High-current low-voltage switches for nanosecond pulse durations based on thyristor (Al)GaAs/GaAs homo- and heterostructures

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A series of low-voltage thyristor current switches based on (Al)GaAs/GaAs homo- and heterostructures with a volume charge region formed in the lightly doped *p*-GaAs base layer have been developed. The transient processes characteristics in pulse generation mode of nanosecond duration have been studied. It has been shown that the use of a wide-bandgap barrier based on AlGaAs at the *n*-emitter/*p*-base junction allows reducing the minimum control current amplitude from 30 to 3 mA, and the turn-on delay time can be shortened to 6 ns. For the developed thyristor switches, a minimum transition time of 3.7−3.9 ns was demonstrated when operating in a circuit with a 1 nF capacitive load. In a circuit with a nominal 1 Ohm resistive load, the thyristor switches provided a peak current of 17.5 A with a pulse duration of 3.7 ns.

Keywords: High-current, switch, nanosecond pulse duration, thyristor, heterostructure.

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1. Introduction

Currently, to create rangefinders and 3D lidars based on the time-of-flight principle, an urgent task is the generation of high-power laser pulses of nanosecond duration. In the general case, the problem of pumping semiconductor lasers with nanosecond current pulses is solved as part of a basic approach, which is based on the use of capacitive electrical energy storage devices and current switches that form a closed circuit with a semiconductor laser. In case where the capacitance can be considered as an ideal current source, its characteristics are determined precisely by the current switch. Several types of current switches are currently being developed. In the works [1,2], lines of laser diodes and pulsed current sources based on GaN transistors were demonstrated. The authors managed to generate current pulses with a duration of 3−10 ns with an amplitude $\sim$ 1 kA, which ensured the generation of laser pulses with a peak power from 0.6 kW for single to 2.2 kW for tunnel-coupled laser structures. Another option for high-speed, high-current switches are avalanche transistors. In the works [3–5], pulsed lasers with a peak power of up to 120 V and a pulse duration of 1−1.5 ns were demonstrated. GaAs *S*-diodes and bipolar avalanche silicon transistors were used as current switches. The current assessment allows to talk about the maximum pulse amplitude up to 45 A, while the operating voltages reached 200 V for *S*-diodes and 100 V for bipolar avalanche silicon transistors. In the works [6–8] the possibility of creating laser pulse sources based on multijunction heterostructures, which included a laser part and provided thyristor-type electrical bistability, was demonstrated. Similar heterostructures at operating voltages up to 25 V allowed to demonstrate pulses with durations from 10 to 100 ns, however, the maximum power of 47 W was obtained only for long pulses, and a reduction in duration was accompanied by a proportional decrease in peak power and a decrease in emissive efficiency. As subsequent studies showed, the drop in emissive efficiency was associated with the spatial localization of the current and the heterogeneity of the current pumping of the amplification region, the influence of which increases with shortening the pulse duration [6,9]. Research has shown that thyristor switches based on AlGaAs/GaAs heterostructures have a number of advantages, such as: 1) the opportunity of vertical integration and creation of assemblies with laser diodes and rulers based on them, which reduces possible electrical losses in the current circuit; 2) high energy efficiency due to low residual stresses; 3) ease of control, which does not require the creation of separate short-pulse control circuits, as in field-effect transistors. The opportunity of solving the problem of current spatial localization in thyristors and using them as current switches was investigated in works [10,11], where designs of heterostructures with optical feedback were considered as basic ones. As a result, the capabilities of generating laser pulses with a duration of 6.5−80 ns with a peak power of 20−80 W at operating voltages up to 30 V were demonstrated. The results obtained showed the

Description of experimental thyristor structures

№ of the layer	Layer Type	Doping, cm^{-3}	Type of structure					
			1		2		3	
			Composition	Thickness, μm	Composition	Thickness, μm	Layer	Composition, μm
1	*n*-emitter *n-p-n*–transistor	10^{18}	*n*-GaAs	1	*n*-GaAs/ *n*-$Al_{0.1}Ga_{0.9}As$	1/0.1	*n*-GaAs/ *n*-$Al_{0.1}Ga_{0.9}As$	1/0.1
2	*p*-base *n-p-n*-of the transistor	$10^{18}/10^{15}$	p^+-GaAs/p_0-GaAs	0.1/4	p^+-GaAs/p_0-GaAs	0.1/4	p^+-GaAs/p_0-GaAs	0.1/4
3	*n*-header *n-p-n*-of the transistor	10^{18}	*n*-GaAs	1	*n*-GaAs	0.5	*n*-GaAs	1
4	*p*-emitter *p-n-p*-transistor	10^{18}	*p*-GaAs	0.5	*p*-GaAs	0.5	*p*-GaAs	0.5

high capabilities of low-voltage thyristors. As part of this work, research continues aimed at optimizing the design of thyristor structures in order to improve their performance characteristics as low-voltage, high-current switches with nanosecond duration.

2. Experimental samples

Three types of structures were developed and studied (see table). The selected types of structures are a compromise between the manufacturability of their manufacture and the desire to realize high transient rates and high energy efficiency when generating short pulses. All developed structures had a number of common design parameters. The space-charge region was formed in the lightly doped p_0 base layer. The thickness of the $p_0$base layer was chosen to be 4 μm, which was optimal in previous studies of laser thyristors [12].

To prevent the effect of closing the*p-n* transitions in the blocking state, the region p_0 of the base was limited to a thin p^+-layer formed on the *n*-side of the emitter of the *n-p-n* transistor part. The first type of structure included only basic structural elements in the following sequence: *n*-GaAs-emitter with a thickness of 1 μm; *p*-GaAs-base, which included layers with various dopings, as described above; *n*-GaAs-collector with a thickness of 1 μm, forming the *n-p-n*-transistor part; Next, a layer of *p*-GaAs-emitter *p-n-p*-transistor part with a thickness of 0.5 μm was grown. The design of the second type of structure differed from the basic one by adding a wide-gap *n*-$Al_{0.1}Ga_{0.9}As$ layer with a thickness of 0.1 μm to the *n*-emitter *n-p-n* transistor, as well as a reduced thickness of the *n*-GaAs collector layer to 0.5 μm. The design of the third type of structure differed from the basic one only by adding a layer of wide-gap *n*-$Al_{0.1}Ga_{0.9}As$ 0.1 μm thick to the emitter of the *n-p-n* transistor, while the thickness of the *n*-GaAs collector layer did not change. The inclusion of a wide-gap layer *n*-$Al_{0.1}Ga_{0.9}As$ was done to evaluate the effect of hole leakage from the *p*-base, which ensures the efficiency of the *n-p-n* transistor part. Reducing the thickness of the collector layer of the *n-p-n* transistor was done to assess the influence of the recombination component for holes injected from the anode contact (*p*-GaAs emitter).

Experimental heterostructures were grown on a *n*-GaAs substrate using MOC-hydride epitaxy. Then, designs of current thyristor switches were formed, for which the Ti/Pt-based anode contact had a diameter of 150 μm. The cathode contact had a solid structure, was made on the basis of AuGe and was deposited on the *n*-GaAs substrate. The control electrode contact was formed in the *n*-GaAs-collector layer of the *n-p-n*-transistor part.

For experimental studies of dynamic characteristics, thyristor chips were mounted in parallel with a capacitor with a nominal value of 1 nF. In this case, depending on the experiments performed, an additional resistive load could also be connected in series with the capacitor. The capacitor was powered from an external voltage source. Dynamic characteristics were studied using a passive probe and an oscilloscope with a frequency band of 300 MHz and 2 GHz, respectively.

3. Results and analysis of experimental studies

Experimental studies of the turn-on delay time were carried out in the first part of the work. Figure 1 shows the dependences for three types of studied structures, obtained for a blocked voltage of 50 V. The basic structure of type 1 is characterized by the longest turn-on delay time, which is due to the absence of a limiting barrier layer. As a result, for a type 1 structure, the operating range of control current pulse amplitudes was from 30 to 220 mA, which corresponded to a controlled change in the turn-on delay time from 184 to 10 ns.

The use of a wide-band barrier at the emitter-base interface for the *n-p-n* transistor part allows to effectively

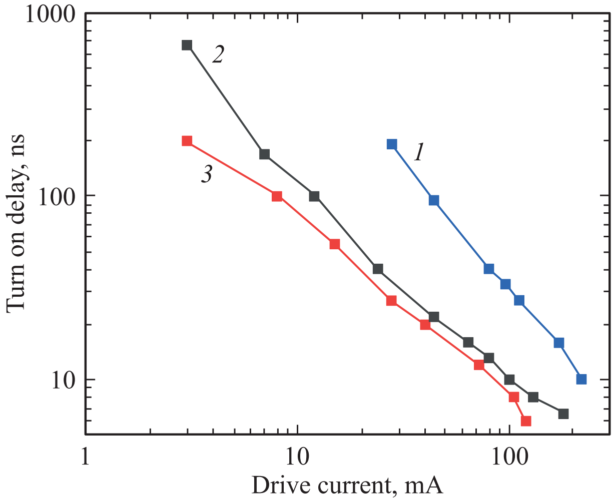

Figure 1. Dependence of the turn-on delay on the amplitude of the control current pulse for a blocked voltage of 50 V for thyristors based on structures: *1* — type 1, *2* — type 2, *3* — type 3.

limit the leakage of excess holes from the *p*-base layer, which significantly increases the efficiency of this transistor and, as a result, allows to increase the efficiency of control of the thyristor structure. As a result, for the same value of the blocked voltage, the minimum amplitudes of the control current pulse at which effective switching was observed were 3 mA for heterostructures of type 2 and 3. Enabling a barrier also allows to reduce the minimum turn-on delay, which reached 6 ns for both structures with barrier layers.

From Figure 1 it is clear that reducing the thickness of the *n*-GaAs collector from 1 μm in a type 3 structure to 0.5 μm in a type 2 structure also led to an increase in the control efficiency of the thyristor switch. This effect is most pronounced in the region of small amplitudes of control currents. Thus, at a control current of 3 mA, the indicated decrease in the thickness of the *n*-GaAs collector led to a decrease in the turn-on delay from 674 to 195 ns.

The second part of the work was related to experimental studies of the dynamics of inclusion. At the first stage, the

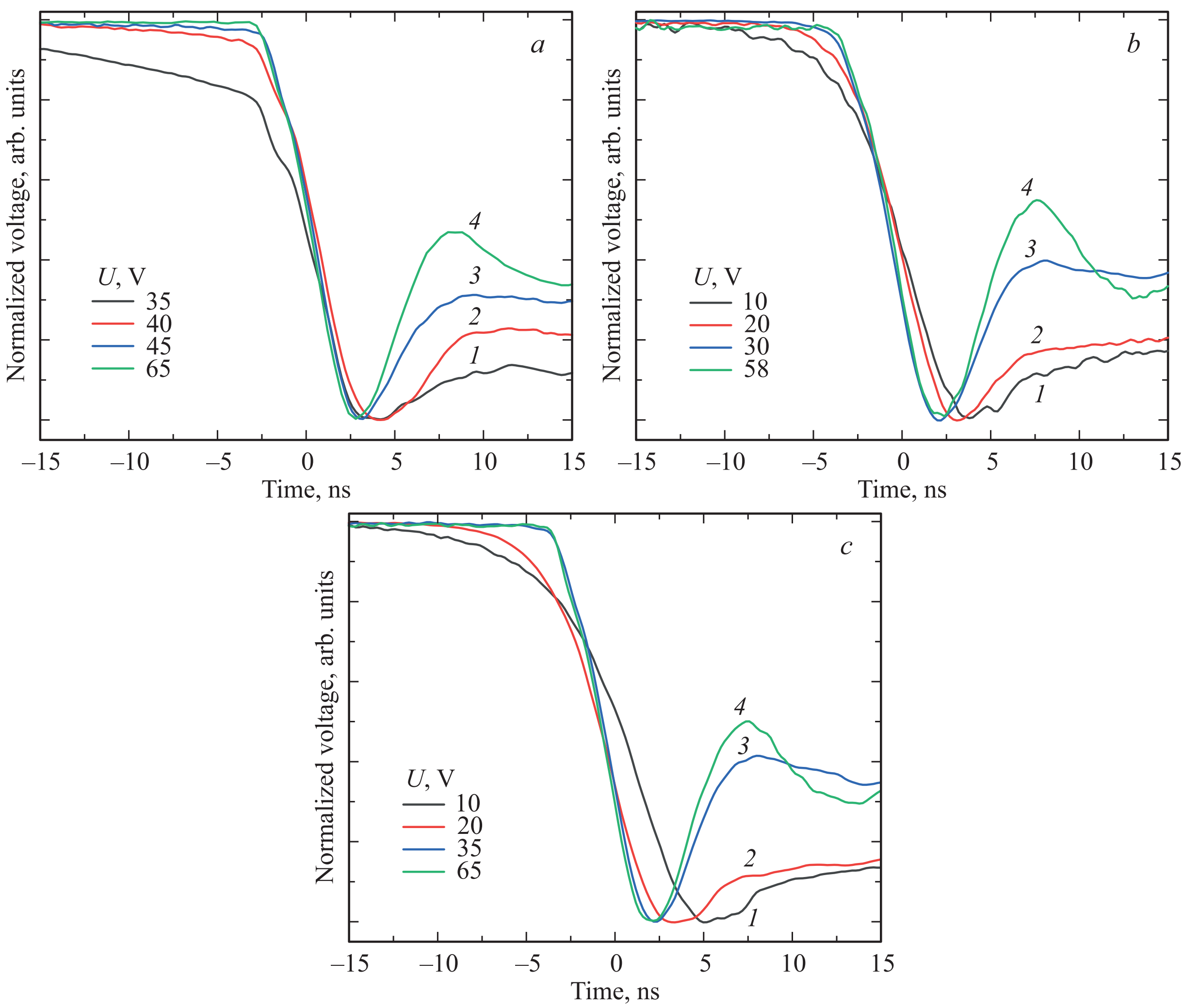

Figure 2. Dependence of the normalized voltage on the discharge capacitor on time during the transition to the on state for the thyristor-capacitor circuit and structures of type 1 (*a*), 2 (*b*) and 3 (*c*) obtained for various blocked voltages. (Colored version of the figure is presented in electronic version of the article).

dynamics of capacitance discharge in a circuit without load resistances was studied, i.e. the capacitor was connected in parallel with the thyristor. Typical dependences of the voltage dynamics when discharging a capacitor with a capacity of 1 nF are shown in Figure 2.

For convenience of analysis, normalized dependencies are presented that allow to clearly compare the change in the speed of the transient process for different values of blocked voltages. It can be seen that there is effective activation of a type 1 structure for minimal blocked voltages 30–35 V, while two sections can be specified in the voltage dynamics. The initial section is characterized by a low turn-on speed, and its duration can reach 30 ns for low blocked voltages. However, the contribution of this section to the overall dynamics is practically absent for blocking voltages close to the maximum (in our case > 45 V). For the second section, the speed of the transition process is maximum, regardless of the blocked voltage, while the transition from the first section to the second in the dynamics of the capacitance discharge is quite sharp. This may indicate different switching mechanisms operating in these areas. For the first section, excess carriers can be supplied to the base regions mainly due to drift-diffusion transport processes, while for the second section, the generation of excess carriers can be associated with impact ionization processes. The achievable minimum transient time at level 10–90% for a type 1 heterostructure is 3.8 ns. For structures of type 2 and 3, the nature of the voltage dynamics and the switching on of the thyristor switch are noticeably different. First of all, there is clearly no slow turn-on section on the dynamics. In this case, a noticeably lower value of the minimum blocked voltage of 10 V is achieved with effective switching. The transient process time for the minimum blocked voltage of 10 V at level 10–90% is 7.3 and 9.2 ns for heterostructures of type 2 and 3, respectively (Figure 2). An increase in the blocked voltage leads to an acceleration of the transient process. As a result, for a blocked voltage of 30 V the time of the transient process at level 10–90% is 3.9 and 3.8 ns for heterostructures of type 2 and 3, respectively, and does not change with a further increase in the blocked voltage (Figure 2). The results obtained demonstrate that for initial values of the blocked voltage, the efficiency of accumulation of excess carriers in the *p*-base contributes significantly. This is associated with the fact that the supply of excess holes to the *p*-base is carried out by drift-diffusion transport from the anode contact region. As a result, recombination losses in the *n*-GaAs collector have a noticeable effect, which is confirmed by the experimental results: there is maximum time of the transition process for a blocked voltage of 10 V for a type 3 heterostructure with a thickness of *n*-GaAs collector 1 μm. For blocked voltages > 30 V it is constant during the transient process and has the same value for structures 2 and 3. This fact may indicate the decisive contribution of impact ionization in the region of the collector *p*-*n* transition of the *n*-*p*-*n* transistor part. In this case, it is impact ionization that is the main source of excess holes for the *p*-base, i.e. the process of supplying holes due to drift-diffusion transport from the anode contact through the *n*-GaAs collector is no longer decisive at blocked voltages > 30 V.

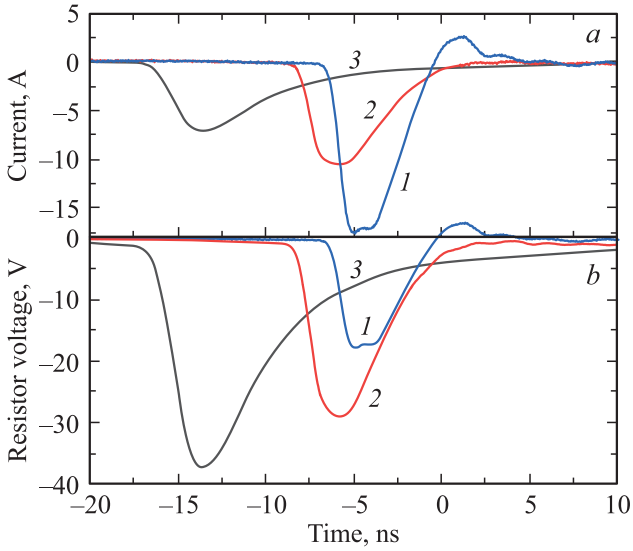

Figure 3. Dependences of the current in the circuit (*a*) and the voltage across the load resistor (*b*) on time for a thyristor switch based on a type 2 structure operating in a circuit with a resistive load with a nominal value of Ohm: *1* — 1, *2* — 2.7, *3* — 5.1. The capacitance of the condenser is 1 nF.

In the final part, the dynamics of transient processes in a circuit with a resistive load was studied. Including a resistor allows to simulate the operation options of a thyristor switch with different load options, as well as estimate the amplitude of the current pulse generated in the circuit. Figure 3, *b* shows typical voltage pulses measured on load resistors of various ratings when the thyristor is turned on with a blocking voltage of 55 V and a capacitor capacitance of 1 nF, as well as certain current pulses in Figure 3, *a*. The achieved maximum amplitude of the current pulse for a resistor with a nominal value of 1 Ohm reached 17.5 A with a duration of half the maximum of 3.7 ns. Using the obtained experimental current pulses, an estimate was made of the rate of current rise when the thyristor switch is turned on for various turn-on conditions: blocked voltage and load resistor. The rate of current rise was determined as the slope of the leading edge of the current pulse at the level of 10–90% of the maximum amplitude. The obtained dependencies are shown in Figure 4.

It can be seen that for all structures the slope of the obtained dependences increases with decreasing load resistance. For structures of type 2 and 3, the dependences also include two sections. In the first section, at blocked voltages 10–20 V, there is a slight increase, corresponding to the slow turn-on of the thyristor. Further, with increasing voltage, a break in the dependence is observed and a transition to fast switching modes of the thyristor (blocked voltage > 20 V). It can be seen that an increase in load resistance helps to reduce the speed of the transient process

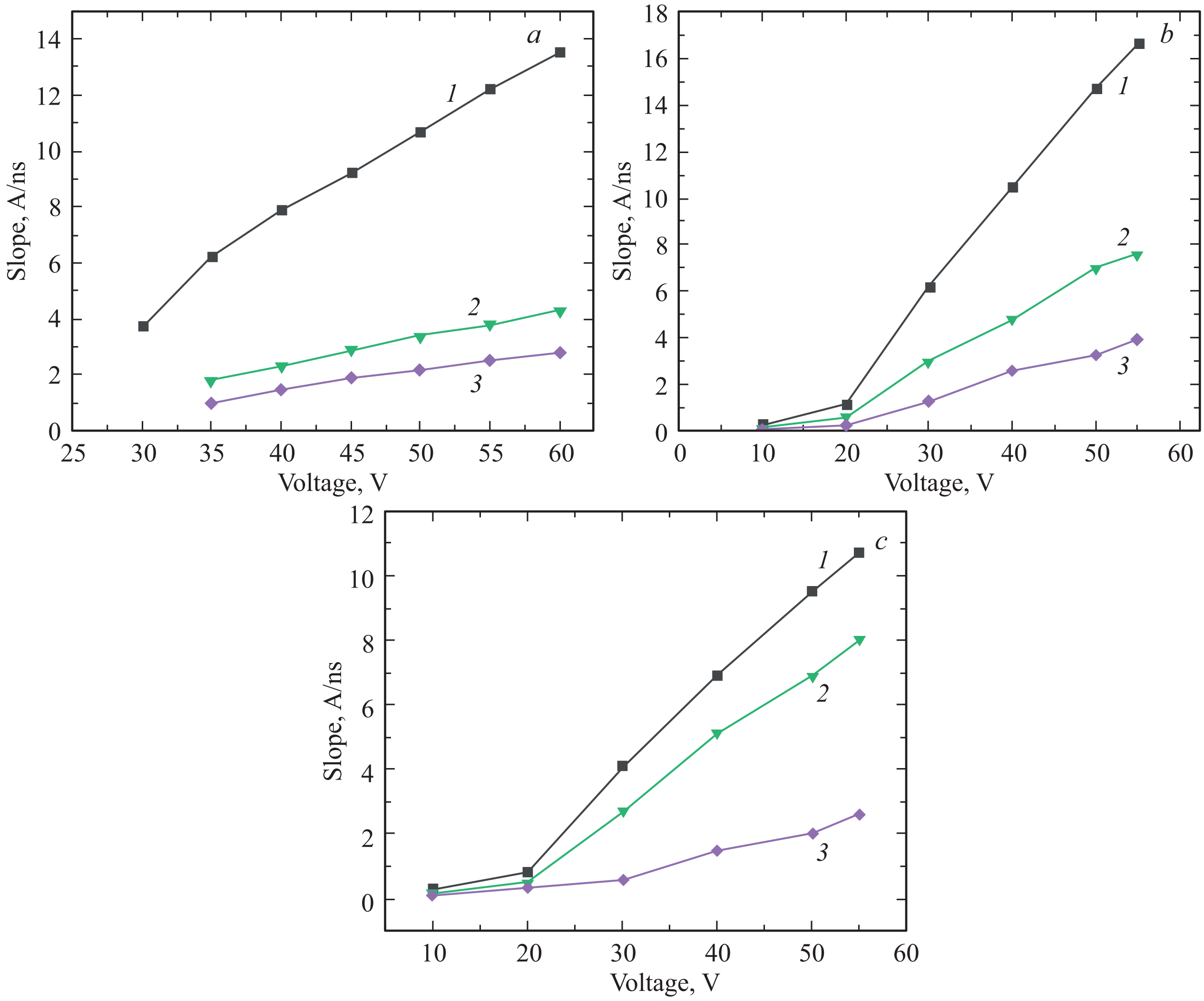

Figure 4. Dependences of the rate of rise of the current pulse at level 10–90% on the blocked voltage for thyristor switches based on heterostructures of type 1 (*a*), 2 (*b*) and 3 (*c*), operating in a circuit with a resistive load with a nominal value of (Ohm): *1* — 1, *2* — 2.7, *3* — 5.1. The capacitance of the condenser is 1 nF.

and at a nominal value of 5 Ohm the kink practically disappears, which may indicate that only the slow operating mode of the thyristor is implemented for the entire voltage range. This fact indicates that to realize the conditions of high speed of the transient process, an important parameter is not only the blocking voltage, but also the current density. This effect can be explained by the fact that at a low current density it is impossible to realize the conditions for the formation of an electric field domain, where impact ionization occurs, which is an important channel for the rapid supply of excess holes to the *p*-base.

4. Conclusion

The developed series of low-voltage thyristor structures demonstrated the opportunity of creating high-current switches that provide switching of current pulses with an amplitude of ≥ 10 A with a minimum transient time in a capacitive circuit of 3.7–3.9 ns. The optimization of the parameters of the thyristor structure allows to say that to create effective switches that provide a solution to the problem of generating single pulses, the optimal design is with a barrier layer at the emitter/*p*-base boundary and a minimum thickness of the *n*-GaAs collector. The developed designs of thyristor switches allow to realize dense packing of a number of elements, which can be used to create matrices in order to increase the peak current. In the future, the results obtained are planned to be used to create pulsed laser radiation sources based on laser diodes.

Conflict of interest

The authors declare that they have no conflict of interest.

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