THE LASER DIODE MODULES

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Laser diodes are in requisition due to a wide range of utilization as optical pump sources of solid-state lasers; in transmission of optical signal through the atmosphere; in monitoring of environment; in medicine; in a military necessity and in others ranges. At present that's impossible existence of any modern medicine without multifunction laser systems take on special significance. The greater is the output power of the laser, the more divers is its application domain. In laser printers, therapeutic apparatus an optical power output in the 10–100 mW range is required and again we see diode laser diodes in most of applications where 10–100 mW optical output is required. The major benefits of semiconductor laser diodes in comparison with other lasers are the greatest efficiency, lower power consumption, reduced size, lower cost, etc. These characteristics of diode lasers are very suitable for the majority of applications.

Low threshold current laser diodes are attractive light sources for GaAs-based optoelectronic integrated circuits, optical interconnections in supercomputers, optical sensor systems, etc. Compared to ridge waveguide laser diodes, buried heterostructure laser diodes have significantly lower threshold current, higher power output, higher temperature operation and lower cavity losses.

1. Basic laser diode structures

Low threshold ($I_{th} < 5$ mA) laser diodes were fabricated using MO CVD grown unstrained AlGaAs/GaAs (λ = 810÷890 nm) initial epitaxial structures and MBE grown strained InGaAs/AlGaAs (λ = 980 nm).

1.1. Quantum-well buried heterostructure AlGaAs/GaAs

The graded index separate confinement quantum-well buried heterostructure AlGaAs/GaAs laser diodes (GRIN SC QW BH LD) was used as well. Laser diode structures were grown by low temperature liquid phase epitaxy (LPE) methods in the temperature range 650–400 ^{0}C. Mesa formation was done by in-situ melt etching at 580 ^{o}C followed by regrowth of AlGaAs reverse *p–n* junction isolating layers at 580–450 ^{o}C. This method allows etching and preservation of sidewalls then regrowth and planarization all in one step with negligible thermal disordering in QWs. Mesa formation in the

LPE regrowth process by in-situ melt etching excludes any oxidation of the etched mesa surface and provides a high quality lateral confining interface. It was shown, that melt-etched mesa shapes depend by: AlAs content x in $Al_xGa_{1-x}As$ cladding layers, stripe orientation and mask adhesivness to the initial epitaxial structure. Have been established that with SiO_2 mask and $x = 0.2 \div 0.5$, there is a strong anisotropy of melt-etch rate, while with $x \geq 0.6$ in the similar processes melt-etching material selectivity becomes the most important factor of mesa shaping. The best results of using SiO_2 masking for in-situ meltback and regrowth are obtained when meltback undercutting is almost as much as the meltback etching depth.

Thus using these results of LPE regrowth technique a GRIN SC QW BH LD with emission wavelength around 853 nm have been fabricated. A scanning electron micrograph of the cleaved cross section of such structure is shown in Fig. 1 and consists of a 2 μm thick n-GaAs buffer layer, a 1.5 μm thick n-$Al_{0.7}Ga_{0.3}As$ widegap emitter, 0.15 μm n-$Al_{0.6-0.3}Ga_{0.4-0.7}As$ GRIN waveguide, 20 nm n-$Al_{0.08}Ga_{0.92}As$ active, 0.15 μm n-$Al_{0.3-0.6}Ga_{0.7-0.4}As$ GRIN waveguide, 1 μm thick p-$Al_{0.7}Ga_{0.3}As$ widegap emitter and a 0.2 μm p^+-GaAs cap layer. The buried heterostructure was formed in the second LPE process by melt etching of the laser structure part not protected by SiO_2 stripes (typical width 6–7 μm), followed by p^+-and n-$Al_{0.4}Ga_{0.6}As$ regrowth to provide lateral electrical and optical confinement.

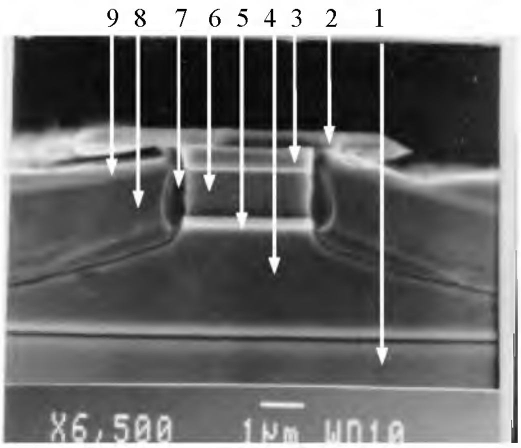

Fig. 1. Scanning electron micrograph of the cross-section of melt-etched and regrowth AlGaAs/GaAs buried heterostructure

(1) n-GaAs buffer layer, (2) SiO_2 stripe, (3) GaAs cap layer, (4) n-$Al_{0.7}Ga_{0.3}As$ widegap emitter, (5) $Al_{0.6-0.3}Ga_{0.4-0.7}As$ GRIN waveguide and QW $Al_{0.03}Ga_{0.97}As$ active region, (6) p-$Al_{0.7}Ga_{0.3}As$ widegap emitter, (7) boundary of etching in the melt (p-$Al_{0.55}Ga_{0.45}As$), (8) p^+-$Al_{0.4}Ga_{0.6}As$, (9) n-$Al_{0.4}Ga_{0.6}As$

The melt etched mesa shapes depend on the mask adhesiveness to the epitaxial structure in undersaturated Ga–Al–As solutions. Besides the fact that adhesion of traditional masking layers such as $Si0_2$ and Al_2O_3 is much worse than that of AlGaAs native oxide, the adhesion of these oxide layers is not uniform and depend very much on the state of multilayer epitaxial structure surface leading to non-reproducible results. Native oxide layers were grown by anodic oxidation of $Al_xGa_{1-x}As$ ($x = 0.5 \div 0.6$) in ammonium citrate electrolyte. The growth mechanism of native oxides provides high material quality and uniform interface with no impurities on it. This oxide is stabilized to resist harsh conditions of melt etching by post growth thermal treatment. It was shown that masking properties of AlGaAs-based native oxide dramatically improve by increasing AlAs composition of AlGaAs. In order to form such a mask an additional AlGaAs layer with the thickness of 200–300 nm is grown on the surface of the multilayer structure. To form a necessary mask pattern this layer is anodized through a photoresist mask. It is very important that no undercutting under the mask takes place in the low temperature LPE mesa melt-etching and regrowth process when using AlGaAs-based native oxides. In this case the form of the mesa is dictated only by the anisotropy of melt etching which ensures that the active layer area is about twice smaller than the contact area. As a result the contact resistivity can be minimized. Only masks with a very good quality do permit the formation of these reverse mesa structures.

After standard procedure of Au–Zn, Au–Ge ohmic contact deposition the laser bars with different cavity lengths were cleaved. The LD chips were "*p*-side down" mounted on the Cu heatsink. Room temperature light-current characteristics of three laser diodes with different cavity length measured under dc conditions are shown in Fig. 2. It gives to evaluate a set of internal laser parameters, i. e., the stimulated emission quantum efficiency η_{st}, zero current density j_0, gain factor β, and internal optical losses ρ. We obtain $\eta_{st} \approx 0.35$, $j_0 \approx 130$ A/cm^2, $\beta \approx 3.8$ cm/A, and $\rho \approx 27$ cm^{-1}.

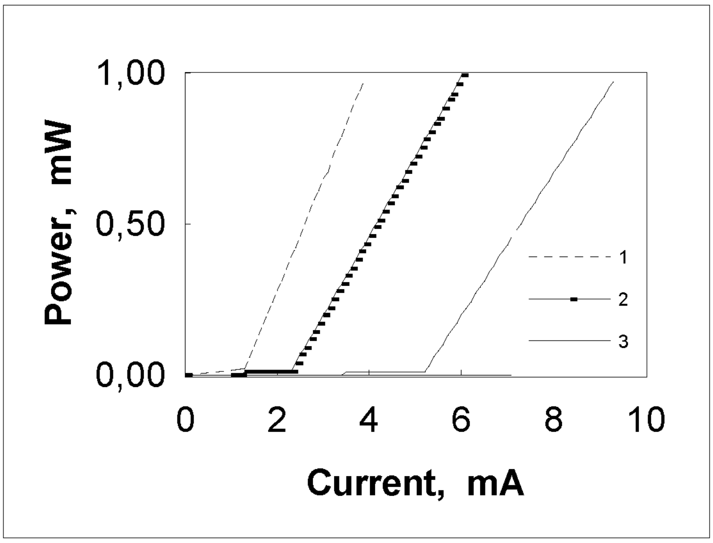

Fig. 2. Room-temperature light-current characteristics of three laser diodes with different cavity length L measured under dc conditions

(1) L = 125 μm, (2) L = 250 μm, (3) L = 530 μm

1.2. Quantum-well buried heterostructure InGaAs/AlGaAs/GaAs

The laser diodes with emission wavelength around 980 nm is the preferred pump source for an erbium-doped fiber amplifier (EDFA) for the next generation of lightwave communication systems because of lower noise, high power conversion efficiency, and low temperature sensitivity under operating conditions.

The basic laser diode structure was a strained QW graded index separate confinement InGaAs/AlGaAs/GaAs heterostructure (GRIN SCH) with central emission wavelength 980 nm and was grown by molecular beam epitaxy technique (MBE) on 3^0 off (100) GaAs substrate. The typical device structure, shown in Fig. 3, is essentially similar to that of an AlGaAs/GaAs QW laser, except that the GaAs QWs are replacedly InGaAs QWs sandwiched between GaAs spacer layers.

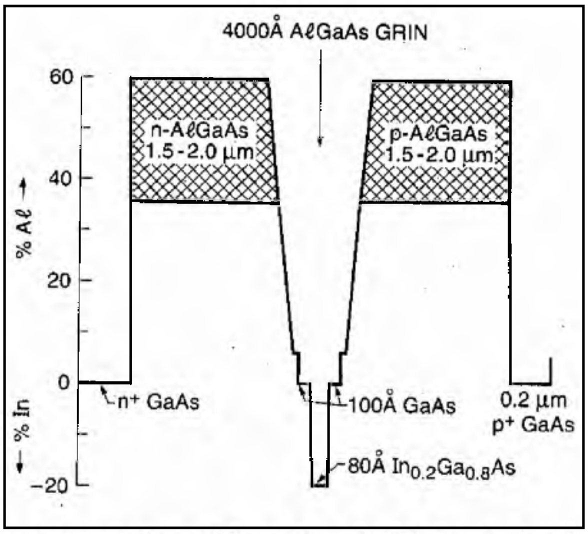

Fig. 3. The schematic representation of $In_{0.2}Ga_{0.8}As$/GaAs strained layer GRIN-SCH-QW laser

The structure consist of 0.5 µm-thick superlattice buffer n^+-GaAs buffer layer, 0.1 µm-thick superlattice buffer layer of five periods of 10 nm GaAs and 10 nm AlGaAs, a 2.0 µm thick n-$Al_{0.6}Ga_{0.4}As$ cladding layer, a 0.15 µm thick linearly graded index layer of n-$Al_xGa_{1-x}As$ with x and n decreasing from 0.6 to 0.15 and from 5×10^{17} to 1×10^{16} cm^{-3}, respectively, a 60 nm-thick undoped $Al_{0.15}Ga_{0.85}As$ layer, three 8 nm InGaAs/10 nm GaAs undoped QW active regions, a 60 nm thick undoped $Al_{0.15}Ga_{0.85}As$ layer, a linearly graded 0.15 µm thick p-$Al_xGa_{1-x}As$ layer with x and p increasing from 0.15 to 0.6 and 1×10^{16} to 5×10^{17} cm^{-3}, respectively, a 2.0 µm thick p-$Al_{0.6}Ga_{0.4}As$ top cladding layer, and a 0.2 µm thick p^+-GaAs contact layer.

The InGaAs/AlGaAs/GaAs samples were processed into ridge waveguide (RW) lasers. To fabricate these devices a standard photolithographic technique was used to define the 4–5 μm and 25 μm width stripes. The 4–5 μm and 25 μm width stripes oriented in (110) direction were formed by chemical etching of the top layer in 5:NaOH+1:H_2O_2+1:NH_4OH solution.

2. Laser diode module fabrication

2.1. Module "laser diode–fiber optic"

For laser module fabrication we have used AlGaAs/GaAs and narrow stripe ($w = 4 \div 5$ μm) InGaAs/AlGaAs/GaAs RW diodes with cavity length 500 μm. LD was mounted on AlN/Cu-Md or BeO/Cu-Md subcarriers and the preliminary light-current and far-field distribution characteristics were measured. After this testing procedure the LD was mounted into package. A special coupling scheme was elaborated in order to achieve efficient coupling of LD emission into single-mode optical fiber (Fig. 4). The device was temperature controlled using thermoelectric cooler TEMO-5 and thermistor, mounted in nearest vicinity of the LD chip.

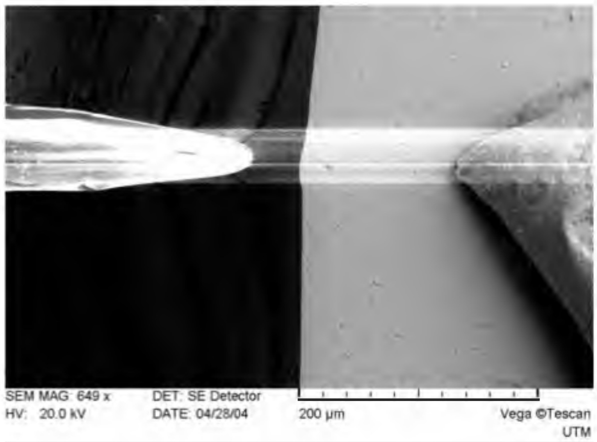

Fig. 4. Picture of coupling of LD with optical fiber

For optical power monitoring the internal InGaAsP/InP *p–i–n* photodiodes were mounted near the rear facet of the laser diode. The end of single-mode fiber was in vacuum metalised and consequently tapered and microlensed, using electric arc equipment. There is a problem of decrease of coupling losses of laser diodes to optical systems in fiber optic communication. They are various methods coupling of laser diode to an optical fiber, such as, different optical systems of spherical and cylindrical lenses, tapering facetted ended fiber, tapered hemispherical ended fiber and butt joint methods. The original making method of fiber optic components, such as: tapered hemispherical ended single-mode and multi-mode fiber is presented. Tapered end with microlens was formed by a combine method of chemical etching and fusion process. Optical fiber was chemical etched in HF acid. To obtain the conical shape of etched ends a special device for slowly immersion of fibers in etching acid was elaborated. After chemical etching, the fiber was cleaved in the region where only core diameter was remained. The end of tapered optical fiber was heated by electric arc discharge of modified equipment KCC121 and fusion hemispherical lens on the fiber end was formed. The hemispherical lens diameter is determinated by the selection of cleaving place, by the duration and current density of the arc discharge. The process of lens formation was monitored by a high-resolution optical microscope and by measuring of optical power output at this time.

Characteristics of output power from fiber optic, for microlenses with radius of lens $R = 8$ μm fabricated by the used only electric arc discharge (curve 1) and fabricated by the combine chemical etching and fused methods (curve 2) are shown in Fig. 5. The coupling efficiency from 1.3 μm laser diode to single mode fiber was measured for several lenses and had values about 60% (2). The fiber lenses fabricated only by fused method had coupling efficiency about 35% (1).

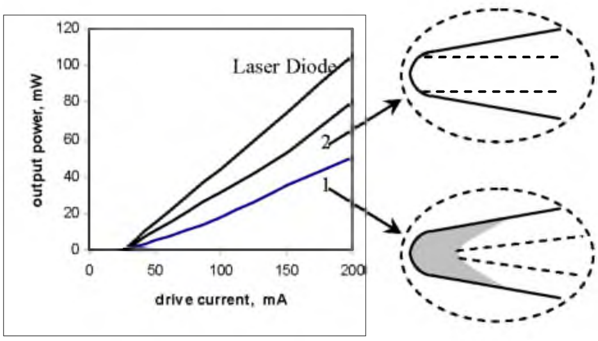

Fig. 5. The laser diode characteristics of output power coupled with microlens fabricated by fused method (1) and by the combine methods (2)

A tapered end of the fiber was installed to the special GaAs-based microsaddle, mounted on the common SiO_2 carrier with two integrated microheater. The positioning of the fiber was performed under continuous control of output power when laser diode operate. As high precision unit for optic fiber positioning a positioner PV-101 was used.

2.2. Collimate laser diode module

Laser diodes with stripe width more than 25 μm are usually used in high power applications as optical pump sources of solid-state lasers; in transmission of optical signal through the atmosphere; in monitoring of environment; in medicine; in a military necessity and in others ranges. Light-current characteristics of these laser diodes are strongly dependent on electrical series resistance and thermal resistance. High power, low aperture LDs emitting at 800–1000 nm wavelength interval are in most cases based on

AlGaAs/InGaAs strained QW epitaxial material and have the maximum optical power of 1–2 W and operating power for long lifetime operation of 0.5–1 W. The further increasing of optical power of AlGaAs-based LDs is very difficult to achieve because this heterosystem has a number of limitations: high oxidation rates of AlGaAs in the air, high recombination rates at AlGaAs/InGaAs free surfaces, high values of electrical and thermal resistance, low optical power densities at catastrophic optical degradation limit of laser facets.

In case of wide stripe lasers asymmetry of far field pattern is quite large (typical values are 40° in the transverse direction by about 10° in the lateral direction) and results in many problems when they are applied for pumping solid state lasers. In order to overcome these difficulties we used silica microlenses that were properly aligned and fixed in the vicinity of LD mirrors. Far field pattern distributions in the planes perpendicular (a, c) and parallel (b) to the active layer plane of a LD with 0.1 mm active layer width are shown on Fig. 6.

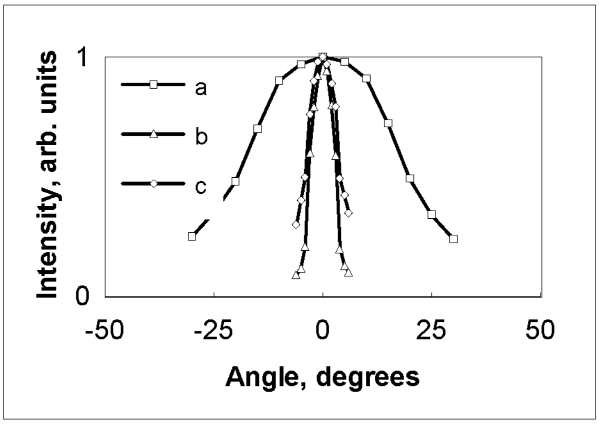

Fig. 6. Far field pattern in the planes perpendicular (a, c) and parallel (b) to the active layer plane before (a) and after (c) fixing the microlenses

In order to reduce the beam divergence in the plane perpendicular to the active layer plane a silica cylindrical microlense with the diameter of 0.2 mm (Fig. 7) and 5 mm length was fixed in the nearest vicinity (0.04–0.1 mm) of the LD mirror.

After fixing the microlense the far field distribution in the parallel plane practically does not change, while the perpendicular distribution changes dramatically (c) and is nearly the same as (b). Optical power measurements have shown that 80 % of all optical power is concentrated in a cone with an angle of 6 degrees.

Cylindrical microlens, placed in the nearest vicinity of the LD mirror has a strong effect on the emission spectra. Without a microlens the FWHA of spectra at 0.2 W emitting power was 1.4 nm, while emission spectra FWHA of a LD with properly placed cylindrical microlens is three times narrower, 0.4 nm. We attribute this narrowing effect to the lateral mode suppressing in a coupled cavity, formed by microlense convex surfaces and LD mirror.

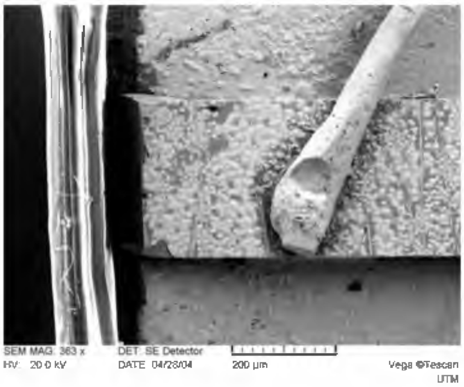

Fig. 7. SEM image of laser diode with cylindrical lens

3. Summary

The quality of AlGaAs-based buried heterostructure lasers has been considerably improved by using an AlGaAs native oxide mask for in-situ mesa melt-etching and LPE regrowth. In this case is no undercutting and the shape of the mesas is dictated only by anisotropy of melt-etching.

Uncoated buried heterostructure laser diodes with the active layer width of 3 mm and less emit in a single spatial mode. The maximum optical power is 10 mW per micron of active layer width for AlGaAs/GaAs lasers and 20 mW per micron of active layer width for InGaAs/AlGaAs lasers. The higher optical power of InGaAs/AlGaAs lasers is attributed to lower electrical and thermal resistance and to linear mirror temperature vs current characteristics. Buried heterostructure AlGaAs/GaAs and InGaAs/AlGaAs/GaAs-based laser diodes have been successfully used in pumping optical fiber lasers, in telecommunication and in medicine.

Using narrow stripe device a single mode fiber pigtailed LD module was fabricated. CW output optical power of 80 mW from the fiber was obtained at 240 mA operating current of the laser diode module. Utilization of described laser diode and optimized collimated system consisting of cylindrical and spherical lenses permit to made the module of laser diode having 500 mW of output power of collimated optical emission with divergence angle of beam less than 3 mrad and collimation power loss less than 20 %.

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