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A Study of Epitaxially Stacked Tunnel-Junction Semiconductor Lasers Grown by MOCVD

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Abstract—Design parameters of epitaxially stacked tunnel-junction asymmetric separate-confinement laser heterostructures are chosen. Technological modes for fabrication of heterostructures of this kind by metal-organic chemical vapor deposition in the system of AlGaAs/GaAs/InGaAs solid solutions are found. It is demonstrated that high-efficiency GaAs:Si/GaAs:C tunnel structures and asymmetric AlGaAs/GaAs/InGaAs laser heterostructures with low internal optical loss can be fabricated in a single technological process. Conditions are chosen in which a deep mesa can be formed for fabrication of mesa-stripe diode lasers based on epitaxially stacked tunnel-junction laser heterostructures. Mesa-stripe diode lasers with a 150 × 12-μm aperture have been manufactured on the basis of these structures. These samples have a threshold current density J_{th} of 96 A cm^{-2}, internal optical loss α_i of 0.82 cm^{-1}, and differential resistance $R = 280$ mΩ. Samples containing three laser structures have a slope efficiency of 3 W A^{-1} and a maximum peak output power of 250 W in the pulsed operation mode (100 ns, 1 kHz).

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1. INTRODUCTION

This study continues research aimed to develop high-power pulsed semiconductor emission sources [1–3]. As noted previously, the optical power of semiconductor lasers can be raised by creating emission sources based on epitaxially stacked tunnel-junction laser heterostructures [4–8]. In [3], technological modes in which GaAs:Si/GaAs:C tunnel *p–n* junctions can be fabricated by MOCVD were determined. The epitaxially stacked tunnel-junction laser heterostructure is a set of *N* laser heterostructures successively grown in a single technological process and connected by tunnel junctions. The aim of the present study was to choose technological conditions for MOCVD epitaxy in which epitaxially stacked tunnel-junction laser heterostructures can be grown in the system of AlGaAs/GaAs/InGaAs solid solutions and mesa-stripe lasers based on these heterostructures can be fabricated.

To accomplish this task, the following problems were solved. The first was to combine the fabrication of a high-efficiency tunnel *p–n* junction and an asymmetric separate-confinement heterostructure with an expanded waveguide in a single technological process. The second problem was to develop a technique for fabricating a deep mesa-stripe design of active elements comprising two and three epitaxially stacked tunnel-junction laser heterostructures.

2. CHOICE OF DESIGN OF THE EPITAXIALLY STACKED TUNNEL-JUNCTION LASER HETEROSTRUCTURE

According to the concept of high-power semiconductor lasers, an asymmetric separate-confinement heterostructure with an expanded waveguide is the basis for high-power CW and pulsed semiconductor lasers [9–11]. The internal optical loss in a separate-confinement laser structure is represented by the sum of losses in the active region, waveguide, and emitter layers. Therefore, the doping level of the emitter layers is commonly chosen so that the effective injection of carriers of both sign is preserved and the loss for scattering by free carriers in the emitter layers, which are the most heavily doped, is at a minimum. In epitaxially stacked tunnel-junction laser heterostructures, a tunnel *p–n* junction is fabricated between the emitters of series-connected structures. It was shown in [3] that, to obtain a high-efficiency *p–n* junction, it is necessary to dope GaAs layers with acceptor and donor impurities to (8–9) × 10^{19} cm^{-3}. With C and Si used as, respectively, acceptor and donor impurities, an abrupt *p–n* junction can be obtained because of the low diffusion broadening of the profiles of both the dopants. It follows from general considerations that the thickness of the epitaxially stacked tunnel-junction laser structure should be minimized to provide optimal conditions for postgrowth procedures in which the mesa-stripe structure of the active element is formed. The thickness of the emitters can be varied in the epitaxially stacked tunnel-junction laser heterostructure because the waveguide thickness of the asymmetric separate-confinement structure is fixed according to the data reported in [9–11]. The thickness of the emitter layers was calculated so as to provide a <5% internal optical loss in the emitters of the epitaxially stacked tunnel-junction laser structure via propagation of light in layers constituting the tunnel *p–n* junction. The band structure of the epitaxially stacked tunnel-junction laser heterostructure and the distribution of the electromagnetic radiation in waveguides of the laser structures are shown schematically in Fig. 1. The table lists the thicknesses, compositions, and doping levels of an epitaxially stacked tunnel-junction laser heterostructure with two tunnel *p–n* junctions.

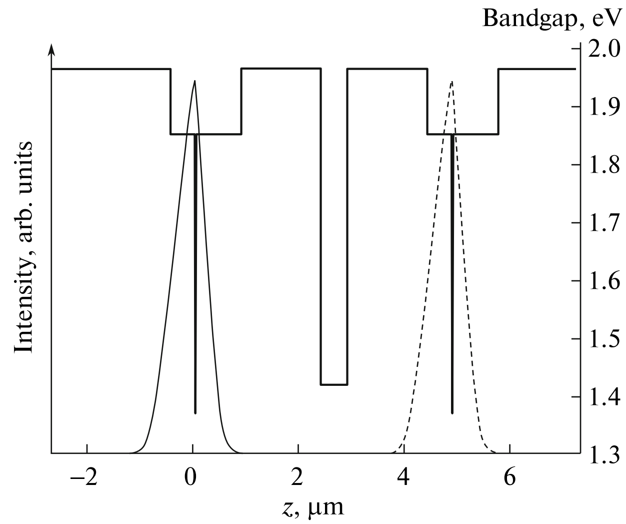

Fig. 1. Band diagram of an epitaxially stacked tunnel-junction laser heterostructure and the distribution of the electromagnetic radiation in the waveguide of the laser structure.

3. EXPERIMENTAL SAMPLES OF MESA-STRIPE LASERS BASED ON EPITAXIALLY STACKED TUNNEL-JUNCTION LASER HETEROSTRUCTURES WITH ONE OR TWO TUNNEL *p–n* JUNCTIONS

MOCVD epitaxy was used to fabricate epitaxially stacked tunnel-junction laser heterostructures with one (type A) and two (type B) tunnel *p–n* junctions. Figure 2 shows a cross-sectional micrograph of an epitaxially stacked tunnel-junction laser heterostructure comprising three asymmetric separate-confinement laser structures (Type B). The total thicknesses of epitaxially stacked tunnel-junction laser heterostructures of types A and B are 11 and 16 μm, respectively. Raising the total thickness of the laser structures imposes additional requirements to maintain the conditions of the technological process constant. The laser structures were fabricated with magnesium and silicon doping impurities by the technique developed in [12]. The tunnel *p–n* junctions connecting the laser structures were fabricated using weakly diffusing carbon and silicon dopants by the technological scheme developed in [3].

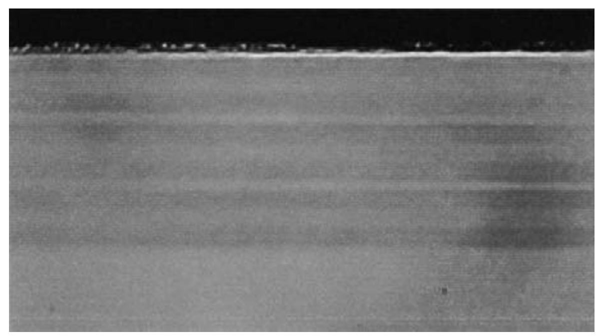

Fig. 2. Cross-sectional micrograph of an epitaxially stacked tunnel-junction laser heterostructure composed of three asymmetric separate-confinement laser structures (type B).

The active laser elements were fabricated on the basis of epitaxially stacked tunnel-junction laser structures by a well-developed scheme for fabrication of multimode mesa-stripe lasers with an emission aperture of ~150 μm [12]. To provide a complete current confinement in all the series-connected laser structures, the mesas bounding the waveguide of the active laser element were etched to a depth of two (type A) or three (type B) laser structures. A trapezoidal mesa was formed to provide uniform and full removal of etching products and technological effectiveness of the subsequent postgrowth procedures. Figure 3 shows a micrograph of an active laser element constituted by epitaxially stacked tunnel-junction laser structure of type B. The electrical insulation was provided by deposition of silicon dioxide, after which a Zn/Au ohmic contact and a reinforcing Au layer were deposited onto the

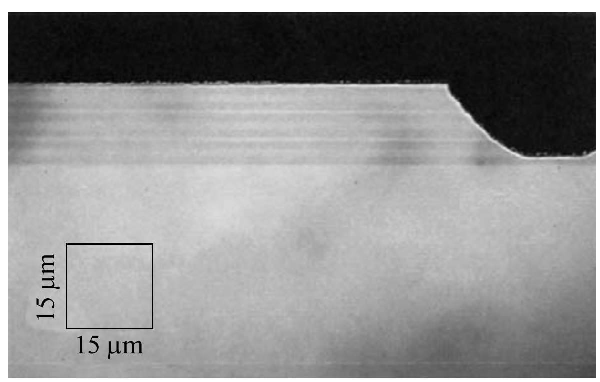

Fig. 3. Cross-sectional micrograph of the Fabry–Perot cavity of a mesa-stripe laser with three asymmetric separate-confinement laser heterostructures series connected by tunnel *p–n* junctions (type B).

Epitaxially stacked tunnel-junction laser structure with two tunnel *p*–*n* junctions

No.	Layer	Composition	Doping level, cm^{-3}	Thickness
1	*n*-type substrate	GaAs (100)	*n*: 3×10^{18}	350 μm
2	*n*-type emitter	$Al_{0.5}Ga_{0.5}As$	*n*: 10^{18} (Si)	1.8 μm
3	Waveguide	$Al_{0.3}Ga_{0.7}As$	Undoped	0.85 μm
4	Spacer	GaAs	″	7 nm
5	Active region (QW)	$Ga_{0.94}In_{0.06}As$	″	10 nm
6	Spacer	GaAs	″	7 nm
7	Waveguide	$Al_{0.3}Ga_{0.7}As$	″	0.45 μm
8	*p*-type emitter	$Al_{0.5}Ga_{0.5}As$	*p*: 10^{18} (C)	1.54 μm
9	Tunnel P^+-layer	GaAs	*p*: 2×10^{20} (C)	0.12 μm
10	Tunnel N^+-layer	GaAs	*n*: 2×10^{20} (Si)	0.12 μm
11	*n*-type emitter	$Al_{0.5}Ga_{0.5}As$	*n*: 10^{18} (Si)	1.54 μm
12	Waveguide	$Al_{0.3}Ga_{0.7}As$	Undoped	0.85 μm
13	Spacer	GaAs	″	7 nm
14	Active region (QW)	$Ga_{0.94}In_{0.06}As$	″	10 nm
15	Spacer	GaAs	″	7 nm
16	Waveguide	$Al_{0.3}Ga_{0.7}As$	″	0.45 μm
17	*p*-type emitter	$Al_{0.5}Ga_{0.5}As$	*p*: 10^{18} (C)	1.54 μm
18	Tunnel P^+-layer	GaAs	*p*: 2×10^{20} (C)	0.12 μm
19	Tunnel N^+-layer	GaAs	*n*: 2×10^{20} (Si)	0.12 μm
20	*n*-type emitter	$Al_{0.5}Ga_{0.5}As$	*n*: 10^{18} (Si)	1.54 μm
21	Waveguide	$Al_{0.3}Ga_{0.7}As$	Undoped	0.85 μm
22	Spacer	GaAs	″	7 nm
23	Active region (QW)	$Ga_{0.94}In_{0.06}As$	″	10 nm
24	Spacer	GaAs	″	7 nm
25	Waveguide	$Al_{0.3}Ga_{0.7}As$	″	0.45 μm
26	*p*-type emitter	$Al_{0.5}Ga_{0.5}As$	*p*: 10^{18} (C)	1.5 μm
27	Contact *p*-layer	GaAs	*p*: 10^{18} (C)	0.5 μm

entire surface of the contact p^+-layer. To achieve full electrical insulation, the thickness of the silicon dioxide layer was not less than 0.2 μm. Mirrors and antireflection coatings were deposited onto edges of the Fabry–Perot cavity after preliminary etching and nitridization of the cleaved surface. The active laser elements constituted by structures of types A and B were mounted on copper heatsinks and prepared for a study of their emission characteristics.

4. A STUDY OF EMISSION CHARACTERISTICS OF MESA-STRIPE LASERS BASED ON EPITAXIALLY STACKED TUNNEL-JUNCTION LASER HETEROSTRUCTURES WITH ONE OR TWO TUNNEL *p*–*n* JUNCTIONS

To characterize semiconductor lasers based on epitaxially stacked tunnel-junction laser structures of types A and B, the dependences of the threshold current density and inverse differential quantum efficiency on the laser cavity length were measured, which made it possible to find the internal loss and the threshold current density for a laser with an infinitely long cavity. All measurements were made in the pulsed mode with current pulse widths of 100 ns and a repetition frequency of 1 kHz. The threshold current density for lasers based on a structure of type B was 96 A cm^{-2}, which almost coincided with the threshold current density for the best samples of single lasers emitting at a wavelength of 905 nm. This pointed to a high degree of current insulation by silicon dioxide in the mesa-stripe design of the active laser element and to reproducibility of the technological process used to fabricate epitaxially stacked tunnel-junction laser structures. The stimulated quantum efficiency reached a value $\eta_i \approx 100\%$ for epitaxially stacked tunnel-junction laser structures, which corresponded to the best values of η_i for single structures. The values of the internal optical loss for epitaxially stacked tunnel-junction laser structures were of particular interest. These val-

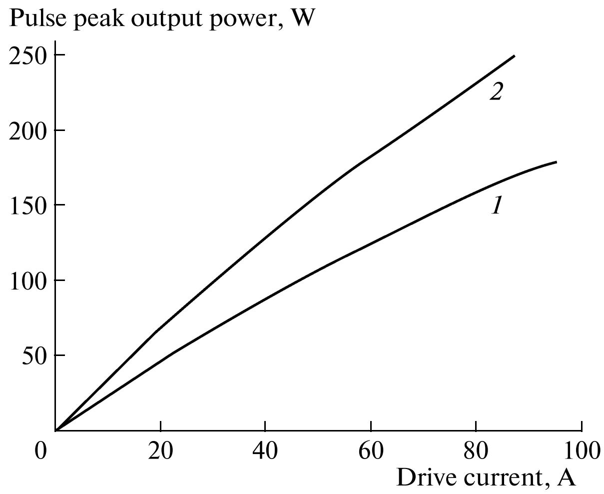

Fig. 4. Light–current characteristics of mesa-stripe lasers based on epitaxially stacked tunnel-junction laser structures with (*1*) one (type A) or (*2*) two (type B) tunnel *p*–*n* junctions.

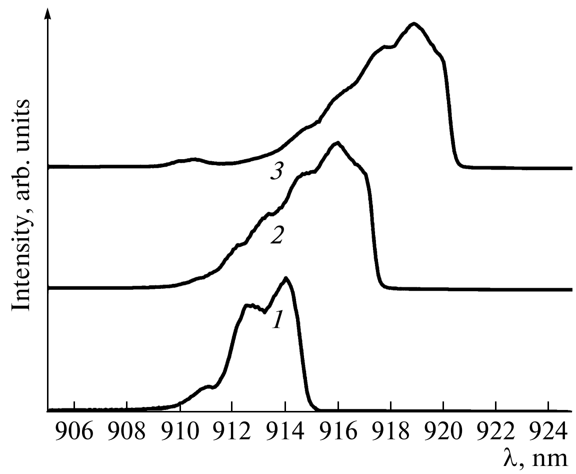

Fig. 5. Emission spectra of mesa-stripe lasers based on epitaxially stacked tunnel-junction structures with two tunnel *p*–*n* junctions (type B) at different drive currents *I*: (*1*) 2, (*2*) 22, and (*3*) 47 A.

ues (0.82 cm^{-1}) were also close to those for the best single laser structures, which is indicative of a correct choice of the design of epitaxially stacked tunnel-junction laser heterostructures.

Figure 4 shows light–current characteristics of mesa-stripe lasers based on epitaxially stacked tunnel-junction laser structures of types A and B. A characteristic feature of the laser structures under study is that the slope efficiency is 2 W A^{-1} for structures of type A and 3 W A^{-1} for those of type B. It should be taken into account that the apertures of mesa-stripe lasers based on structures of types A and B are 150 × 7 and 150 × 12 μm, respectively, compared with 150 × 2 μm for single laser structures. The mesa-stripe lasers based on structures of both types failed to reach the lasing threshold in the CW mode, which points to the high temperature sensitivity of the mesa-stripe lasers fabricated. In the pulsed lasing mode, a weak deviation of the light–current characteristics from linearity was observed for structures of both types up to drive currents of 80–100 A.

The series resistances of the mesa-stripe lasers based on structures of types A and B at a cavity length of 3–4 mm were 240 and 280 mΩ, respectively, which makes it possible to attribute the high temperature sensitivity of the semiconductor lasers to their large distance from the heatsink.

Figure 5 shows integral spectral characteristics of the mesa-stripe epitaxially stacked tunnel-junction lasers of type B. A certain broadening of the emission spectra is observed, especially at high drive currents, which is due, in our opinion, to the different temperatures of the active regions of the epitaxially stacked tunnel-junction laser structures.

In the far-field patterns of the lasers under study, there are no differences from lasers constituted by a single laser structure, because these patterns are fully determined by the size of the emitting surfaces forming the waveguides and by the refractive indices of the constituent semiconducting materials. The laser beam divergence angle was 15° and 32° in the parallel and perpendicular planes, respectively.

5. CONCLUSIONS

The study demonstrated the possibility of combining fabrication of asymmetric separate-confinement laser heterostructures and high-efficiency tunnel *p*–*n* junctions in a single technological MOCVD process in the system of AlGaAs/GaAs/InGaAs solid solutions. The possibility of satisfying the requirements of the concept of high-power semiconductor lasers in laser structures series connected by heavily doped layers of a tunnel *p*–*n* junction was demonstrated. This is manifested by the fact that a value of 0.82 cm^{-1} is obtained for the internal optical loss by scattering. The formation conditions of a deep mesa were chosen for providing a full electrical insulation of several laser and tunnel *p*–*n* junctions in fabrication of mesa-stripe lasers based on epitaxially stacked tunnel-junction laser heterostructures. It was shown that introduction of two high-efficiency tunnel GaAs:Si/GaAs:C *p*–*n* junctions into the epitaxially stacked tunnel-junction structure makes it possible to obtain a series differential resistance R = 280 mΩ in a mesa-stripe laser.

The series connection of three laser heterostructures with tunnel *p*–*n* junctions enables a threefold increase in the slope efficiency, compared with a single laser, which makes it possible to raise its value to 3 W A^{-1} in the pulsed lasing mode (100 ns, 1 kHz). In this case, the maximum emission power is as high as 250 W.

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