Semiconductors, 2024, Vol. 58, No. 3

Low-voltage current switches based on AlInGaAsP/InP thyristor heterostructures for nanosecond pulsed laser emitters (1.5 μm)

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Received April 25, 2024
Revised May 3, 2024
Accepted May 6, 2024

The study examines current switches based on InP thyristors designed for pulsed 1400−1600 nm laser emitters. The heterostructure of the switch includes an InP transistor section and an upper InP/AlInGaAs/InGaAsP heterodiode, simulating a laser heterostructure. For switch samples with an anode contact size of $200 \times 250\,\mu$m and two control contacts of $200 \times 250\,\mu$m, the ability to generate current pulses with durations of 3−5 ns and amplitudes exceeding 6−8 A at a supply voltage of 16 V was demonstrated. The pulse repetition frequency reached 100 kHz.

Keywords: Thyristor, current switch.

DOI: 10.61011/SC.2024.03.58841.6404

1. Introduction

Currently, an urgent area of practical application of pulsed semiconductor laser sources of nanosecond and subnanosecond duration is the creation of lidar systems for autonomous vehicles based on the technology of time-of-flight (ToF) three-dimensional scanning (time-of-flight 3D range imaging) [1,2]. The safety of radiation for human vision is one of the key requirements for laser pulse sources when creating a ToF lidar for use in road transport. The use of radiation sources at a wavelength of $\sim 1.5\,\mu$m solves this problem [3]. Another serious problem is the complexity of organizing current pumping at the required pulse durations < 5 ns. In particular, a semiconductor laser for a current pulse source is a low-resistance load. In this case, the impact of the parasitic inductance of the current circuit becomes critically important. The traditional method of pumping from an external current switch (pump current pulse source) [4,5] has significant limitations. The limitations are attributable to parasitic inductances and resistances of the current circuit or requirements for a high-frequency (HF) pump current pulse delivery line. An increase of the voltage of the pump pulse in combination with an increase of the resistance of the current circuit reduces the negative effect of parasitic inductance [6,7]. Another promising way to overcome this problem is to reduce the size of the current circuit by using vertical integration of laser emitters and current switches (hybrid [6–10] and epitaxial integration [11,12]). The dynamic characteristics of current switches based on InP-thyristors are studied in this paper as well as hybrid vertical assemblies based on a laser diode and a current switch designed to create pulse emitters at a wavelength of 1400−1600 nm. The objectives of this study are: (1) study of the possibility of creating emitters with nanosecond optical pulse duration based on hybrid vertical assemblies for the spectral range of 1400−1600 nm, (2) demonstration of the promising possibility of creating epitaxially integrated pulse emitters based on a laser thyristor heterostructure with the radiating part at a wavelength in the range of 1400−1600 nm.

2. Experimental samples and measurement scheme

The schematic diagram of the hybrid vertical assembly considered in this paper is shown in Figure 1. The current switch was fabricated on the basis of a thyristor heterostructure grown using the MOCVD method. The heterostructure of the switch was similar to the structure described in Ref. [13] and included a transistor part and an upper InP/AlInGaAs/InGaAsP heterodiode. The transistor part included p-InP base doped with zinc up to 10^{16} cm^{-3} with a thickness of $3\,\mu$m and n-InP-collector doped with silicon up to 10^{18} cm^{-3} with a thickness of $1.3\,\mu$m. n-InP-layer doped with silicon to 10^{18} cm^{-3} located on the side of the substrate functioned as the n-emitter. A heterodiode was grown onto the transistor part, simulating a laser heterostructure at a wavelength in the range of 1400−1600 nm. The heterodiode simulated energy barriers of a laser heterostructure in the

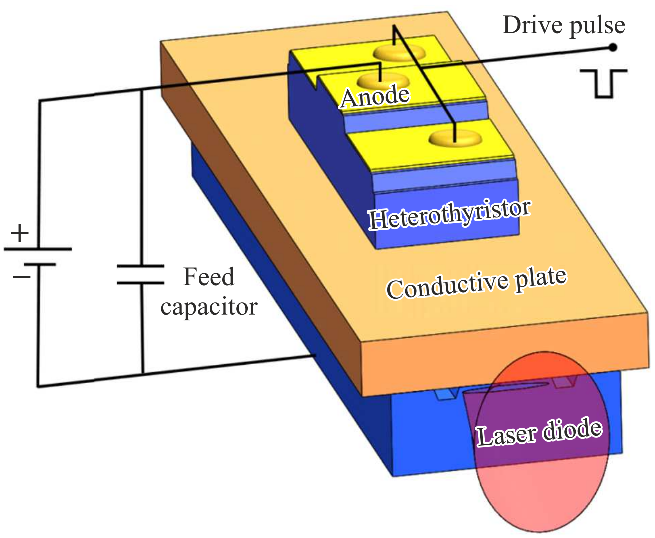

Figure 1. Schematic wiring diagram of a vertical assembly of a current switch and a laser diode. (A color version of the figure is provided in the online version of the paper).

wavelength range of 1400–1600 nm, which prevent the through flow of holes from the anode contact into the collector p–n-junction of the lower transistor part of the current switch heterostructure. This was achieved by using n-InP and p-InP wide-band emitters in the structure of the heterodiode, as well as a narrow-band waveguide based on AlInGaAs with a thickness of 0.4 μm. Samples of current switches of a mesastripe design with an anode contact width of 200 μm and two side control contacts with a width of 200 μm each were fabricated from the proposed heterostructure. The cathode contact was applied in a continuous layer on the side of the substrate, thinned to 150 μm. Current switch chips with a total size of $250 \times 650\,\mu$m with an anode size of $250 \times 200\,\mu$m were fabricated by splitting. The maximum static blocking voltage of the collector p–n-junction of the current switch reached 18 V. Experimental samples of two types were studied in this paper. The first type of samples (Figure 1) was in the form of a vertical hybrid assembly of a current switch chip and a stripe-shaped laser diode chip with a wavelength of 1550 nm with an aperture width of 100 μm. The second type of samples consisted only of a current switch chip soldered with the cathode side directly onto a copper heat sink.

3. Measurement procedure and results

The dynamics of switching on samples of thyristor current switches was studied using a high-resistance high-speed measuring probe with a frequency band of 500 MHz. The order of operation of the electrical circuit was as follows: (1) DC voltage was supplied to the sample, while the supply capacitor was charged to the required static voltage (Figure 1); (2) a control pulse was applied after that to the control contact from the generator (the amplitude of the control current pulse was 50 mA), the typical on-delay was 25–15 ns for voltages of 4–16 V and was similar to the results obtained earlier in Ref. [13]. The control current pulse allowed the thyristor switch to be set to an open state with low resistance, which ensured effective discharge of the supply capacitor. The shape and amplitude of the current pulse generated in the laser thyristor switch circuit was evaluated using two methods. The parameters of the generated current pulse were estimated for the first method using an optical power pulse received by a laser diode mounted in series with a current switch. A Fabry-Perot semiconductor laser with a wavelength of 1.47 μm and a radiating aperture width of 100 μm was used in this study. A vertical hybrid design of a current switch and a laser diode was assembled to reduce the size of the current circuit and reduce parasitic resistances and inductances (Figure 1). The amplitude of the current in the circuit was calculated in the second method based on the time dependences of the voltage dynamics on the discharge capacitor from the ratio of $I = C \cdot dU/dt$, where C — the rating of the supply

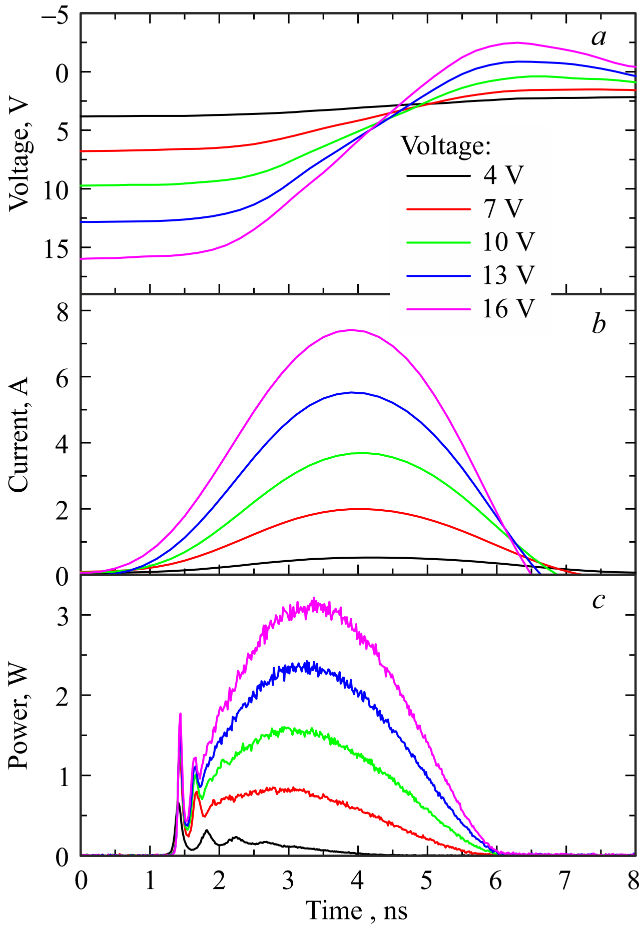

Figure 2. Time dependences of dynamics: a — voltage on the supply capacitor, b — calculated current in the circuit, c — output optical power of the laser emitter (the shape of the laser pulse was recorded by a photodetector with frequency band 20 GHz).

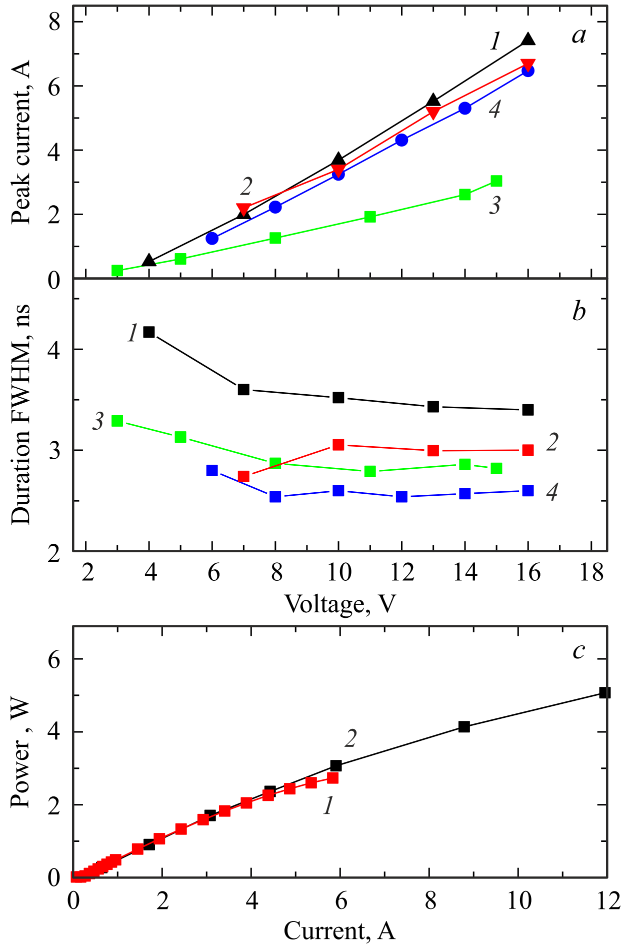

Figure 3. *a* — calculated amplitude of the current pulse and *b* — duration of the current pulse at half-height for various ratings of the supply capacitor, nF: *1* — 1.41, *2* — 1.41 (calculation of the optical pulse amplitude), *3* — 0.47, *4* — 0.94. *c* — dependences of the optical output power on the pumping current obtained separately for laser diodes pumped by external sources: *1* — continuous pumping mode, *2* — pumping with pulses of 100 ns duration.

capacitor, U — voltage on the supply capacitor, obtained using a high-speed measuring probe. The dynamics of voltage, current and optical power in hybrid assemblies with a supply capacitor rating of 1.4 nF are considered at the first stage of the study. A good matching of the calculated shape of the current pulse and the measured shape of the optical pulse can be seen from the presented dependencies (Figure 2).

The calculated amplitude of the current pulses reached 6.8 A for a supply voltage of 16 V, and the duration of the optical and current pulses were 3.2 and 3.5 ns at half maximum (the difference is attributable to the presence of a laser generation threshold).

Further, the current pulse amplitudes in the discharge circuit of the studied current switch were evaluated from the amplitude of the recorded optical pulses (Figure 3, *a*, dependencies *1, 2*). The watt-ampere characteristics measured separately for similar laser diodes pumped by external current sources, both in pulsed mode with a duration of 100 ns and in continuous mode were used for this purpose (Figure 3, *c*) [14]. The estimates of the current amplitudes in the discharge circuit obtained by two methods have a good match (Figure 3, *b*, dependencies *1* and *2*). The dependences of the amplitude on the voltage are linear. Thus, the dynamics of the voltage on the supply capacitor can be used to evaluate the operation of a thyristor current switch. The possibility of reduction of the duration of the received current pulse was studied at the second stage, for which samples of the second type were studied — current switches with 0.47 and 0.94 nF supply capacitors. The amplitudes of the current at a supply voltage of 16 V reached 3 A and for 0.47 nF and 6.2 A for 0.94 nF, while the pulse durations at half maximum in the voltage range of 8–16 V were about 2.8 and 2.6 ns, respectively. Thus, the use of a lower capacitor rating made it possible to reduce the duration of the current pulse to < 3 ns. The pulse repetition rate in the experiments reached 100 kHz.

4. Conclusion

The achieved maximum amplitudes (6–8 A) and pulse durations (< 3 ns) of current make the proposed low-voltage (supply voltage up to 16 V) current switches promising sources of current pumping pulses for emitters used in ToF lidars since such durations will significantly increase the spatial resolution of such lidar systems. The use of multi-element structures for hybrid vertical assemblies in the future will increase the amplitude of the pump current pulses and, consequently, the output optical power of the laser emitter. It should also be noted that the InP/InGaAsP heterostructure with an InP transistor part and an upper *p–n*-heterojunction simulating a laser heterostructure is promising for creating epitaxially integrated emitters based on it by replacing the upper *p–n*-junction to a laser heterostructure. At the same time, unlike GaAs/AlGaAs thyristors, the available wavelength range of 1400–1600 nm meets the radiation safety requirements for modern ToF lidar emitters used in automotive autonomous control systems.

Funding

The experimental samples were developed, fabricated and studied within the scope of the project of the Russian Science Foundation No. 22-79-10159. Post-growth operations were developed within the scope of the state assignment of Ioffe Institute of Physics and Technology.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by A.Akhtyamov