http://dx.doi.org/10.5755/j01.eie.25.4.23968 ELEKTRONIKA IR ELEKTROTECHNIKA, ISSN 1392-1215, VOL. 25, NO. 4, 2019

Blocking Characteristics of Photoconductive Switches Based on Semi-Insulating GaP and GaN

Marek Suproniuk[1], Karol Piwowarski[1], Bogdan Perka[1], Pawel Kaminski[2], Roman Kozlowski[2], Marian Teodorczyk[2]
[1]Department of Electronics, Military University of Technology, Gen. Witolda Urbanowicza St. 2, 00-908 Warsaw, Poland
[2]Institute of Electronic Materials Technology, Wólczyńska St. 133, 01-919 Warsaw, Poland
karol.piwowarski@wat.edu.pl

***Abstract*—This article presents results of research work aimed at manufacturing photoconductive semiconductor switches (PCSSs) based on semi-insulating (SI) gallium phosphide (GaP) and gallium nitride (GaN). Currently, the work is in progress to determine the optimal values of PCSS parameters. In this article, the parameters of the selected semiconductor materials used for making PCSSs, the device operation principle, and possible areas of use are presented. The paper demonstrates the construction of test PCSSs based on SI GaP and SI GaN and results of blocking characteristics measurements without the illumination, as well as with illumination with a small photon flux. Further research directions are presented also.**

***Index Terms*—Photoconductive semiconductor switches; Pulse generators; Semi-insulating GaN; Semi-insulating GaP.**

I. INTRODUCTION

In currently developed pulse power systems, both for civil applications and military usage photoconductive semiconductor switches (PCSSs) are increasingly used. These devices meet the criteria of withstanding high blocking voltages while preserving possibility of transition into a state of decreased resistance during the time of nanoseconds. In the open state, the switches can work at voltages up to 100 kV, while in the conducting state, the flowing current can be of the order of 1 kA [1], [2]. Working with these parameters, they provide power of tens of megawatts at periods of nanoseconds with repetition rates up to 1 kHz. Since in optical switches the control is carried out by means of a photon flux with adequate energy, there is a possibility of precise switching on the circuit with an external optical pulse. Thus, the important advantage of these devices is the fact that the switch control and work circuits are entirely isolated from each other.

A PCSS is made of a semiconductor material with a thickness of 0.5 mm to 1 mm, on the surface of which there are contacts enabling the connections of the switch to the electrical system. An overview of basic PCSS switch structure is presented in reference [3], and the solution used in the research is presented in Fig. 1.

Manuscript received 20 November, 2018; accepted 6 June, 2019.

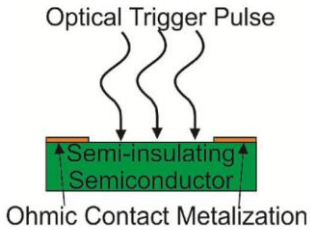

Fig. 1. Planar structure of a semiconductor photoconductive switch based on a bulk semi-insulating material.

The PCSSs operation is based on the phenomenon of transient photoconductivity, which is associated with the generation of excess charge carriers due to the absorption of photons in a semi-insulating material. The absorbed photons` energy, equal to the product of the Planck constant h and the incident light frequency v, is usually larger than the width of the semiconductor band gap, e.g., optically excited electron-hole pairs participate in the process of current conduction and increase of the material conductivity [4]. Characteristics of PCSS, however, depend on the defect structure of the used semi-insulating material. A method, that can be used for studies of deep-level defects in SI materials, is the high-resolution photoinduced transient spectroscopy (HRPITS) with the implementation of the correlation and Laplace procedures [5].

The semi-insulating material, most commonly used to build photoconductive switches, is SI GaAs. It is characterized by the energy gap of 1.424 eV between the valence band maximum and the conduction band minimum, a critical electric field of 1 MV/cm, and a resistivity ranging from 10^7 Ωcm to 10^8 Ωcm at room temperature. It has been proven that a semiconductor switch made of GaAs operating in non-linear mode at an electrical field strength of more than 4 kV/cm is able to block a voltage of 40 kV and conduct a current of 400 A. This type of switch can withstand about 350 pulses of 400 A current at 20 kV blocking voltage triggered by optical pulses with the energy of 90 mJ and duration time of 300 ns generated by a laser emitted the beam with the wavelength of 1.064 µm [1], [2].

Semi-insulating materials with a wider bandgap may theoretically give better performance. These include GaP, 6H-SiC, 4H-SiC, and GaN whose bandgaps at 300 K are 2.26 eV, 3.0 eV, 3.23 eV, and 3.39 eV respectively. The critical electric field strength values for these materials are equal to 1.0 MV/cm, 3.0 MV/cm, 3.0 MV/cm, and 5.0 MV/cm [3]. The main advantage of using materials with a wider energy gap is the PCSS`s ability to block significantly higher voltages and conduct higher currents than in the case of switches made of SI GaAs. Research conducted in recent years has proved experimentally that the performance of PCSSs made of SI 6H-SiC, SI 4H-SiC and SI GaN is much better compared to that made of SI GaAs [6]. In this paper we demonstrate the blocking characteristics of PCSSs made of the Si GaN and Si GaP.

II. BLOCKING CHARACTERISTICS OF PCSSS MADE OF SI GALLIUM PHOSPHIDE AND GALLIUM NITRIDE

A. Construction of Switches

The research was carried out on two switches made of SI bulk gallium phosphide wafers labelled GaP #369 and GaP #275 and on a switch labelled as GaN #6187 made of SI gallium nitride epitaxial layer deposited on SI 6H-SiC substrate doped with vanadium. The Si GaP wafers thickness was 500 µm. The thickness of the SI GaN epitaxial layer, grown by Metal Organic Chemical Vapour Deposition (MOCVD) method, was 2.3 µm. The SI 6H-SiC substrate wafer thickness was 500 µm. The resistivity of Si GaP wafers at 300 K exceeded 1×10^{10} Ωcm and that of epitaxial SI GaN was ~2×10^{6} Ωcm. All switches were built of the chips of 1 cm×1 cm in area. First, the two strips of Au ohmic contacts were made on the SI material surface. The distance between the Au strips was 2 mm. Next, the 10 mm wide and 50 mm long electrical connections made of the electrolytic copper sheet with a thickness of 0.3 mm were attached to the two Au electrodes on the chip. Before fixing, the connections had been chemically cleaned and covered with a layer of silver. After attaching the copper connections, the surface of the chip was cleaned mechanically and chemically to remove metallic particles. The surface of the GaP #275 chip was coated with a 200 nm layer of SiO_2 to provide a better protection from the ambient environment and increase the surface recombination velocity. The SiO_2 layer was deposited by the vacuum evaporation using an electron gun. Figure 2 shows the design of a PCSS used for the blocking characteristic measurements.

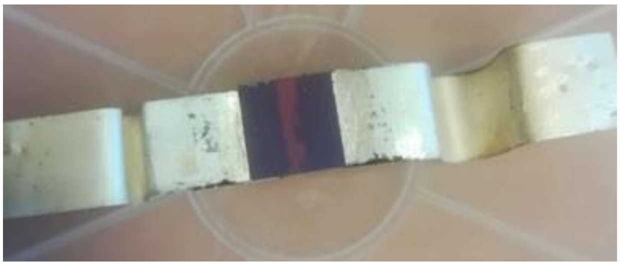

Fig. 2. Image of a photoconductive switch made of SI GaP . The chip with the active region and electrical connections is visible.

B. Measurement Results

The blocking characteristics of the photoconductive switches made of SI GaP and SI GaN were measured using a METREL MI 3210 TeraOhm XA meter enabling voltages from 50 V to 10 kV to be applied and currents ranging from 0.1 nA to 5 mA to be measured.

For each switch being in the off state, the voltage, current, and resistance were measured. The three series of measurements were made by varying the voltage value from 110 V with a step of 100 V to the maximum voltage, at which the electrical discharge between the electrodes was observed. The current-voltage characteristics of the SI GaP and SI GaN switches are shown in Fig. 3 and the highest voltage values, up to which the measurements were made for each switch in the blocking state, are listed in Table I.

TABLE I. THE HIGHEST VOLTAGES APPLIED TO THE SWITCHES MADE OF SI GaP AND SI GaN BEFORE THE DISCHARGE HAS OCCURRED.

Switch label	**Voltage [kV]**
GaP #369	3.38
GaP #275	3.38
GaN #6187	2.88

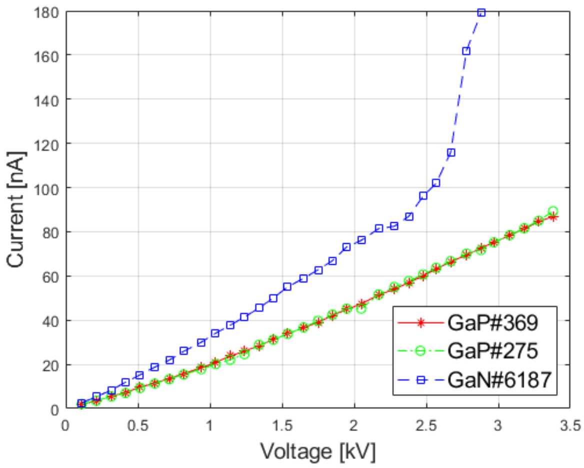

Fig. 3. Current- voltage characteristics for photoconductive switches made of SI GaP and SI GaN measured in the dark at 300 K.

After exceeding the voltage values presented in Table I, the discharge, visible as a spark between the electrodes on the material surface, was observed. It is worth adding that the surface of the GaP #369 and GaN #6187 chips was not covered with SiO_2 and was directly exposed to the atmospheric air containing water molecules. The surface of the GaP #275 chip was covered with a thin SiO_2 layer. However, the protection from the external ambient influence has not been sufficient. The spark discharge occurred at the interface between the air and the switch active area indicating that the air and water molecules can come through the SiO_2 layer and reach the material surface. Therefore, it can be concluded that the breakdown voltage depends on both the properties of the air surrounding the switch and the properties of the switch active region material.

Figure 4 presents the SI GaP and SI GaN switches blocking resistance as a function of the electric field strength in the active region.

The results in Fig. 3 indicate that the blocking characteristics of the switches made of SI GaP are better than that made of SI GaN. This effect is expected because the resistivity of the used SI GaP being above 10^{10} Ωcm, which is much higher than that of the epitaxial GaN equal to ~2×10^{6} Ωcm. As it is seen in Fig. 4, the SI GaP switches well operate at the electric field strength values ranging from 0.56 to 16.90 kV/cm. According to the characteristics shown in Fig. 3, the SI GaN switch works well only in the voltage range from 0.11 kV to 2.67 kV, which corresponds to the electric field strength values from 0.56 kV to 12.35 kV/cm (see Fig. 4). For this switch, a significant increase in the leakage current is observed in the voltage range from 2.67 kV to 2.88 kV (see Fig. 3). This effect corresponds to a significant decrease in the resistance at the electric field strength values ranging from 12.35 kV/cm to 14.40 kV/cm visible on Fig. 4. Although the blocking characteristic in this range is strongly nonlinear, the switch resistance in the dark is above 10 GΩ and this value is acceptable in terms of applications.

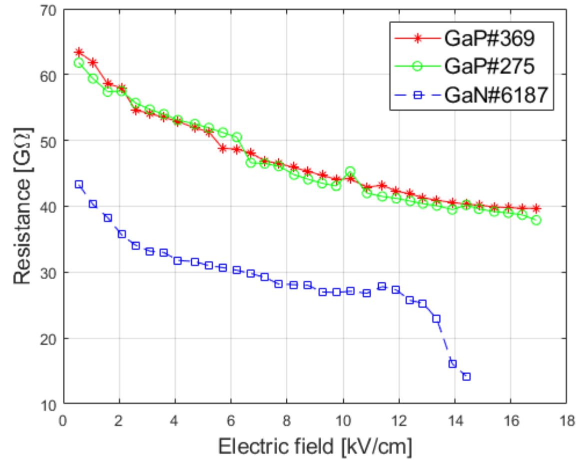

Fig. 4. Dependences of the SI GaP and SI GaN switches blocking resistance on the electric field strength in the active region determined from the dark current measurements at 300 K.

The results of measurements of blocking properties while the excess charge carriers are generated for the GaP #369 switch are shown in Fig. 5 and Fig. 6.

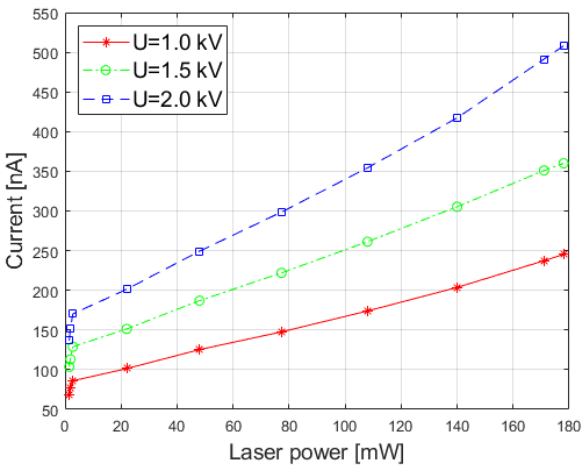

Fig. 5. Dependences of the photocurrent on the laser beam power for the GaP #369 switch measured at 300 K at various applied voltages of 1.0, 1.5, and 2.0 kV corresponding to the electric field strength values of 5.0 kV/cm, 7.5 kV/cm, and 10 kV/cm.

In order to assess the switches blocking properties in conduction state, the devices were illuminated with a laser beam with a wavelength of 375 nm corresponding to the photon energy of 3.31 eV. Tests were carried out for three voltage values of 1.0 kV, 1.5 kV, and 2.0 kV. During the measurements, the laser beam power was changed in the range from 1.5 mW to 178 mW.

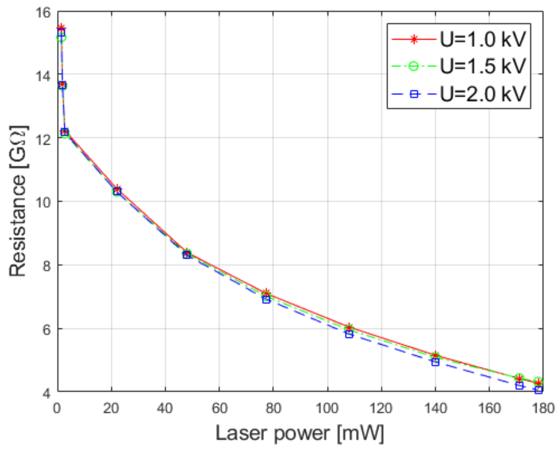

Fig. 6. Blocking resistance of the GaP #369 switch at 300 K as a function of the laser beam power generated the excess charge carriers in the active region. The voltages of 1 kV, 1.5 kV, and 2 kV correspond to the electric field strength values of 5.0 kV/cm, 7.5 kV/cm, and 10 kV/cm.

Based on the characteristics presented in Fig. 5 and Fig. 6, we can conclude that under the illumination, the GaP #369 switch resistance remains high for the all applied voltages. It should be noted that the characteristics are non-linear. The changes observed for small values of the laser beam power in the range of 1.5–2.8 mW are presumably related to the changes of the laser beam shape. When the beam power exceeds 2.8 mW, we observe a significant reduction of the effect and the photocurrent almost linearly increases with rising the number of incident photons. According to the dependences shown in Fig. 6, the electric field strength ranging from 5.0 kV/cm to 10 kV/cm has very small effect on the GaP #369 switch active region resistance. This resistance is mainly dependent on the laser beam power and non-linearly decreases with increasing the illumination intensity. The effect is clearly seen for the largest electric field (10 kV/cm) at the beam power values ranging from 100 mW to 180 mW.

Figure 7 shows the photocurrent generated in the GaP #369, GaP #275, and GaN #6187 switches as a function of the excitation beam power. Tests were performed at a 1.0 kV voltage when the switch active area between electrodes was illuminated with the 3.31 eV photons. It is easy to notice that the photocurrent significantly increase when the laser beam power goes up. However, there are big differences in the values of the generated photocurrent for the GaP #369 and GaP #275 switches as well as visible differences in these values for GaP #275 and GaN #369 switches. It is worth adding that the surface of the GaP #275 chip has been subjected to the passivation process by covering it with a silicon dioxide layer. This switch shows substantially better conducting properties than the GaP #369 switch, for which the photocurrent at the beam power ranging from 100 mW to 180 mW is approximately by two orders of magnitude lower. Passivation of the active region surface reduces the surface recombination velocity of the generated excess charge carriers. This effect results in a significant decrease of the surface recombination rate of excess charge carriers and consequently increases the photocurrent by approximately two orders of magnitude. The effect of the surface recombination velocity on the excess charge carriers concentration is particularly important for the SI GaP switches because at 300 K the GaP absorption coefficient at the photon energy of 3.31 eV is 1.5×10^5 cm^{-1} [7]. In other words, the 3.31 eV photons are predominantly absorbed in the near surface region located at the depth of ~0.07 µm from the wafer surface. At 300 K, the GaN absorption coefficient at the photon energy of 3.31 eV is 2×10^3 cm^{-1} [8] and the photon penetration depth is 5 µm. The changes of the SI GaP and SI GaN switches resistance under the illumination with 3.31 eV photons versus the laser beam power (Fig. 8) are adequate to the characteristics shown in Fig. 7.

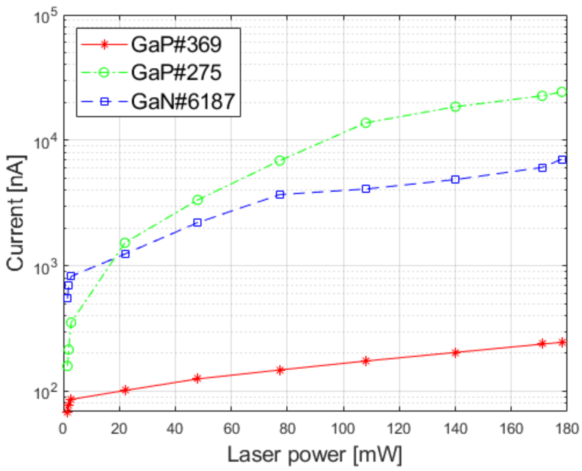

Fig. 7. Dependences of the photocurrent measured for the SI GaP and SI GaN switches at an applied voltage of 1 kV and temperature of 300 K on the laser beam power. The current axis is in logarithmic scale.

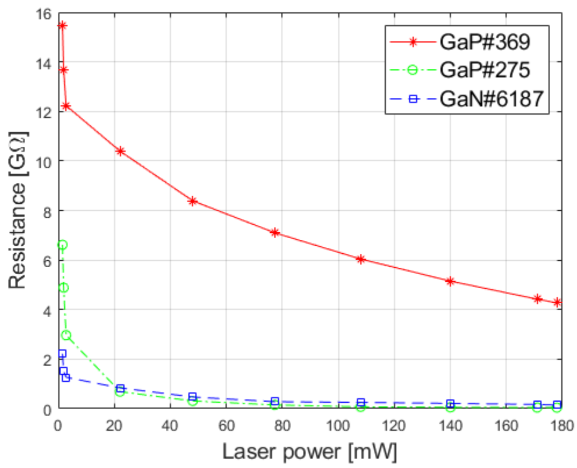

Fig. 8. Dependences of the SI GaP and SI GaN switches resistance at an applied voltage of 1 kV and temperature of 300 K on the laser beam power.

III. CONCLUSIONS

The article describes the construction and operation principle of PCSSs based on SI GaP and SI GaN. The results of tests carried out in order to investigate the blocking characteristics of these switches are also presented.

It is demonstrated that, in the blocking state, the current-voltage characteristics of the tested SI GaP switches are approximately linear through the entire range of applied voltages. In the case of the SI GaN switch, the non-linear current increase is observed when the voltage exceeds 2.67 kV.

The effect of illuminating the switches active region on the blocking characteristics has been also studied.

It is shown that the passivation of the switch surface with a layer of SiO_2 may have a substantial impact on the photocurrent generated in the device. For the laser beam power of 178 mW and applied voltage of 1.0 kV, the SI GaP switch with the passivation gave the photocurrent of 24.3 µA compared to the value of 254.3 nA achieved without the passivation.

The main advantage of semiconductor photoconductive switches is the ability to block high voltages and conduct very high currents in a short in time period. The blocking voltages achieved for the SI GaP and SI GaN switches before occurrence of the undesirable sparking, significantly limit the possibility of using them in the power industry or for military purposes.

In the next step of research, the measures will be taken in order to increase the maximum blocking voltage by separating the active area of the switches from the ambient air containing oxides and moisture. This can be done by using appropriate polymer encapsulates.

REFERENCES

[1] Wei Shi, Liqiang Tian, Zheng Liu, Linqing Zhang, Zhenzhen Zhang, Liangji Zhou, Hongwei Liu, and Weiping Xie, "30 kV and 3kA semi-insulating GaAs photoconductive semiconductor switch", *Appl. Phys. Lett.*, vol. 92, pp. 043511–1–3, 2008. DOI: 10.1063/1.2838743.
[2] Liqiang Tian and Wei Shi, "Analysis and operation mechanism of semi-insulating GaAs photoconductive semiconductor switches", *J. Appl. Phys.*, vol. 103, pp. 124512¬1¬7, 2008,. DOI: 10.1063/1.2940728.
[3] E. Majda-Zdancewicz, M. Suproniuk, M. Pawłowski, and M. Wierzbowski, "Current state of photoconductive semiconductor switch engineering", *Opto-Electronics Review*, vol. 26, pp. 92–102, 2018. DOI: 10.1016/j.opelre.2018.02.003.
[4] Sudip K. Mazumder, "An Overview of Photonic Power Electronic Devices", *IEEE Transactions on Power Electronics*, vol. 31, no. 9, pp. 6562–6574, 2016. DOI: 10.1109/TPEL.2015.2500903.
[5] M. Suproniuk, M. Pawłowski, M. Wierzbowski, E. Majda-Zdancewicz, and M. K. Pawłowski, "Comparison of methods applied in photoinduced transient spectroscopy to determining the defect center parameters: The correlation procedure and the signal analysis based on inverse Laplace transformation", *Review of Scientific Instruments*, vol. 89, pp. 04470–0044710, 2018. DOI: 10.1063/1.5004098.
[6] K. S. Kelkar, N. E. Islam, C. M. Fessler, and W. C. Nunnally, "Design and characterization of silicon carbide photoconductive switches for high-field applications", *J. Appl. Phys.*, vol. 100, pp. 124205–1–5, 2006. DOI: 10.1063/1.2365713.
[7] M. R. Lorenz, G. D. Pettit, and R. C. Taylor, "Band gap of gallium phosphide from 0 to 900 K and light emission from diodes at high temperatures", *Phys. Rev. B*, vol. 171, pp. 876–886, 1968. DOI: 10.1103/PhysRev.171.876.
[8] S. G. Sridhara, R. P. Devaty, and W. J. Choyke, "Absorption coefficient of 4H silicon carbide from 3900 to 3250", *A. J. Appl. Phys.*, vol. 84, pp. 2963–2964, 1998. DOI: 10.1063/1.368503.