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Low-voltage InP heterostyristors for 50−150 ns current pulses generation

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Current switches based on low-voltage InP heterothyristors with a maximum blocking voltage of 20 V were developed and studied. In current pulse generation mode, the efficient operation of InP heterothyristors with a low-resistance load in the form of a capacitor was demonstrated. It has been shown that the minimum turn-on delay time is about 6 ns at a control current amplitude of 60 mA. The possibility of generating current pulses with a duration of 53−154 ns and amplitudes of 38−130 A was demonstrated when the capacitor values were changed in the range of 56−1000 nF.

Keywords: Thyristor, heterothyristor, current switch.

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The approaches to construction of compact and efficient sources of high-power laser pulses ranging in duration from several nanoseconds to several hundred nanoseconds are currently being developed actively [1–3]. Such sources are built based on power semiconductor lasers and a high-current pulse switch, which is often constructed using field-effect transistors. A laser diode and a high-current switch should be positioned in the immediate vicinity of each other to minimize parasitic coupling and operating voltages. This requirement complicates the assembly procedure further. Ideally, these discrete elements should be fabricated in an integrated form. This was achieved in the structures of low-voltage laser thyristors (see, e.g., [4]). The potential to construct high-power pulse sources operating in the spectral range around 900 nm based on multijunction AlGaAs/InGaAs/GaAs heterostructures was demonstrated. However, the spectral range of these integrated laser thyristor structures is limited in the long-wave part by the capacity to fabricate a high-quality active region in a GaAs−InGaAs system [5,6]. A thyristor structure with a typical bistable current-voltage characteristic operating at 1550 nm has been presented in [7]. However, controlled turn-on was not implemented in the proposed design (the device could be rendered conducting only by excess voltage), and its dynamic characteristics were not examined. In addition, the blocking voltage was much too low to construct high-power pulse emitters. These are the reasons why the issue of development of low-voltage thyristor structures in other solid solution systems (specifically, the InGaAsP/AlInAs/InP system, which provides an opportunity to produce highly efficient high-power semiconductor lasers operating in the 1300−1900 nm spectral range [8,9]) remains topical.

The present study is the first to report on the construction and characteristics of a low-voltage InP heterothyristor heterostructure that has the capacity to generate current pulses ranging in duration from several tens to hundreds of nanoseconds. It will be used in the future as a basis for high-power pulse laser thyristors operating in the 1300−1900 nm spectral range.

As was demonstrated earlier, a low-voltage laser thyristor heterostructure may be presented as a light-emitting diode/*n*−*p*−*n*- phototransistor optocouple. This approximation for AlGaAs/GaAs laser thyristor heterostructures was substantiated by a suppressed through hole injection with heterobarriers operating in the waveguide layer. Excess holes in the *p*- base of an *n*−*p*−*n*- phototransistor are then supplied as a result of impact ionization in the collector *p*−*n*- junction field domain and photogeneration in the *p*- due to absorption of a fraction of spontaneous emission of the active region. However, in the general case, hole leakage may occur in certain LED operating modes at a high threshold concentration, thus opening an additional channel of excess hole supply to the *p*- base. Thus, the following three mechanisms may establish positive feedback for a heterothyristor in the on state: photogeneration, impact ionization, and hole leakage. It was found that an *n*−*p*−*n*- transistor part design with a space-charge region formed in the weakly doped *p*- base layer is best suited for efficient operation at low voltages in the pulse mode. This allows one to preserve the position of the maximum of the collector *p*−*n*- junction field domain in transition from the off state to the conducting state. Following this analysis, we chose an InP- heterothyristor heterostructure design that incorporates an LED part based on *n*- and *p*-AlInAs emitters, a waveguide layer with an active region based on AlInGaAs, and a homojunction transistor part with an *n*-InP emitter, a *p*-InP base with a thickness of 4 μm, and a *n*-InP collector adjacent to the LED part. A heterostructure of this design was grown by metalorganic vapor-phase epitaxy (MOS hydride epitaxy). A sequence of post-growth operations was then performed to fabricate a strip anode contact 200 μm in width on the *p*-AlInAs emitter side of the LED part (bounded on both sides by strip contacts of the control electrode, which were formed in the *n*-InP collector layer of the homojunction transistor part) and a solid cathode contact on the *n*-InP substrate side. Heterothyristor crystals of various lengths were then fabricated from this structure and mounted onto copper heat sinks with indium solder.

Static characteristics were examined first. The examination of static current-voltage curves revealed that the maximum blocking voltage is as high as 20 V, while the residual voltage in the conducting state does not exceed 1.4 V, which is a minimum value for such a structure and is indicative of efficient feedback maintaining the conducting thyristor state. Heterothyristor crystals were introduced into an elementary circuit in order to study their dynamic characteristics. This circuit featured a capacitor connected in parallel to a heterothyristor, a power supply for charging the capacitor to the needed voltage when the heterothyristor is in the off state, and a generator used to pump the LED part by control current pulses via the control electrode. No additional load resistors limiting the operation capabilities of thew designed low-voltage heterothyristor were installed. The dynamic performance of a heterothyristor operated as a current switch was analyzed by measuring the variation of voltage of the discharging capacitor. A fast-response high-frequency electric probe with a band width of 1 GHz connected to an oscilloscope with the same band width was used to examine the capacitor discharge dynamics. In the general case, the heterothyristor turn-on dynamics has a characteristic turn-on delay time that is defined as the time elapsed from the origin of a control current pulse to the onset of the process of irreversible capacitor discharge. The turn-on delay magnitude may vary from several nanoseconds to several milliseconds and depends on the operation conditions: the amplitude and duration of a control current pulse and the blocking voltage. One may also determine the energy efficiency of control [10], which is specified by the energy of a control pulse and depends on the same indicated parameters. In addition, the turn-on delay time is crucial to the generation of high-frequency pulse trains. In view of this, typical turn-on delay times of the designed structures were examined experimentally. Figure 1 shows the characteristic dependences of the turn-on delay time for a heterothyristor crystal 700 μm in length and a 56 nF capacitor. It can be seen that the turn-on delay time decreases with an increase in the blocking voltage and the pump current amplitude. The minimum delay is 6 ns at a control current amplitude of 60 mA and a blocking voltage of 20 V. It is also evident that the range of variation of the turn-on delay time expands as the control current amplitude

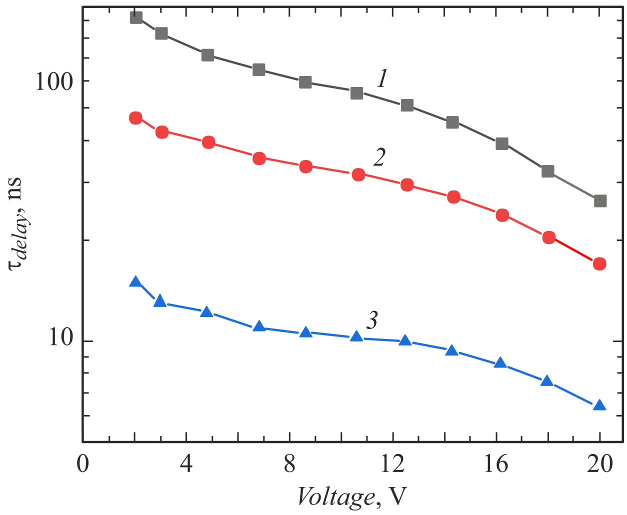

Figure 1. Dependences of turn-on delays on the supply voltage at control current pulse amplitudes of 18 (*1*), 34 (*2*), and 60 mA (*3*). The discharge capacity is 56 nF.

decreases. For example, the turn-on delay time decreases from 93 to 26 ns as the blocking voltage rises from 2 to 20 V at a control current amplitude of 18 mA.

The operation speed is another important parameter of a thyristor heterostructure. In the present study, current pulses were generated as a result of discharge of a capacitor connected in parallel to a heterothyristor. The considered circuit is elementary and provides only for a controlled transition of a heterothyristor into the on state induced by a control current pulse. A heterothyristor in the on state is characterized by a low resistance, which allows for efficient capacitor discharge. When the current in the circuit drops below the holding current, a heterothyristor is turned off. Thus, the pulse duration is specified by the used capacitor value and the parameters of a thyristor acting as a fast current switch. Figure 2 shows the experimental dependences characterizing the variation of capacitor voltage in transition of a heterothyristor into the conducing state. The thyristor and the capacitor remained connected to the power supply in the course of measurement, since their disconnection did not affect the examined characteristics in single-pulse operation. The current pulse duration was estimated additionally as the width of an optical signal pulse of the LED part at 20% of its maximum (Fig. 2). A circuit featuring lenses with a numerical aperture of 0.5, which collected spontaneous emission efficiently within the photodetector area, was used to detect this optical signal. A photodetector with a receiving area 300 μm in diameter and a frequency band in excess of 1 GHz was used in the experiment. The spectral sensitivity at a wavelength of 1550 nm was 0.8 A/W. As was expected, an increase in capacity provided an opportunity to extend the discharge time and, consequently, the current pulse duration in the heterothyristor circuit. The current pulse duration in our

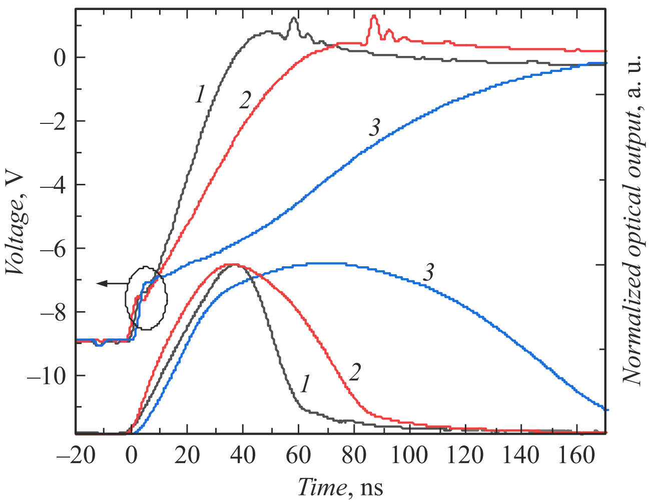

Figure 2. Time dependences of the measured capacitor voltage and normalized optical pulses at a control current amplitude of 60 mA for a discharge capacity of 56 (*1*), 220 (*2*), and 1000 nF (*3*).

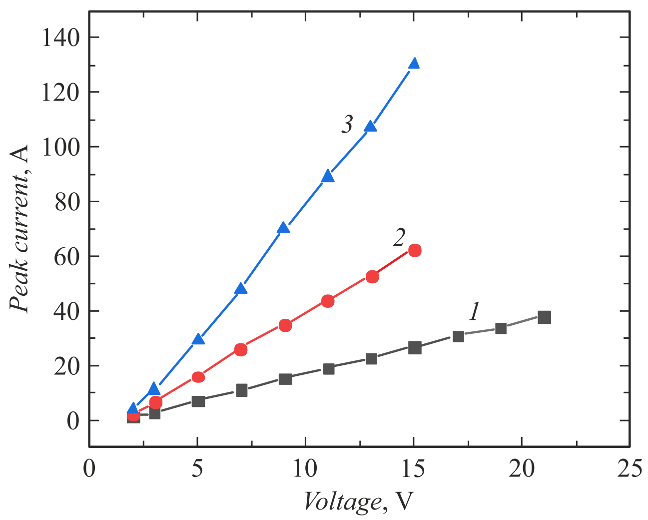

Figure 3. Dependences of the peak current generated by a heterothyristor on the blocking voltage for a discharge capacity of 56 (*1*), 220 (*2*), and 1000 nF (*3*).

experiments was 53, 76, and 154 ns at a capacitor value of 56, 220, and 1000 nF, respectively.

The amplitude of a current pulse generated in the heterothyristor circuit is a parameter of practical importance. Figure 3 presents the dependences of peak current on the blocking voltage calculated based on the experimental dynamics of the discharge voltage and the capacitor values. The peak current was estimated as $I = CdU/dt$, where C is the capacitor value, by differentiating the voltage dependences in the range of voltages from -3 to -4 V (Fig. 2). The peak currents were 38, 62, and 130 A at a capacitor value of 56, 220, and 1000 nF, respectively. It is evident that the dependences of peak current on the blocking voltage are linear and the slope is 2, 4.6, and 9.7 A/V at a capacitor value of 56, 220, and 1000 nF, respectively. The slope grows sublinearly with increasing capacitor value, since the pulse duration increases. The peak currents are comparable to the amplitudes of pump currents at which the optical power of semiconductor lasers operating at a wavelength of 1500 nm and pumped by an external generator still continues to grow efficiently [11,12]. Therefore, the obtained results may be used in the future for the construction of both high-power pulse laser thyristors operating at 1500 nm and hybrid assemblies with semiconductor lasers for pulse pumping.

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Conflict of interest

The authors declare that they have no conflict of interest.

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