High-Power 980-nm AlGaAs/InGaAs Strained Quantum-Well Lasers Grown by OMVPE

Y. K. Chen, M. C. Wu, W. S. Hobson, S. J. Pearton, A. M. Sergent, and M. A. Chin

Abstract—**High-power lattice-strained AlGaAs/InGaAs graded-index separate-confinement heterostructure quantum-well lasers emitting at a 980-nm wavelength have been grown by organometallic vapor phase epitaxy and fabricated with a self-aligned ridge-waveguide structure. Using a 3-μm-wide and 750-μm-long AR–HR coated laser, 30 mW of optical power was coupled into optical fibers with 28.6% efficiency. A dominating single-lobe far-field radiation pattern was also obtained from a wedge-shaped ridge-waveguide laser for output power as high as 240 mW with a maximum output power of 310 mW.**

THE recent rapid progress in the erbium-doped fiber amplifier has established it as a promising contender for optical fiber communication systems around 1540 nm [1]. Pumping sources using semiconductor laser diodes are available at 980 and 1480 nm. When pumped at a 980-nm wavelength, the Er^{3+} atoms behave like an ideal three-level system [2]. As a result, this pump band offers the further advantages of higher pumping efficiency in the absence of excited state absorption (ESA) [2] and a lower amplifier noise figure close to the 3 dB quantum limit because of a lower spontaneous emission factor as compared to that of the 1480 nm pump wavelength [3], [4]. Therefore, high-power 980-nm semiconductor diode lasers with a high coupling efficiency into a single-mode fiber are needed. Recently, excellent characteristics such as low threshold current density, high differential quantum efficiency, and high output power in free space were demonstrated by strained AlGaAs/InGaAs quantum-well lasers in the 980-nm regime [5]–[7]. Despite the high coupling efficiency of 47% using a wedge-shaped single-mode fiber, only 11.8 dBm power was coupled into the fiber from a broad-area laser [8]. To obtain high coupling efficiency into an optical fiber, special attention is needed to maintain the fundamental transverse mode operation up to a high-power level. However, only a few lasers have demonstrated good single spatial mode control under high power for efficient coupling into optical fibers [9], [10]. In this paper, we report the performance of narrow ridge-waveguide strained AlGaAs/InGaAs quantum-well lasers with a self-aligned contact scheme which launch 30 mW of continuous-wave optical power into fibers with a coupling efficiency of 28.6%. Because the maximum output power is limited by the catastrophic optical damage at the exit facets, wedge-shaped lasers were fabricated to maximize the power at the AR-coated flared facets [11]. A dominating single-lobe far-field radiation pattern was obtained for output power as high as 240 mW. A maximum single-ended output power of 310 mW was also demonstrated.

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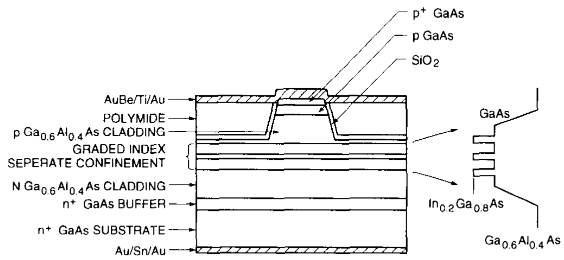

Fig. 1. The layer structure of the graded-index separate-confinement (GRINSCH) laser grown by organometallic vapor phase epitaxy.

The laser structure shown in Fig. 1 was grown by organometallic vapor phase epitaxy (OMVPE) in an atmospheric-pressure vertical reactor on misoriented n^+–GaAs substrates. The graded-index separate-confinement (GRINSCH) laser structure consists of a 500-nm n^+–GaAs buffer layer, two 1000 nm $Al_{0.4}Ga_{0.6}As$ cladding layers, two 150-nm $Al_xGa_{1-x}As$ confining layers with x graded from 0 to 40%, and three pairs of strained $GaAs/In_{0.2}Ga_{0.8}As$ multiple quantum wells (MQW's) as the active region. The thickness of the well and barrier layers is 7 and 12 nm, respectively. The misoriented substrates were 2° off (100) toward the nearest (110). Trimethylgallium, trimethylaluminum, trimethylindium, and arsine were employed as the source chemicals with ultrahigh-purity helium as the carrier gas. Diethylzinc and diluted disilane in hydrogen were used as the p- and n-type dopant precursors, respectively. The substrate temperature was 725°C for the buffer, cladding, confining, and cap layers, and 625°C for the multiple quantum wells. A growth rate of 1.8 μm/h was used for GaAs, and 3.0 μm/h was used for AlGaAs. Growth interruptions were introduced before and after the growth of MQW's to reach the desired growth temperature.

Ridge-waveguide laser structures are simple to fabricate and could circumvent potential yield-limiting problems using buried heterojunction regrowth steps. To obtain a single far-field lateral mode pattern for efficient coupling power into a single-mode fiber, a narrow ridge is needed. We devised a self-aligned ridge (SAL ridge) structure to reduce the contact resistance to the narrow stripe, passivate the surface, and provide a planarized surface for bonding and interconnections. The 3-μm-wide ridge stripes, oriented along [110] direction, were formed by etching the top layers to within 0.1

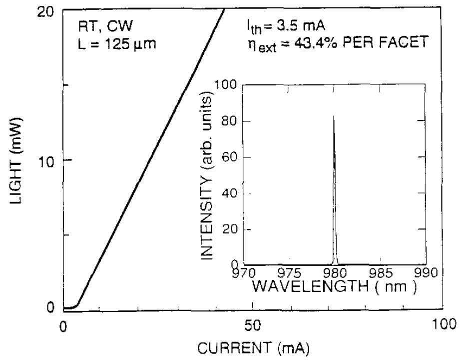

Fig. 2. A typical continuous-wave light–current characteristics of a 3-μm-wide and 125-μm-long ridge waveguide laser at room temperature with cleaved facets. A low threshold current of 3.5 mA with a high differential quantum efficiency of 87% is obtained. The inset shows the lasing spectra at 980 nm with the laser biased at $1.6I_{th}$.

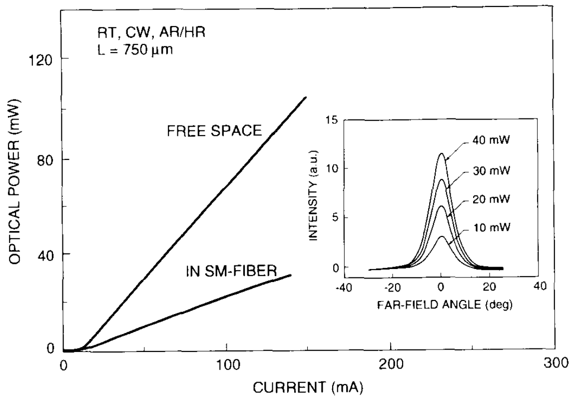

Fig. 3. Typical light–current characteristics of a $3 \times 750\ \mu m^2$ ridge-waveguide laser in free space (solid curve) and in a 9 μm core fiber (dashed curve). A peak power of 30 mW was coupled into the fiber with a coupling efficiency of 28.6%. The same coupling efficiency was also obtained with a spherical lensed single-mode fiber with a 4-μm core diameter. The facets of the laser were coated with AR/HR dielectric layers with reflectivities of 10 and 91%, respectively. A maximum continuous-wave power of 120 mW was emitted before the facet was permanently damaged.

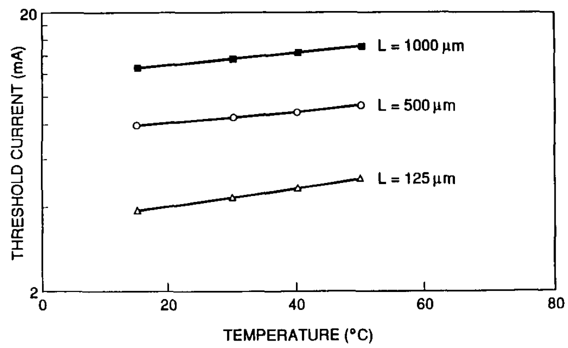

Fig. 4. The temperature dependence of the threshold currents of as-cleaved 3-μm-wide AR/HR-coated ridge lasers from 15 to 50°C. A high characteristic temperature of 220 K is derived for lasers with 500 μm and 1 mm cavity lengths.

μm above the upper graded-index layer using an H_2SO_4:H_2O_2:H_2) solution. Tight control of the etched depth is needed to ensure single lateral-mode operation. After the etching step, a CVD SiO_2 layer was deposited to passivate the etched surfaces and was followed by a polyimide planarization step. The top contact layer of the stripes was then exposed by first thinning down the planarized polyimide layer in an oxygen plasma using the reactive ion etching technique and then removing the cap oxide layer. After the wafer was thinned down to 100 μm, AuBe/Ti/Au and Au/Sn/Au metal layers were evaporated for p and n contacts, respectively. The contacts were then alloyed at 450°C for 10 s. This self-aligned ridge structure provides low-resistance contacts only to the exposed cap layer, and it may enhance the long-term reliability under high-power operations. Finally, individual lasers were obtained by cleaving the wafers into stripes of various lengths and were mounted junction side down on copper heat sinks.

A typical continuous-wave light–current (L–I) characteristic of a 125-μm-long cleaved-facet ridge laser is shown in Fig. 2. A low threshold current of 3.5 mA is obtained at room temperature with a high differential quantum efficiency of 43.4%/facet. The lasing wavelength is centered at 980 nm at $I = 1.6I_{th}$, as shown in the inset of Fig. 2. To measure the far-field patterns and coupling efficiency, 750-μm-long ridge lasers were used, with the output facet coated by an anti-reflective SiO_2 layer and the other facet coated by three pairs of Si/SiO_2 dielectric layers for high reflectivity. The far-field pattern parallel to the junction plane is shown in the inset of Fig. 3 under various powers. The FWHM far-field angle is 10.4° for all of the power levels tested, without measurable broadening. Fig. 3 shows a typical L–I characteristic of a coated laser in free space (solid curve) and in an AT&T 5D fiber with a 9-μm core diameter (dashed curve). Optical power up to 30 mW was coupled into a cleaved flat-end fiber with a coupling efficiency of 28.6%. The same coupling efficiency was also obtained with a spherical lensed single-mode fiber with a 4-μm core diameter. A maximum single-sided CW output power of 120 mW was obtained in free space before the laser facet was permanently damaged. By measuring the lasing threshold current of uncoated lasers at elevated temperatures from 15 to 50°C, a high characteristic temperature (T_0) of 220 K was achieved for lasers with 500-μm and 1-mm cavity lengths, as shown in Fig. 4. The T_0 was lower for short-cavity lasers because of the higher carrier concentration at threshold.

In order to lower the optical power density at the AR-coated exit facet as well as to maintain a good far-field radiation pattern at high output power, wedge-shaped SAL ridge lasers were fabricated [11], [12]. The width of the HR-coated facet of this 375-μm-long wedge laser is 3 μm, and it is flared to 10 μm at the AR-coated exit facet. Fig. 5 shows the far-field pattern parallel to the junction plane. A dominant single-lobe radiation pattern is observed up to 240 mW. The measured FWHM far-field angle is 4.6° up to 160 mW. The broadening of the far field above 200 mW is due to spatial hole burning and possible thermal guiding in a widened ridge.

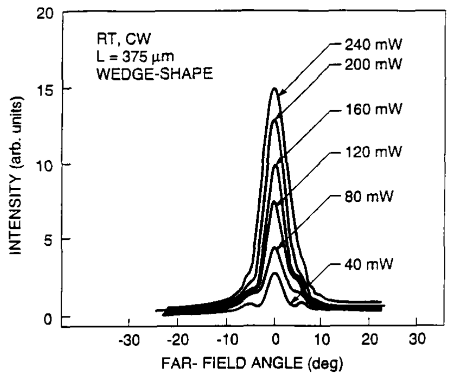

Fig. 5. The far-field radiation patterns measured from a 375-μm-long wedge-shaped ridge-waveguide laser showing the dominating single-lobe operation up to 240 mW of continuous-wave output power. A maximum output power of 310 mW was obtained from this AR/HR-coated laser before the facet was damaged.

Because of the asymmetry of the far-field pattern in the vertical and horizontal directions, the coupling efficiency is lower than that using the simple narrow ridge-waveguide laser. Nevertheless, a maximum output power of 310 mW into the free space was demonstrated. By further optimizing the transverse beam divergence with an expanded vertical optical field perpendicular to the junction [13] and using a cylindrical lensed fiber [7], much higher coupling efficiency should be achieved.

In summary, AlGaAs/InGaAs GRINSCH strained multiple-quantum-well lasers emitting at a 980 nm wavelength have been successfully grown by OMVPE and fabricated using a self-aligned ridge-waveguide structure. The 3-μm-wide 250-μm-long stripe lasers demonstrated a very low threshold current of 3.5 mA, a high differential quantum efficiency of 87%, and a high characteristic temperature of 220 K. The 750-μm-long lasers show a very large output power of 120 mW into free space with good far-field radiation patterns. Up to 30 mW of optical power was coupled into optical fibers with a high coupling efficiency of 28.6%. A dominant single-lobe far-field radiation pattern was also demonstrated by a wedge-shaped ridge laser which produced a maximum output power of 310 mW. We have demonstrated that, by properly controlling the far-field radiation patterns for efficient power coupling into fibers, these simple self-aligned ridge lasers will be future contenders as highly efficient high-power pump sources for high-gain, low-noise optical fiber amplifiers.

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