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The Role of the Photo-Generated Carrier in Surface Flashover of the GaAs Photoconductive Semiconductor Switch

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ABSTRACT The development of Gallium arsenide photoconductive semiconductor switch has been hampered by the surface flashover. The surface flashover threshold with the laser excitation is far lower than the one without the laser excitation. In this paper, the phenomena of surface flashover, including the infrared video, flashover spectrum, and the voltage waveforms are presented to research their work mechanism. The dynamic development process of surface flashover is divided into four typical states. Based on the 1-D time domain finite element method, the role of the photo-generated carrier in the surface flashover is analyzed. Our results suggest that the photo-activated charge domain (PACD) will enhance the local electric field and result in the surface flashover occurrence between the electrodes and semiconductors. So the atoms of GaAs semiconductors and electrodes are involved in the surface flashover. According to the PACD theory, the experimental phenomena can be explained reasonably.

INDEX TERMS Photoconducting devices, surface discharges, Gallium arsenide, electric breakdown.

I. INTRODUCTION

The Gallium arsenide photoconductive semiconductor switch (GaAs PCSS) is being widely used in the field of the sub-nanosecond rise time and high-voltage pulse generator system [1]–[4]. The GaAs PCSS have many advantages over others conventional switches, such as jitter-free, high repetition rate, high dark resistance, low parasitical capacitance and inductance, and so on [5], [6]. At present, it is possible to use the nonlinear mode of GaAs PCSS for meeting the need of miniaturization and integration [7], [8]. But the surface flashover will create destructive surface breakdown and reduce the device lifetime, which restricts the maximum stand-off voltage and hampers the development of the GaAs PCSS in the nonlinear mode severely [9]. The intrinsic breakdown field of GaAs reaches up to 250kV/cm [10], while the surface flashover may occur in a low electric field (20kV/cm). The electric field of surface flashover is an order of magnitude lower than the intrinsic breakdown field. Many surface flashover theories of insulators have been put forward to explain it, such as secondary electron emission [11], surface polarization relaxation [12], electron-stimulated desorption [13], and so on. However, the previous models about insulators can not account well for the surface flashover in semiconductors. The surface flashover mechanisms of semiconductors are fundamentally different from that of insulators. The electrons movement in the insulators may be ignored, whereas the carriers' movement inside the semiconductor plays an important role in the surface flashover. The thermal effect of the intrinsic carrier has been researched in the high voltage [14], [15]. However, when the GaAs PCSS is illuminated by laser, a large number of carriers will be generated in the GaAs PCSS. These photo-generated carriers not only result in the joule heat, but also change the electric-field distribution. The surface flashover of GaAs PCSS is a complicated process which is related to multiple elements, so the whole physical process of surface flashover is still need to be researched. In this paper, the surface flashover of GaAs PCSS is investigated on the basis of the high-speed infrared thermal imager, fiber optical spectrometer and digital storage oscilloscope. Meanwhile, the infrared

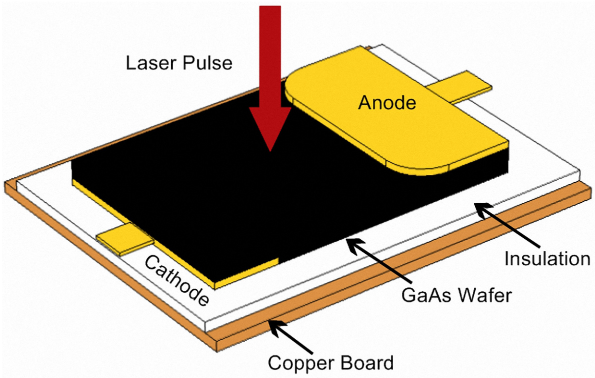

FIGURE 1. The schematic diagram of a GaAs PCSS with the an opposed structure.

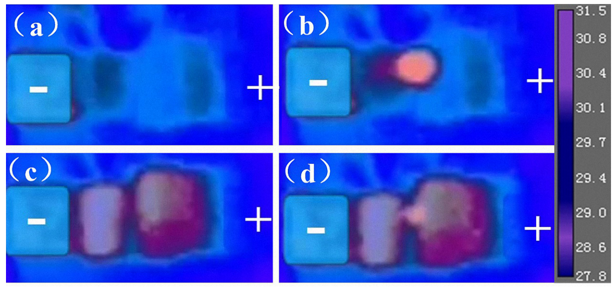

FIGURE 2. The four typical states in the flashover process.

video, flashover spectrum and the voltage waveforms are recorded to analyze flashover comprehensively.

II. EXPERIMENTAL SETUP

In our experiments, the GaAs PCSS with an opposed structure is used, as is shown in Figure 1. The semi-insulation GaAs is the core component. Its resistivity is larger than $5 \times 10^7\ \Omega \cdot \mathrm{cm}$, and the electron mobility is greater than $5000cm^2/(V{\cdot}s)$. The electrodes with ohmic contacts are made of Au/Ge/Ni alloy. The distance between the two electrodes is 0.7mm. The 900nm Si_3N_4, which is coated on the surface of the GaAs PCSS, is used for the insulation protection. Finally, the whole switch is placed in air at room temperature. The laser with a wavelength of 1053nm, a pulse width of 1ns and an optical energy of 2.2mJ is used for triggering. When the switch is illuminated, the output pulse is attenuated by an attenuator (60dB), and then measured by a digital storage oscilloscope with the bandwidth of 1GHz. Meanwhile, infrared thermal imager (FLIR A325sc) and fiber optic spectrometer (Ocean Optics HR4000, 200∼1100nm) are used for the observation of the surface flashover.

III. RESULTS AND DISCUSSION

When the bias voltage is 1400V (the electric field is only 20kV/cm), there is no abnormal radiation on the surface of switch. After the switch was illuminated by laser, the flashover occurs on the surface of switch. We can see bright light and hear clear sounds. Obviously, the electric field threshold of surface flashover is lowered under the laser excitation. But in others experiments, the bias electric field can be reached 30kV/cm without the illumination [7]. So the surface flashover threshold is lower about 10kV/cm at least. In others words, the surface flashover threshold with the laser excitation is far lower than the one without the laser excitation in the GaAs PCSS, which must be closely related to the movement of photo-generated carriers.

In our experiments, the surface flashover was recorded simultaneously by the high-speed infrared thermal imager, fiber optical spectrometer and digital storage oscilloscope. As shown in Figure 2, these before-and-after figures of the flashover occurrence present four typical states. In figure 2(a), the switch has not been yet triggered. The temperature distribution is uniform on the surface of switch. The figure 2(b) shows the initial state of the flashover occurrence. The flashover begins in the anode, and then quickly goes to cathode. Subsequently, two local flashovers occur in the anode and cathode respectively, which are shown in Figure 2(c). In the fourth state, a micro flashover links to the two local flashovers together and runs through the whole switch, as seen in Figure 2(d). In our experiments, the fourth state occurs twice in all. Figure 2(d) is used to describe one of the run-through flashovers, which will result in a sharp rise of the output pulse. As shown in Figure 3, there are two sharp rises in the output pulse. There is a one-to-one correspondence between the fourth state and the sharp rise. As mentioned previously, in our experiments we can find that the surface flashover of GaAs PCSS firstly occurs in the anode and there are two typical flashovers: the local flashover and the run-through flashover.

The flashover spectrum is shown in the Figure 4. The horizontal ordinate represents the wavelength, and the vertical coordinate represents relative intensity. The main peak of flashover spectrum is 545.4nm. From the spectrums, we can see that the flashover is a very complicated process, and many atoms are involved in this process. Compared with the spectrum of air ionization [16], it appears four different wavelengths: 545.4nm (As), 593.5nm (Ga), 618.3nm (Ni), 890nm. The atoms of GaAs semiconductors and electrodes are involved in the surface flashover. 890nm is the spectrum of direct radiation recombination in the GaAs PCSS. Although the GaAs band gap is 1.42eV (876nm), the band gap will become narrow in the high electric field due to F-K effect [17]. So the spectrum of direct radiation recombination has the trend of shift to long wavelength direction. After our calculation, the wavelength variation is 13.9nm [18]. In other words, the wavelength of direct recombination radiation will be changed from 876nm to 889.9nm, which is identical with the observed results from experiments.

In the optically-activated semiconductors devices, the movements of the photo-generated carriers cannot be ignored. As well known, the GaAs has a characteristic of negative differential conductance (NDC) with the bias electric field increasing. Under certain conditions of optical and

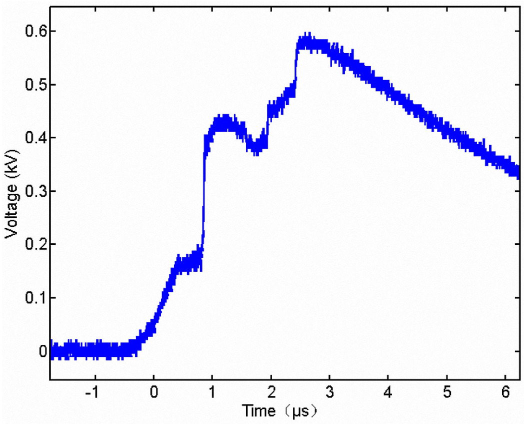

FIGURE 3. The output waveform of the surface flashover.

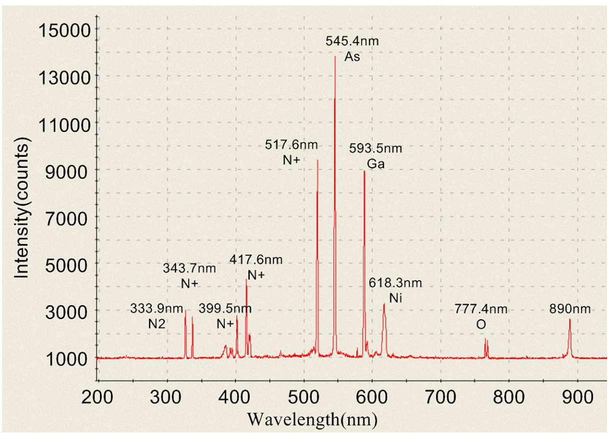

FIGURE 4. The spectrum of the surface flashover.

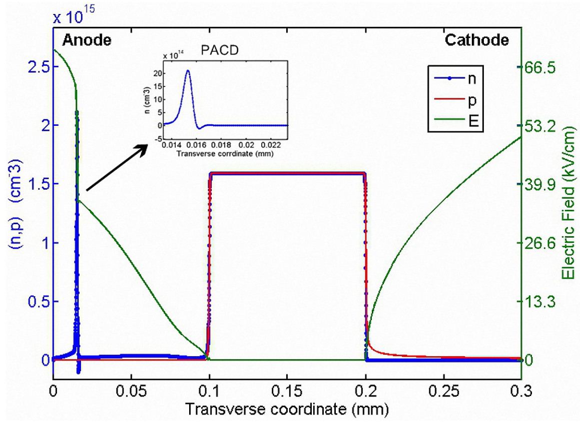

FIGURE 5. The distribution of the electric field and carrier density at 2.47ns in our simulation.

electrical thresholds, the photo-activated charge domain will be formed in the GaAs PCSS, which make the local electric field strengthen. One-dimensional model is established on the basis of the semiconductors device equations and NDC equation that are computed by a time domain finite element method [19], [20]. In the model, the length is 0.3mm, the bias electric field is 20kV/cm, and the photo-generated carriers are orderly activated between 0.1-0.2mm. We compute from 0ns to 10ns with the step of 0.01ns.

As seen in the Figure 5, the distribution of carrier density and the electric field are shown at 2.47ns. After triggering, a mass of electrons and holes are generated in the illumination region. The photo-electrons are driven to the anode. Because of the NDC effect, the PACD with high carrier density are formed in the anode nearby. The domain width is about 2μm, which gets the same conclusions as the previous reports [21]–[23]. Whereas many photo-generated carriers will be stuck in the illumination region due to the electric field shielding of the PACD [24]. Based on above discussions, our simulation is in agreement with the actual situation.

It is the critical factor that a strong enough electric field in the surface flashover. In our simulation, we found that the PACD can strengthen the local electric field. From Figure 5, we can see that the electric field reaches up to 66.5kV/cm in the anode, which is much higher than the bias electric field (20kV/cm). Thus, the surface flashovers happen between the anode and semiconductor firstly, while the electric field also reaches up to 53kV/cm in the cathode. Because of the development of the anode flashover, the flashover will also occur in the cathode. Finally, two local flashovers occur in the anode and cathode respectively. Meanwhile the electrodes materials and semiconductor are involved in the local flashover. The strengthened local electric field is the main reason for electrodes degradation. In the middle of switch, there is a neutral plasma region consisted of electrons and holes. When the two local flashovers occur on the switch surface, the PACD will be quenched inside the semiconductor switch [9]. Furthermore, the electric field will be decreased nearby the electrodes and strengthened in the middle of switch. So the run-through flashover will occur in the middle of the two local flashovers. In total, the formation and disappearance of PACD have an important influence in the surface flashover in the GaAs PCSS.

IV. CONCLUSION

This paper presents the dynamic development process, spectrum and the output waveforms of surface flashover in the GaAs PCSS. Under consideration of the photo-generated carrier's movement, the observed phenomena are fully explained on the basis of the 1D time domain finite element method. It is demonstrated that the movement of the photo-generated carrier plays an important role in the surface flashover of the GaAs PCSS. Our results reveal the different flashover mechanism between the semiconductors and the insulators, and contribute to improve the GaAs PCSS system.

REFERENCES

[1] C. Ma *et al.*, "Study of the lifetime of high-power GaAs PCSSs under different energy storage modes," *IEEE Trans. Power Electron.*, vol. 32, no. 6, pp. 4644–4651, Jun. 2017.

[2] T. Wolfe *et al.*, "High power ultrawideband short pulse (UWBSP) electromagnetics (EM) application for wide band gap (WBG) photoconductive semiconductor switches (PCSS)," in *Proc. IEEE Int. Conf. Electromagn. Adv. Appl.*, 2015, pp. 1500–1503.
[3] S. K. Mazumder, "Photonic power electronics: Past, present, and future," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, Charlotte, NC, USA, 2015, pp. 1241–1249.
[4] N. E. Islam, E. Schamiloglu, and C. B. Fleddermann, "Characterization of a semi-insulating GaAs photoconductive semiconductor switch for ultrawide band high power microwave applications," *Appl. Phys. Lett.*, vol. 73, no. 14, pp. 1988–1990, 1998.
[5] W. Wang *et al.*, "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, 2015, Art. no. 022108.
[6] H. Gui *et al.*, "The jitter time of GaAs photoconductive switch triggered by 532-and 1064-nm laser pulse," *IEEE Photon. Technol. Lett.*, vol. 27, no. 19, pp. 2001–2003, Oct. 1, 2015.
[7] W. Shi, S. Wang, C. Ma, and M. Xu, "Generation of an ultra-short electrical pulse with width shorter than the excitation laser," *Sci. Rep.*, vol. 6, Jun. 2016, Art. no. 27577.
[8] M. Xu *et al.*, "High-gain operation of GaAs photoconductive semiconductor switch at 24.3 nJ excitation," *IEEE Electron Device Lett.*, vol. 37, no. 6, pp. 751–753, Jun. 2016.
[9] W. Shi and Z. Jiang, "Mechanism analysis of the flashover quenching the photoconductive semiconductor switch in SF6," *IEEE Trans. Plasma Sci.*, vol. 40, no. 9, pp. 2221–2224, Sep. 2012.
[10] L.-M. Wang, "Relationship between intrinsic breakdown field and bandgap of materials," *Microelectronics*, vol. 36, no. 6, pp. 576–579, 2006.
[11] H. C. Miller, "Surface flashover of insulators," *IEEE Trans. Elect. Insul.*, vol. 24, no. 5, pp. 765–786, Oct. 1988.
[12] G. Blaise and C. L. Gressus, "Charging and flashover induced by surface polarization relaxation process," *J. Appl. Phys.*, vol. 69, no. 9, pp. 6334–6339, 1991.
[13] R. A. Anderson and J. P. Brainard, "Mechanism of pulsed surface flashover involving electron−stimulated desorption," *J. Appl. Phys.*, vol. 51, no. 3, pp. 1414–1421, 1980.
[14] W.-B. Zhao, G.-J. Zhang, G.-B. Qin, K. Ma, and Z. Yan, "Surface microcosmic phenomena induced by pulsed flashovers," in *Proc. IEEE Int. Symp. Elect. Insul. Mater.*, vol. 2, 2005, pp. 324–327.
[15] F. E. Peterkin *et al.*, "Surface flashover of silicon," *IEEE Trans. Electron Devices*, vol. 37, no. 12, pp. 2459–2465, Dec. 1990.
[16] Z.-X. Lin, J.-Q. Wu, and S.-S. Gong, "Spectroscopic study on the air plasma induced by delayed dual laser pulses," *Acta Phys. Sinica*, vol. 55, no. 11, pp. 5892–5898, 2006.
[17] T. E. V. Eck, L. M. Walpita, W. S. C. Chang, and H. H. Wieder, "Franz–Keldysh electrorefraction and electroabsorption in bulk InP and GaAs," *Appl. Phys. Lett.*, vol. 48, no. 7, pp. 451–453, 1986.
[18] K. H. Schoenbach, J. S. Kenney, F. E. Peterkin, and R. J. Allen, "Temporal development of electric field structures in photoconductive GaAs switches," *Appl. Phys. Lett.*, vol. 63, no. 15, pp. 2100–2102, 1993.
[19] L. E. Kingsley and W. R. Donaldson, "Numerical analysis of electric field profiles in high-voltage GaAs photoconductive switches and comparison to experiment," *IEEE Trans. Electron Devices*, vol. 40, no. 12, pp. 2344–2351, Dec. 1993.
[20] S. N. Vainshtein, V. S. Yuferev, and J. T. Kostamovaara, "Ultrahigh field multiple Gunn domains as the physical reason for superfast (picosecond range) switching of a bipolar GaAs transistor," *J. Appl. Phys.*, vol. 97, no. 2, pp. 1–9, 2005.
[21] S. Vainshtein *et al.*, "Superfast high-current switching of GaAs avalanche transistor," *Electron. Lett.*, vol. 40, no. 1, pp. 85–86, Jan. 2004.
[22] L. Hu, J. Su, Z. Ding, and Q. Hao, "A low-energy-triggered bulk gallium arsenide avalanche semiconductor switch with delayed breakdown," *IEEE Electron Device Lett.*, vol. 36, no. 11, pp. 1176–1179, Nov. 2015.
[23] S. Wei, "Optically activated charge domain model for high-gain GaAs photoconductive switches," *Chin. J. Semicond.*, vol. 2, no. 12, pp. 1481–1485, 2001.
[24] W. Shi *et al.*, "Current limiting effects of photoactivated charge domain in semi-insulating GaAs photoconductive switch," *Appl. Phys. Lett.*, vol. 94, no. 7, pp. 1–3, 2009.

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