Light controlled prebreakdown characteristics of a semi-insulating GaAs photoconductive switch*

Ma Xiangrong(马湘蓉)[1,†], Shi Wei(施卫)[2], Ji Weili(纪卫莉)[2], and Xue Hong(薛红)[2]

[1]Institute of Physics and Electronic Engineering, Xinjiang Normal University, Urumqi 830054, China
[2]Department of Applied Physics, Xi'an University of Technology, Xi'an 710048, China

Abstract: A 4 mm gap semi-insulating (SI) GaAs photoconductive switch (PCSS) was triggered by a pulse laser with a wavelength of 1064 nm and a pulse energy of 0.5 mJ. In the experiment, when the bias field was 4 kV, the switch did not induce self-maintained discharge but worked in nonlinear (lock-on) mode. The phenomenon is analyzed as follows: an exciton effect contributes to photoconduction in the generation and dissociation of excitons. Collision ionization, avalanche multiplication and the exciton effect can supply carrier concentration and energy when an outside light source was removed. Under the combined influence of these factors, the SI-GaAs PCSS develops into self-maintained discharge rather than just in the light-controlled prebreakdown status. The characteristics of the filament affect the degree of damage to the switch.

Key words: light controlled prebreakdown; photo activated charge domain; self-maintained discharge; exciton effect

DOI: 10.1088/1674-4926/32/12/124006 **PACC:** 7220H

1. Introduction

A photoconductive semiconductor switch has many advantages, such as high power, fast switching speed, small parasitic capacitance, high repetition frequency and absence of jitter. Therefore, it shows broad prospective applications in the fields of superspeed electronics, high power electrical pulse generation, fine-synchronization control and terahertz technology[1−4]. In 1982[5], the linear photoconduction working mode was investigated in semi-insulating semiconductors. Willamson discovered the high gain mode (which is also called lock-on or nonlinear mode) in a GaAs chip. A number of subsequent experimental studies indicated that the nonlinear mode of SI-GaAs photoconductive switch (PCSS) can be divided into three phases: triggering (transition process), sustaining (lock-on or steady-state), and recovery. Its typical characteristics are as follows: the electric field threshold and the optical-energy threshold are required. A time delay lies between the trigger optical impulse and the electrical pulse. The current risetime is not limited by the intensity of the optical pulse, conduction capacities are not limited by the photon flux and conduction periods are not limited by the duration of the optical pulse. The observed switch closure time is much shorter than the time for carriers moving at the saturated drift velocity to cross the switch. A stable lock-on electric field exists at the maintaining stage and a filament occurs along with light[6, 7]. These behaviors also indicate that new carriers must be generated during the breakdown in SI-GaAs PCSS.

Photo-activated charge domain (PACD) theories[8−10] can be used to explain some characteristics of the nonlinear mode. The high-field domain in the semiconductor must comply with $nL \geqslant 10^{12}$ cm^{-2} condition, where n is the electron concentration and L is the length of the device. The material in a switch chip is made of negative differential conductance (NDC) for photoconductive switches and the carrier concentration is too low to meet the requirement of domain formation. However, under the condition of a high trigger light, the concentration of the photo-generated carriers can be up to 10^{19} cm^{-3} and its injection can enable the domain to form. The existence of the PACD is proved by a simulated result[11].

Many aspects of a high gain photoconductive switch are remarkably similar to streamer formation and electrical breakdown in gases. Gas streamers bridge the interelectrode gap in a time shorter than the drift time. Once the conduction channel is ionized, the current is effectively circuit limited. In addition, the filament channels observed in high gain photoconduction[6] resemble arcs in gas[12−15]. Due to this great similarity, the applicability of gaseous ionization mechanisms, specifically a streamer mechanism, to high gain photoconduction in bulk semiconductor devices has been investigated[16]. A special breakdown mode of a SI-GaAs photoconductive switch occurs in the nonlinear operation, some breakdown phenomena, such as collision ionization, avalanche multiplication, radiation recombination and filaments, which normally cause self-maintained discharge in a switch, will appear. However, the breakdown does not develop into self-maintained discharge, but in the maintaining stage of lock-on. The maintaining voltage is independent of the bias voltage, but is related to external environment and the properties of switch chip material. We define this unique breakdown phenomenon as light controlled prebreakdown[17], and more detail has been published in Refs. [18, 19], yet those explanations were not perfect. Light controlled prebreakdown characteristics of SI-GaAs PCSS are

* Project supported by the National Natural Science Foundation of China (Nos. 50837005, 10876026) and the State Key Laboratory of Electrical Insulation for Power Equipment (No. EIPE09203).
† Corresponding author. Email: mxr310@163.com
Received 20 April 2011, revised manuscript received 1 August 2011

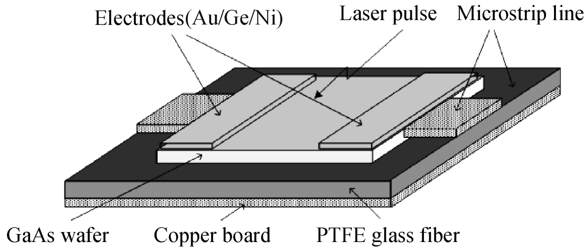

Fig. 1. Schematic diagram of the lateral PCSS.

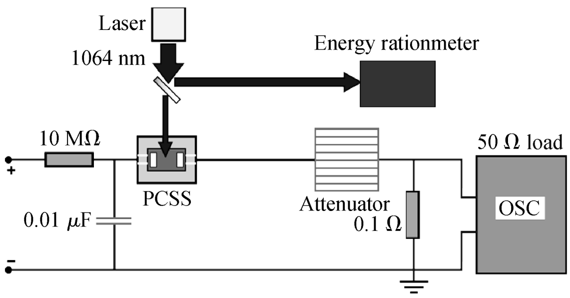

Fig. 2. Diagram of the electrical circuit for testing PCSS.

discussed in this paper in order to further research the working principle in nonlinear mode, and have the significance in improving performance and extend the life of a switch.

2. Experimental setup and results

In our experiment, the photoconductive material used for the PCSS was SI-GaAs with a dopant density of 1.5×10^7 cm^{-3}. The resistivity in total darkness was larger than 5×10^7 Ω·cm and the mobility was larger than 5500 cm^2/(V·s). The overall size of the GaAs wafer was 8 mm wide × 10 mm long × 0.6 mm thick. Using the electron beam evaporation technique, a AuGeNi alloy electrode forms ohmic contact by using a standard mixture of Ni/Au–Ge/Au for the metallization at 450 ℃ and the thickness is 700 nm. The electrode dimension is 8×3 mm^2 and the gap between the two electrodes was 4 mm. The geometry of the PCSS is shown in Fig. 1. The GaAs chip was placed on the copper clad board with a transmission line and the transmission line was connected with two coaxial connectors. The experimental setup is shown in Fig. 2, where a high-voltage power supply charged capacitor (0.01 μF) and a 10 MΩ resistor were used to limit the current. The capacitor provided a bias voltage to the PCSS. The Nd:YAG nanosecond laser emitted 5 ns laser pulses with wavelength of 1064 nm, energy of 0.5 mJ. An energy meter KSDP2210-CAS-1 was used to measure the laser energy. In addition, a Lecory-8600A oscilloscope (6G) was used to detect the voltage on the 0.1 Ω sampling resistors after being attenuated by a 60 dB coaxial attenuator. When the bias voltage was 4.0 kV, corresponding to the bias electric field of 6.5 kV/cm, a nonlinear current waveform of the PCSS was observed. The nonlinear waveforms superposed 50 times are shown in Fig. 3. The switch samples triggered continuous 50 times and 1500 times appeared at 4 kV bias voltage, as shown in Figs. 4 and 5, and damage trace of filament in switch samples was clearly shown in Fig. 5. These phenomena show that the material of switch chip had not been damaged by many triggering, and switch can still be used not until triggering reached to an extent.

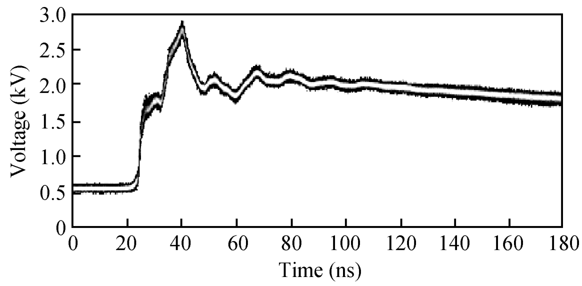

Fig. 3. Output electrical waveform of switch triggered 50 times.

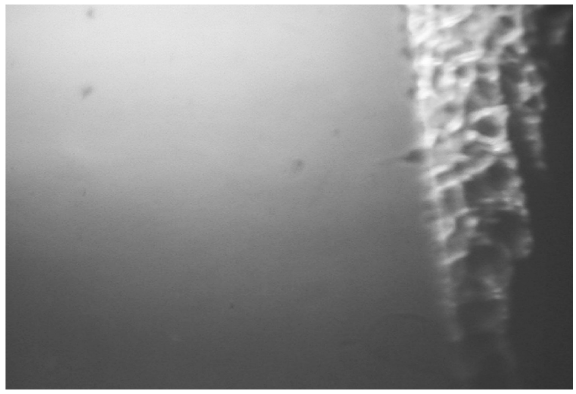

Fig. 4. Switch sample triggered 50 times.

Fig. 5. Damage trace of filament in switch sample triggered 1500 times.

3. Discussion

The process of non-self-maintained discharge transforming into self-maintained discharge occurs in gas discharge. Lebo and Meek think that self-maintained discharge can be induced only if there is enough space photoionization, secondary electrons generate without cathode action and the breakdown voltage does not depend on the cathode material. When an external electric field is correspondingly weakened, a lot of electrons enter into anode after the initial electron avalanche went through whole electrode gap, also positive

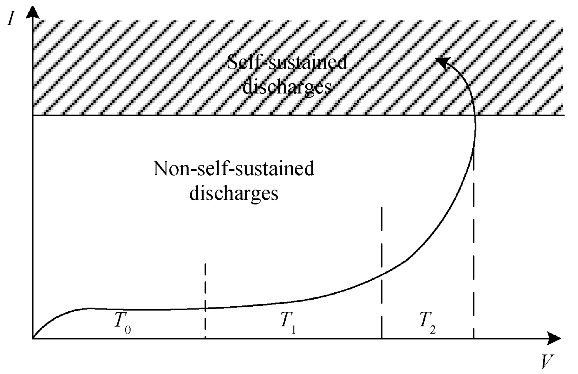

Fig. 6. Current–voltage characteristic in gas prebreakdown zone.

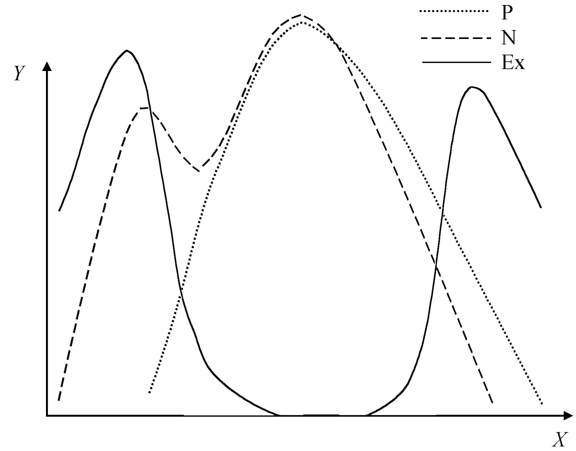

Fig. 7. Distribution diagram of electrons, holes and built-in electric fields[11].

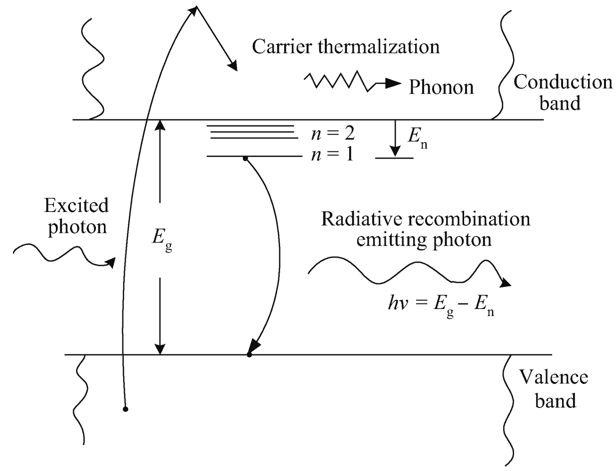

Fig. 8. Process of exciton formation and radiative recombination by photoactivated[20].

ions are gradually neutralized and lose their charge. Then the electron avalanches vanish and gas discharge can not change into self-maintained discharge. When electron avalanches go through the whole electrode gap and the external electric field reaches the breakdown voltage, the concentration of space charge rapidly increases and a streamer starts to form ahead of an electron avalanche. Many photons constantly radiate from the tip of streamer to its surroundings, and secondary electron avalanches occur through space photoionization. Secondary electrons are constantly attracted to the streamer tip, thus streamer channel is extended and pushed forward to the cathode rapidly. The whole electrode gap is connected by conducting positive and negative particles. When the streamer expands to the cathode, current jump occurs, a new current pulse will be developed and then breakdown forms. Formation and development of the streamer is taken as the self-maintained discharge stage. Current–voltage characteristic of gas prebreakdown in whole gap is shown in Fig. 6. Current slowly rises in T_0 with the applied initial voltage, then reaches saturation; electrons obtain enough energy with increasing voltage in T_1; the speed of the current rise becomes very fast due to space photoionization in the T_2. The T_0, T_1 and T_2 period belong to non self-maintained discharge.

The sufficient concentrations of the photo-generated carrier and the bias electric field are necessary conditions to form the PACD. When the bias field surpasses its threshold, PACD will generate and grow, and the initial electron concentration in domain is determined by the laser energy. Photoconductive switch chip material can generates 10^3–10^5 electron–hole pair after absorbing a photon in nonlinear mode. The electric field between PACD and photo-generated hole is opposite to the bias electric field, which screens the bias electric field, so electric field of the domain tip is enhanced and the electron concentration in the domain tip is higher than in other regions. If the bias electric field exceeds the turn-on electric field of NDC, the photo-genetated electron space accumulation can be formed during the drift process and its concentration gradient rises exponentially, with the results of the exhaustion of rear electrons. Figure 7 is the distribution diagram of electrons, holes and built-in electric fields at the formation stage of the PACD. With the growth of the PACD, the electric field in domain increases and then exceeds the electric field with a negative resistance effect. X-axis forward direction is the direction of the bias electric field. When the PACD is steady-state with its growth coming to a halt, the PACD begins to drift toward the anode with a stable electron concentration and finally becomes absorbed by the anode to form the output current[11].

Gas streamer models make the assumption that the optical generation of carriers occurs ahead of the impact ionization zone. Since the streamer model hinges on the availability of appropriate photons, it is necessary to explore the conditions under which such photon activity can occur in PACD. GaAs materials having a direct band gap structure are much more likely to support domain ionization events since optical emissions from band-to-band recombination and exciation are critical to PACD process. Some of the recombination radiation produced in domain immediately behind the tip is absorbed ahead of the domain to produce seed carriers that avalanche in the high field, some photons can be absorbed into the head of domain where the high electric field multiplies the photocharge by impact ionization.

For GaAs material, recombination lifetime of band–band is $\tau = 10^{-7}$ s, but that of exciton is $\tau = 10^{-9}$ s. The time of electron and hole forming exciton is far less than the lifetime of band–band transition radiation recombination, so luminescence caused by exciton recombination is the main feature of intrinsic radiation recombination. The physical process can be shown visually in Fig. 8[20]. When laser trigger GaAs chip, firstly carrier relaxes to conduction band border by emitting a photon and phonon to form free exciton. However electrons of valence band in GaAs absorb a certain photon energy and release from valence band, the excited valence band electrons still do not have enough energy to transit to conduction band and become free electron, but they will form free excitons under the action of a hole Coulomb field. Excitons can move freely in semiconductors and participate in radiation recombination to emit photon finally. Moreover, phonon will participate in free exciton radiation recombination[21−23] and energy can be lost in the process. Exciton shows electrically neutral, thus current cannot form, but it can transmit energy by moving and energy releases from recombination.

The formation required optical energy of excition is:

$$h\nu = E_{\rm g} - E_n + \frac{\hbar k^2}{2(m_{\rm e}^2 + m_{\rm p}^2)}, \quad (1)$$

where $E_{\rm g}$ is band gap of GaAs and $E_{\rm n}$ is excition energy level.

The excition energy level[24] is defined by

$$E_n = -\frac{\mu q^4}{8\varepsilon^2 h^2 n^2}, \quad (2)$$

where ε is dielectric constant, q is the electric quantity of electron, n is the number of energy level, μ is the reduced mass of electron and hole ($\mu = m_{\rm p}^* m_{\rm e}^*/(m_{\rm p}^* + m_{\rm e}^*)$), and $m_{\rm e}^*$, $m_{\rm p}^*$ are electron and hole effective mass respectively.

In Eq. (2), there are infinity energy levels in exciton, ground state level of exciton is $E_1 = 4.56$ meV for $n = 1$; energy level is nearly continuous for $n > 2$; it is $E_\infty = 0$ for $n = \infty$, which is the same as the energy level of conduction band bottom, it shows that electron–hole completely move from bondage each other, electrons enter into conduction band, but holes still stay put. So exciton effect can contribute to photoconduction. The lowest single photon energy of absorption for exciton forming is 1.4254 eV, namely long wavelength edge of absorption is 869.8 nm.

An exciton is electron–hole pair due to their mutual Coulomb interaction and the interaction is relatively weak, so exciton level is close to bottom of conduction band. It shows that exciton absorption is most likely to happen when optical wavelength and intrinsic absorption wavelength in GaAs are extremely similar. Because light wavelength of direct band gap recombination in GaAs is 875±10 nm, exciton easily dissociates when it absorbs photons by electron–hole recombination generated in outside domain. Exciton overcome Coulomb binding force and the process of electron transition to conduction band finished. The interactions between PACD and exciton are shown in Fig. 9. Electron of high concentration and energy ahead of the domain drift to anode with 5×10^8 cm/s[25], Electric field of domain tip is more and more strongly with domain approaching to anode, electron density of domain tip is more highly and collision ionization of electron is more intensely, exciton of domain tip is shielded. When strength of avalanche multiplication is reached, equivalent to an incident photon excite many times electron–hole to participate in conduction, this is high gain photoconduction. Also exciton can absorb heat,

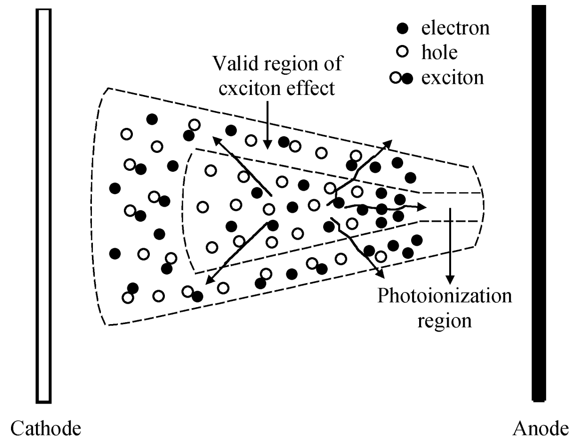

Fig. 9. Schematic diagram interactions between PACD and exciton.

which domain emits in the drifting process, and heat dissociation will occur. Many electrons by exciton dissociation converge domain head from different directions around domain at the same time, the electric field in domain tip is strengthened. Exciton effect contributes to photoconduction with the aid of generation and dissociate. The interaction between radiation recombination of high concentration carrier in PACD, exciton effect and avalanche multiplication supply exactly enough carrier due to extinction of outside trigger light source induce decrease of carrier concentration.

The equilibration time between the L and Γ valleys are in near 1 ps. GaAs is a direct gap material, but it becomes pseudo-indirect under the influence of a high electric field. Hence inhibiting band-to-band recombination and decreasing radiative emissions, so the optical generation rate in the avalanche zone will be decreased. Near the domain tip fields will be far larger; hence the majority of electrons in the impact ionization region at the tip of the domain will lie in the L valley. This extends the carriers lifetime in proportion to the fraction of electrons transferred to the L valley. Radiation recombination reaches the optimum efficiency (this is saturation point). Also, recombination coefficient of carrier will change with temperature, the higher the temperature was and the lower the recombination coefficient was. The stability of exciton effect depends on temperature, field, carrier concentration etc, exciton effect will quenched at a certain temperature; Coulomb of between electron and hole will be shielded and exciton effect has little or no use. When PACD drifting to anode reaches to a critical level, owing to inhibition of radiation recombination and shielding effect of exciton effect in certain conditions, the numbers and lifetime of carrier have reached a saturation point, corresponding to SI-GaAs PCSS in lock-on state. Free electron and hole are generated by the interactions between exciton and PACD, transmission and dissociation of exciton; they provide an essential condition for photoconduction of exciton effect.

The typical pulse waveform of the SI-GaAs PCSS in lock-on mode is shown in Fig. 3. Compared with the curves in Fig. 6, this indicates that it would experience a pulse again when gas discharge enters into self-maintained discharge. However, the electric field outside domain is inferior to the minimum threshold while the PCSS began to nucleate and grow. For impact ionization and exciton effect, it will produce fresh electron–hole pair outside domain zone. The fresh electrons precisely supply the insufficiency of carriers when pulse removed. External source has been taken away, initial electron and fresh electron enter into anode together and disappear. Because of radiation recombination, the exciton effect and because the external circuit also constantly consumes and dissipates energy, the electric field in the switch is not enough to provide lock-on electric field. A new domain can not produce and grow because the existing conditions of domain had been destructed. However, lifetime of photon-generated carriers is a certain, concentration of carriers constantly decrease until gradually disappeared after a long period of lock-on, due to unbalanced carriers vanish, the light controlled prebreakdown process destroy, then PCSS turns off and enters into the high impedance state. After the PACD is rapidly absorbed by anode, the hole still stays into electrode gap and slowly drifts to cathode. Field is reduced because lots of hole accumulates nearby anode. Streamer cannot form, which does not make self-maintained discharge development. Owing to the non-uniform electric field in GaAs switch, when non self-maintained discharge transforms into self-maintained, local region of high field possibly occurs self-maintained discharge, however field of broad external domain is so low, that the condition of self-maintained discharge can not be satisfied.

Initial electron in switch chip generated by laser is seed source on the condition of a certain bias voltage and triggered light energy. Carrier concentration which is provided with light injection and negative resistance effect make the field in domain increase to the required electrical field of avalanche collision ionization rapidly. Although many fresh electrons are produced by avalanche multiplication, these electrons are triggered by laser ultimately during the process of domain formation. Initial electron and fresh electron enter anode and vanish associated with domain, so the process of avalanche collision ionization can not make discharge process transfer to self-maintain stage. For above, PCSS does not have the inducing condition of self-maintained discharge, but in the non self-maintained discharge. It is discovered in Fig. 4 that filaments similar to breakdown have not damage the material in switch chip by many triggering and thus a filament having breakdown can not develop into self-maintained discharge. The material defect in chip will have certain effect on characteristics of filament. Microdefect absorption will play a dominant role after many repeat laser triggering. Defect absorption will form local high temperature. When local high temperature reaches a certain degree, it will lead to change of material structure and property that will further enlarge defect. But above-mentioned influences do not create macroscopic damage, they only cause development of inner microcosmic defect in material. The microcosmic defects have low damage degree in initial time and have a little effect on material structure and property. If each defect develops and accumulates, it will increase absorption of following laser pulse and a greater microcosmic defect will occur. Owing to the fact that characteristics of microdefect will seriously influence damage degree of filament, once laser trigger reaches to a certain limit, it will result in the essential and irreparable damages in the chip when accumulated microdefect reached at a definite scale. Damaged trace of filament can be clearly observed in Fig. 5 by repeatedly laser triggering, working performance of the switch significantly decreased. GaAs PCSS shows non-balance thermal conduction behavior of thermal relaxation, namely transient thermal effect of carrier temperature more than lattice temperature control the damage characteristic of filament and affect the damage degree of GaAs PCSS in the light controlled prebreakdown process[26].

4. Conclusion

Many aspects of SI-GaAs PCSS are remarkably similar to gas discharge. The key distinction is that gas discharge occurs non self-maintained transforming into self-maintained discharge process. Some breakdown phenomenon in PACD is similar to self-maintained action of gas discharge, such as, collision ionization, avalanche multiplication, radiation recombination, filament, which normally causes self-maintained discharge in switch. However, the breakdown does not develop into self-maintained discharge, but is in the maintaining stage of lock-on. Excitons continually produce and dissociate by radiation recombination on interaction between exciton effect and domain, collision ionization and avalanche multiplication all generate fresh carrier. The required carrier concentration is supplied and maintaining voltage is controlled in the lock-on stage. Radiation recombination, exciton effect and external circuit continually consume and dissipate energy; electric field is insufficient to provide lock-on electric field. Carrier concentration continually decreases until to gradually disappear after long time lock-on. SI-GaAs PCSS is only in the non self-maintained discharge and has non-balance transient thermal effect characteristic in the light controlled prebreakdown process.

References

[1] Shi Wei, Dai Huiying, Sun Xiaowei. Photon-activated charge domain in high-gain photoconductive switches. Chin Opt Lett, 2003, 1(9): 553

[2] Shi W, Tian L. Mechanism analysis of periodicity and weaking surge of GaAs photoconductive semiconductor switches. Appl Phys Lett, 2006, 89(20): 202103

[3] Shi Wei, Jia Wanli, Ji Weili. Ultra-wideband electromagnetic radiation from GaAs photoconductive switches. Chinese Journal of Semiconductors, 2005, 26(1): 11

[4] Shi Wei, Jia Wanli, Hou Lei, et al. Terahertz radiation from large aperture bulk semi-insulating GaAs photoconductive dipole antenna. Chin Phys Lett, 2004, 21:1842

[5] Williamson S, Albrecht G F, Mourou M. Laser triggered Cr: GaAs HV sparkgap with high sensitivity. Rev Sci Inst, 1982, 53(6): 867

[6] Loubriel G M, Zutavern F J, O'Malley M W, et al. High gain GaAs switches for impulse sources: measurement of the speed of current filaments. International Power Modulator Symposium, Costa Mesa, CA, USA, June 1994

[7] Loubriel G M, Zutavern F J, Hjalmarson H P, et al. Measurement of the velocity of current filaments in optically triggered high gain GaAs switches. Appl Phys Lett, 1994, 64(6): 3323

[8] Shi Wei, Zhang Xiangbing, Li Qi, et al. High gain lateral semi-insulating GaAs photoconductive switch triggered by 1064 nm laser pulses. Chin Phys Lett, 2002, 19(3): 351

[9] Shi Wei. Optically activated charge domain model for high-gain GaAs photoconductive switches. Chinese Journal of Semiconductors, 2001, 22(12): 1481

[10] Shi Wei, Tian Liqiang, Liu Zheng, et al. 30 kV and 3 kA semi-

insulating GaAs photoconductive semiconductor switch. Appl Phys Lett, 2008, 92(4): 043511

[11] Shi Wei, Qu Guanghui, Xu Ming, et al. Current limiting effects of photoactivated charge domain in semi-insulating GaAs photoconductive switch. Appl Phys Lett, 2009, 94: 072110

[12] Loubriel G M, Zutavern F J, Hjalmarson H P. Closing photoconductive semiconductor switches. Proceedings of the 7th IEEE Pulsed Power Conference, Monterey, CA, 1989: 365

[13] Brinkmann R P. Nonlinear behavior of optically activated switches at high electrical fields. Proceedings of the 20th IEEE Power Modulator Symposium, Myrtle Beach SC, 1992: 316

[14] Loubriel G M, O'Malley M W, Zutavern F J. Toward pulsed power uses for photoconductive semiconductor switches. Closing switches Proceedings of the 6th IEEE International Pulsed Power Conference, 1987: 145

[15] Zutavern F J, Loubriel G M, O'Malley M W, et al. Characteristics of current filamentation in high gain photoconductive semiconductor switching. International Power Modulator Symposium, Myrtle Beach, SC, USA, Jun 1992: 305

[16] D'yakonov M I, Kachorovskii V Y. Theory of streamer discharge in semiconductor. Sov Phys JETP, 1988, 67(5): 1049

[17] Shi Wei, Liang Zhenxian. Optically activated charge domain phenomena in high gain ultra fast high voltage GaAs photoconductive switches. Chinese Journal of Semiconductors, 1999, 20(1): 53

[18] Shi Wei. Optically activated charge domain model for high-gain GaAs photoconductive switches. Chinese Journal of Semiconductors, 2001, 22 (12): 1481

[19] Shi Wei, Liang Zhenxian. Analysis and characteristic of high gain ultrafast GaAs photoconductive switches. ACTA Electronica Sinica, 2000, 28(2): 20

[20] Thomas D G, Hopfield J J. Excitation and Absorption edge of ZnO. J Appl Phys, 1961, 32(10): 2282

[21] Gross E, Permogor S, Razbirin B. Free exciton motion in crystals and exciton–phonon interaction. Journal of Physics and Chemistry of Solids, 1966, 27(10): 1647

[22] Msalle M E, Wolfe J P. Phonon production in weakly photoexcited semiconductors: quasidiffusion in Ge, GaAs and Si. Phys Rev B, 1997, 56(15): 9557

[23] Sermage B, Voos M. Reabsorption of excitonic luminescence in direct band-gap semiconductors. Phys Rev B, 1977, 15(8): 3935

[24] Gross E, Permogor S, Razbirin B. Free exciton motion in crystals and exciton–phonon interaction. Journal of Physics and Chemistry of Solids, 1966, 27(10): 1647

[25] Loubriel G M, Zutavern F J, Hjalmarson H P, et al. Measurement of the velocity of current filaments in optically triggered high gain GaAs switches. Appl Phys Lett, 1994, 64(24): 3323

[26] Shi Wei, Ma Xiangrong, Xue Hong. Transient thermal effect of semi-insulating GaAs photoconductive switch. Acta Phys Sin, 2010, 59(8): 5700