34}) is Planck constant and c (3 $\times$ 10^{-8}m/s) was velocity of light. Because the spot area is larger than

TABLE 1. The key performance parameters of GaAs PCSS.

GaAs PCSS	Bias electric field	Trigger energy	Multiplication rate	Width of pulse
This works	94 kV/cm	0.567 nJ	998	3 ns
Previous works	78 kV/cm	8 nJ	73.4	1.23 ns
Commercial devices	60 kV/cm	87 nJ	3.1	1.3 ns

the switch gap, the actual absorption is about 34.76% of the triggered light energy (0.567 nJ). The number of photons absorbed is calculated as 7.932×10^8.

The multiplication rate (M) can be used to describe the strength of the avalanche multiplication of GaAs PCSS [8]. Its expression is:

$$M = \frac{N_e}{N_0} \tag{5}$$

The multiplication rate of 998 at the lowest trigger optical energy of only 0.567 nJ was achieved. And we list a table to compare the key performance parameters of PCSS with commercial devices and previous works [3], [8], as shown in TABLE 1.

IV. CONCLUSION

In this paper, the avalanche multiplication rate of 998 of a high gain GaAs PCSS at the trigger optical energy of 0.567 nJ is demonstrated. It is shown that the linear pulse and the avalanche pulse have a delay of 3.2 ns, and that the delay decreases with the bias voltage. The mechanism of this delay is analyzed based on the PACD. The results presented in this work pave the way for study on high-gain GaAs PCSS at a low optical energy and high multiplication rate.

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CHENG MA was born in Shaanxi, China, in February 1986. He received the master's degree in physical electronics and the Ph.D. degree in microelectronics and solid electronics from the Xi'an University of Technology, Xi'an, China, in 2011 and 2015, respectively. He is currently a Lecturer with the Xi'an University of Technology. His fields of interest focus on high power pulse application and terahertz generation from GaAs antenna.

WEI SHI was born in Shaanxi, China, in November 1957. He received the master's degree in optics from Northwest University, Xi'an, China, in 1989, and the Ph.D. degree in electrical engineering from Xi'an Jiaotong University, Xi'an, in 1997.

He is currently a Professor and the Head of the Department of Applied Physics, Xi'an University of Technology. His fields of interest focus on high power pulse application, terahertz generation from GaAs antenna, and so on.

CHENGANG DONG was born in Weinan, Shaanxi, China, in 1987. He received the bachelor's degree in applied physics and the master's degree in microelectronics and solid-state electronics from the Xi'an University of Technology, Xian, China, in 2011 and 2014, respectively, where he is currently pursuing the Ph.D. degree.

His research interest includes terahertz science and technology.

LEI YANG was born in Fuping, China, in 1990. He received the master's degree in physical electronics from the Xian University of Technology, Xi'an, China, in 2016, where he is currently pursuing the Ph.D. degree. His research interest includes terahertz science and technology.

ZHIQUAN WANG was born in Shangqiu, Henan, China, in 1991. He received the bachelor's degree in physics from Huanghuai University, Zhumadian, China, in 2014, and the master's degree in physical electronics from the Xi'an University of Technology, Xi'an, China, where he is currently pursuing the Ph.D. degree.

His research interest includes terahertz science and technology.

MEILIN WU was born in Xianyang, Shaanxi, China, in 1992. She received the master's degree in physics from the Xi'an University of Technology, Xian, China, in 2018, where she is currently pursuing the Ph.D. degree.

Her research interest includes ultrafast photoelectron and technology.

HAIQING WANG was born in Baoji, Shaanxi, China, in 1988. She received the bachelor's degree in physics from the Baoji University of Arts and Sciences, in 2012, and the master's degree in optics from Northwestern University, Xian, China, in 2015. She is currently pursuing the Ph.D. degree with the Xi'an University of Technology.

Her research interest includes terahertz science and technology.

CHUANHUI ZHONG was born in Shangluo, Shaanxi, China, in 1994. He received the bachelor's degree in applied physics from the Xi'an University of Technology, where he is currently pursuing the M.S. degree in physics.

His research interest includes high power pulse application.

CHAOFAN LI was born in Shaanxi, China, in 1998. He received the bachelor's degree in engineering from the Changsha University of Technology, in 2014. He is currently pursuing the M.S. degree in physics with the Xi'an University of Technology.

His research interest includes terahertz science and technology.