High-speed current switches based on AlGaAs/GaAs heterostructure thyristors with a thick p-base (8 μm)

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AlGaAs/GaAs heterostructures with thick p-base (8 μm) have been developed for thyristors, and current switches based on these structures have been created. In static mode, a maximum blocked voltage of 120 V has been demonstrated. Minimum turn-on delays reached 7 ns under control current of 220 mA. It was shown that generation of pulse sequences with frequency up to 20 kHz at operating voltage of 110 V and up to 120 kHz at operating voltage of 30 V is possible. Evaluation of dynamic characteristics indicates the capability of generating current pulses with amplitude of 68 A and duration of 2.9 ns.

Keywords: heterostructure, thyristor, fast current switch, semiconductor laser, short pulse.

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1. Introduction

In recent years, there has been an increased interest in high-speed solid-state switches, which are characterized by nanosecond transient times. This is due to the possibility of using such switches in switching circuits of semiconductor laser diodes. The search for the optimal component base of such circuits is associated with the need to develop solutions that would increase the amplitude and frequency of repetition while maintaining a minimum duration of current pulses, which is caused by the requirement to increase the peak power and average energy of laser pulses. Traditional solutions are based on the use of silicon transistors, for example, IAUZ40N08S5N100, manufactured by Infineon Technologies [1]. However, these transistors have a fairly large form factor and, as a result, a high value of gate capacitance and inductance. The use of GaN field-effect transistors makes it possible to significantly reduce the form factor due to high temperature stability. As a result, modern samples demonstrate the possibility of generating current pulses with a duration of units of ns and an amplitude of tens of Ampere, such as the EPC2252 model from Efficient Power Conversion Corporation [2]. Despite the existing solutions using field effect transistors, other approaches are also being developed. In particular, based on avalanche S-diodes [3], avalanche bipolar transistors [4]. Separately, current switches based on thyristor heterostructures can be distinguished. Recently, a number of studies have been published demonstrating the possibilities of using such devices in pumping circuits of semiconductor lasers [5–7]. Studies in Ref. [8] have shown the possibility of generating laser pulses with a duration of 2.25 ns and a peak power of 45 W, which suggests the possibility of generating current pulses with a duration of $\sim$ 3 ns and an amplitude close to 50 A with an operating voltage. of 50 V. The advantage of thyristor current switches is the possibility of vertical integration with semiconductor laser crystals. This reduces the length of the current loop, which is important to reduce the inductance. In addition, thyristor switches have a low requirement for control current pulses, unlike field-effect transistors, for which the speed of the control pulse determines the speed of transition to the open state. The research results demonstrated in recent studies have shown that one of the limitations for further increasing the amplitude of the current of thyristor switches while maintaining the pulse duration in the nanosecond range is the parasitic inductance of the circuit. To solve this problem, thyristor heterostructures were developed within the framework of this work, in which an increase of more than 2 times the operating voltage was realized in comparison with known analogues, as well as studies of their basic dynamic characteristics were carried out.

2. Production of experimental samples

The general design of the thyristor switch heterostructure can be described using two transistors $n-p-n$ and $p-n-p$ connected in parallel. In most studies of low-voltage switches based on thyristor heterostructures, the maximum locking voltage ranged from 40 to 60 V and was provided by a lightly doped p-base, the thickness of which was $2-4\,\mu$m [9,10]. A further increase in the blocked voltage is possible due to the expansion of the weakly doped region of the collector p-n junction of the $n-p-n$-transistor part. The simulation showed that the composite structure of the p-base of the $n-p-n$-transistor based on thin highly doped and thick weakly doped layers plays an important role in effectively increasing the blocked voltage. In this case, the effect of the $p-n$-junction can be suppressed and an increase in the blocked voltage can be realized in structures of smaller thickness, which is important from a technological point of view, since it requires lower costs in the manufacture of the heterostructure. The weakly doped region of the collector $p-n$-junction of the $n-p-n$-transistor part, which provides an increase in the blocked voltage, can be implemented both by expanding only the lightly doped part of the p-base, and by adding a weakly doped layer of the n-collector. Simulation has shown that while maintaining the total thickness of weakly alloyed layers, the dynamic characteristics of the structures do not differ significantly. However, from a technological point of view, a simpler solution is based on using a weakly doped layer of only one type of conductivity. Another important parameter of the heterothyristor structure design is the thickness of the n-collector of the $n-p-n$-transistor part. The value of this parameter affects the switch-on delay, which is associated with recombination losses of holes during injection into the $p-n-p$-transistor part. A decrease in the thickness of this layer leads to a decrease in this component of recombination losses and, as a result, a decrease in control currents. However, the developed design of the thyristor switch implies the use of a control electrode, which is formed precisely to the n-collector of the $n-p-n$-transistor part due to etching of the mesocanaves that open access to this layer. For this reason, the choice of the thickness of this layer should also take into account the manufacturability. As a result, a heterothyristor structure design was proposed for implementation, including the following main layers: n-$Al_{0.1}Ga_{0.9}As$ ($n = 10^{18}\,cm^{-3}$), $0.1\,\mu$m thick; p-GaAs ($p = 10^{18}\,^{-3}$), $0.1\,\mu$m thick; p^0-GaAs ($p = 10^{15}\,cm^{-3}$), $8\,\mu$m thick; n-GaAs ($n = 10^{18}\,cm^{-3}$), thickness $1\,\mu$m; p-GaAs ($p = 10^{18}\,cm^{-3}$), thickness $1\,\mu$m. The thickness μ of the collector of the $n-p-n$-transistor part was selected based on the technological requirements for the convenience of forming the control electrode. The developed heterostructure was grown by the method of moshydride epitaxy on a n-GaAs substrate. Next, a circular anode contact with a diameter of $200\,\mu$m and a control electrode were formed from the side of the epitaxial layers. A solid cathode contact was formed from the side of the substrate. For experimental studies, separate crystals of thyristor wrenches were made, which were soldered onto the copper bases with the substrate facing down. A schematic representation of the studied crystals of thyristor switches is shown in Figure 1, *a*.

3. Experimental procedure

To study the dynamic characteristics, we assembled: a circuit including a storage capacitor with a capacity of 1 nF, an external power source that provides charging of the capacitor, and a control pulse generator. Studies of the switching dynamics were carried out using a high-frequency probe and an oscilloscope with a frequency band of 6 GHz. The assembled circuit allows both to provide controlled activation of the thyristor switch and to investigate its dynamic characteristics. Controlled activation is provided by using a control pulse generator, the parameters of which, as will be shown below, significantly affect the switch-on delay. An important feature of the assembled circuit is the ability of the thyristor switch to operate in the controlled pulse sequence generation mode. In this case, the operating mode will include the following steps. The thyristor is in the closed state until the control signal is turned on, while the energy stored by the capacity is determined by its nominal value and operating voltage. The control pulse switches the thyristor to an open state with low resistance, which allows the accumulated energy capacity to discharge, resulting in a current pulse in the thyristor switch-capacitive storage circuit. As soon as the capacitance is discharged and does not allow the current in the thyristor circuit to be maintained more than the holding current, the thyristor will arbitrarily switch to a closed state with high resistance. The high resistance of the thyristor allows the tank to be charged from an external power source. From this it can be seen that the nominal value of the storage capacity will determine the duration and amplitude of the generated current pulses. In this paper, the choice of the storage capacitor capacity rating was based on a series of previous studies of low-voltage thyristor switches providing pulse durations ~ 2 ns [10].

4. Results and analysis of experimental studies

The first part of the experimental studies included measurements of volt-ampere characteristics in a quasi-static mode, for which the characterograph TECHO-L2-100 was used. The typical shape of the volt-ampere characteristic is shown in Figure 1, *b*. It is important to note that no control pulses were used when measuring the VAC, i. e. the thyristor switch was turned on arbitrarily and, in our opinion, was associated with an increase in the intensity of the shock ionization current generated in the region of the collector $p-n$-junction displaced in the opposite direction. It can be seen that the maximum blocked voltage reaches 120 V. It is important to note that the residual voltage in

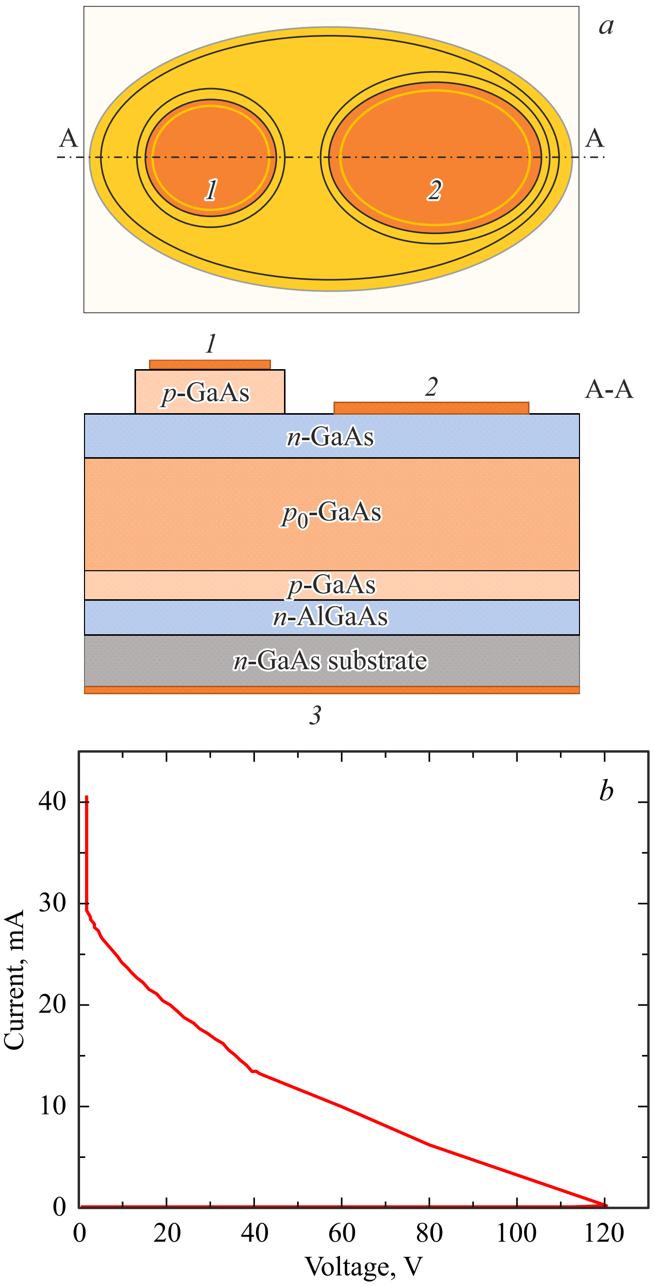

Figure 1. *a* — schematic representation of a thyristor switch (A-A cross section of a structure with layers, *1* — anode, *2* — control electrode, *3* — cathode). *b* — volt-ampere characteristic of a thyristor switch in quasi-static mode.

the switched-on state is ~ 1.5 V, which indicates the high efficiency of the developed design, which ensures operation in the switched-on state without wide electric field domains and additional potential barriers.

The second part of the work was aimed at studying the dynamic characteristics of a thyristor switch. Figure 2, *a* shows the time dependence of the voltage on the storage capacitor, characterizing its discharge rate. It can be seen that the heterothyristor turns on at low operating voltages, which confirms the high feedback efficiency of the developed structure.

However, the switching rates are quite low in the voltage range of 10–40 V, which is caused by the low rate of accumulation of excess charges in the *p*-base. As the voltage increases, the switching process begins to be affected by shock ionization in the collector *p*–*n*-junction, which significantly increases the rate of accumulation of excess charge carriers in the *p*-base and, as a result, increases the speed of the transient process. To evaluate the shape of the current pulse generated in the thyristor switch-storage capacitor circuit, a calculation was performed based on the experimental data obtained on the dynamics of the discharge of a storage capacitor using the following ratio:

$$I(t) = C \cdot dU(t)/dt, \quad (1)$$

where C is the storage capacitor capacity, $U(t)$ is the time dependence of storage capacitor voltage, t is the time. To demonstrate the possibility of the developed switch, the amplitude and shape of the pulse were calculated at a maximum operating voltage of 120 V (the experimental dependence of the voltage on the storage capacitor on time is shown in Figure 2, *a*). The estimates made show that for an operating voltage of 120 V, the maximum amplitude of the current pulse in the circuit of a thyristor switch–finally, a pi capacitor can reach 68 A, with a duration of 2.9 ns at half-height (see the box in Figure 2,*a*), which can be considered a significant progress in the high-speed high-current thyristor switches being developed compared to the known results [8].

An important part of the dynamic characteristics is the delay in switching on the thyristor switch, which is characterized by the difference between the beginning of the control pulse and the beginning of the transition to the switched state. Figure 3 shows the dependence of the switch-on delay time on the amplitude of the control current and the blocked voltage.

It can be seen that the switch-on delay decreases with an increase in the amplitude of the control current pulse and the blocked voltage, and the minimum value of 7 ns is reached for a current of 220 mA and a voltage of 100 V. At the same time, there are such minimum amplitudes of the control current and the blocked voltages, below which the heterothyristor does not turn on. For example, no thyristor activation is observed for a control current of 24 mA and a blocked voltage of < 60 V. This is due to the fact that the recombination losses cannot be compensated by the control current used, i. e., the feedback efficiency is insufficient to turn the thyristor on. Despite a significant increase in the thickness of the *p*-base of the developed thyristor switches, the turn-on delay times achieved are comparable to those previously demonstrated in structures with a thinner base [9].

Figure 4 shows the dependence of the maximum pulse repetition rate on the blocked voltage.

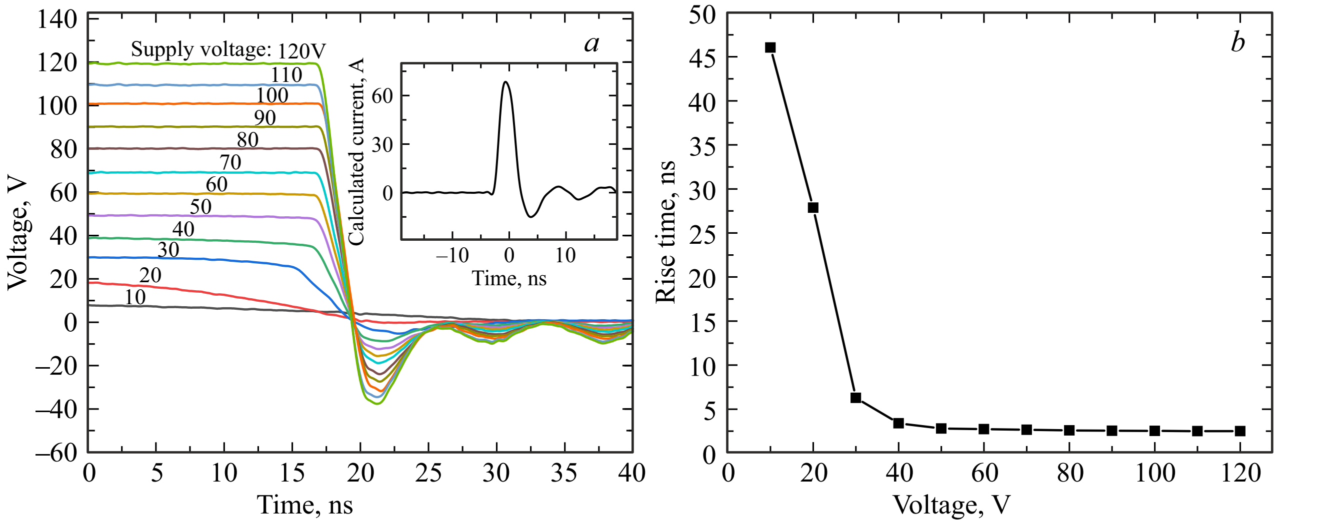

Figure 2. *a* — experimental voltage tracks characterizing the discharge of a storage capacitor obtained for operating voltages from 10 to 120 V. The insert shows the calculated current pulse in the circuit thyristor switch–capacitor at an operating voltage of 120 V, *b* — the dependence of the voltage drop time on the storage capacitor at the level of 10—90 on the supply voltage. Storage capacitor capacity is 1 nF, control current pulse amplitude is 100 mA.

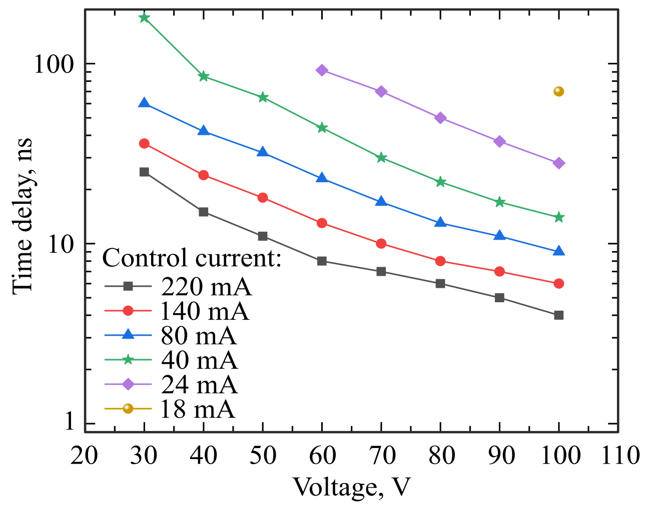

Figure 3. The dependence of the delay time of switching on the thyristor switch on the amplitude of the current, control and operating voltage. Storage capacitor capacity is 1 nF.

It can be seen that an increase in the blocked voltage leads to a decrease in the maximum frequency. As a result, the maximum frequencies for interlocked voltages of 30 and 110 V are 120 and 20 kHz, respectively. The observed dependence can be caused by two mechanisms: effect dU/dt, which generates a barrier capacitance current, as well as the charge current of the storage capacitor, which can be comparable to the holding current, which will not allow the key to switch to a closed state. To assess the second factor, measurements of the capacitor charging currents were carried out. Measurements have shown that charging currents range from 3 to 13 mA, and also decrease with increasing blocked voltage, which allows us to assert the minimal contribution of this factor. Evaluation of the effect dU/dt at a barrier capacity of 200 pF gives an equivalent current of 2 mA. Despite the fact that the value obtained is noticeably less than the required control currents, it may be sufficient to start the process of switching on the thyristor switch. This is due to the fact that the charging current of the barrier container ensures the accumulation of holes directly in the *p*-base, while the flow of holes from the anode contact towards the *p*-base, triggered by the control current, experiences losses due to recombination processes in the doped layer of the *n*-collectors.

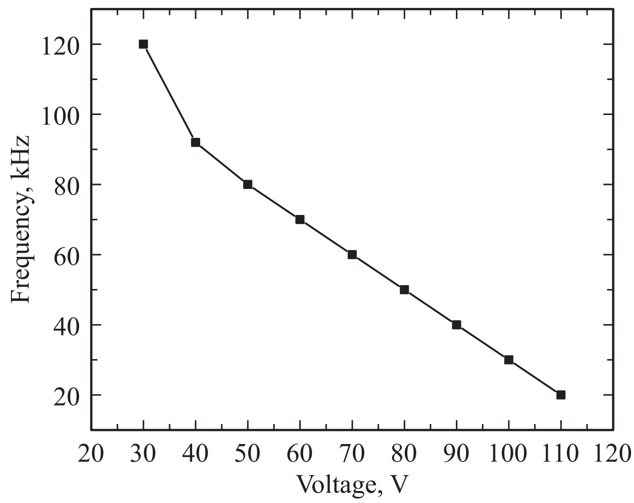

Figure 4. The dependence of the maximum frequency of repetition of current pulses in the thyristor switch-storage capacitor circuit on the operating voltage. Storage capacitor capacity is 1 nF, control current pulse amplitude is 100 mA.

5. Conclusion

In conclusion of the conducted research, it can be said that the developed design of the thyristor switch heterostructure makes it possible to solve the problems of generating current pulses of noticeably higher amplitude while maintaining the required pulse durations in the nanosecond range. Evaluation of the dynamic characteristics of the current pulse shows the possibility of achieving an amplitude of 68 A, and with a duration of 2.9 ns. Achieving these characteristics became possible by increasing the maximum blocked voltage to 120 V in static mode in a structure with an increased thickness of *p*-base. The demonstrated dynamic characteristics show that, despite the increased thickness of the *p*-base, the switch-on delay characteristics and control current pulse parameters are comparable to thyristor switches having thinner base areas. As a result, minimum switching delays of 7 ns were demonstrated at a control current of 220 mA. For dynamic operation, the possibility of generating a sequence of pulses with a frequency of 20 kHz at an operating voltage of 110 V and a frequency of 120 kHz at an operating voltage of 30 V.

Conflict of interest

The authors declare that they have no conflict of interest.

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