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High-temperature operation of the InGaAs/GaAs/AlGaAs quantum well lasers with an expanded vertical optical mode is demonstrated for the first time using a periodic index separate confinement heterostructure (PINSCH) laser. Continuous wave (cw) operation up to 145 °C is achieved with a coated 3 μm×508 μm PINSCH laser. The measured characteristic temperature (170 K) and external differential quantum efficiency (0.75 mW/mA) are comparable to those obtained in a graded index separate confinement heterostructure laser fabricated at the same time. These results illustrate the excellent capability of the PINSCH laser to compress the transverse beam divergence without sacrificing the electrical carrier confinement.

High-power semiconductor lasers with small beam divergence are very important for coupling output power into silica fibers and focusing emitted power onto small areas. These capabilities are very important for many applications such as semiconductor diode pump sources for erbium-doped fiber amplifiers, optical data storage, and display. In order to generate a diffraction-limited circular beam profile at the far field, a round optical field inside the laser cavity is needed. The lateral dimension of the optical waveguide is limited by the lithographic process and is typically larger than 1 μm. It is desirable to expand the transverse optical field (perpendicular to the junction plane) inside the laser cavity to match the lateral mode size. As the transverse mode size is expanded, the maximum output power, which is usually limited by the catastrophic-optical damage (COD) at the exiting facet, would also increase because of the reduced photon density. Various waveguide structures, such as large optical cavity[1,2] and multiple active/passive waveguide stacks,[3,4] have been proposed to expand the vertical optical mode size and to reduce the transverse beam divergence.

Many applications require the lasers to operate over wide temperature ranges or without thermoelectric coolers. Previously, there were several reports on the high-temperature operation of tightly confined InGaAs/GaAs/AlGaAs lasers beyond 100 °C.[5,6] However, very few studies were reported on the high-temperature operation of lasers with expanded vertical mode field. The optical confinement factor of the gain medium Γ is reduced with the expansion of the optical mode size in these laser structures. To operate these lasers at high temperature, enough gain should be provided to compensate for the reduction of the confinement factor. Special considerations should also be included in the laser design to provide effective carrier confinement at high temperature. In this letter, we report on the first high-temperature operation of semiconductor lasers with expanded transverse optical mode size up to 145 °C using a periodic index separate confinement heterostructure (PINSCH) laser structure. In the PINSCH laser structure, the bulk optical confinement layers are replaced by periodic index confinement layers to control the vertical beam divergence and to confine the electrical carriers. The measured characteristic temperature (T_0) of the threshold current as well as the external differential quantum efficiency of the PINSCH laser are comparable to those of the graded index separate confinement heterostructure (GRINSCH) laser, despite the much reduced optical confinement factor.

It is well known that the threshold condition for laser operation is $\Gamma g_{\text{th}} = \alpha_c + (1/L)\ln(1/R)$, where g_{th} is the threshold gain coefficient, α_c is the cavity loss, L is the cavity length, and R is the mirror reflectivity. We utilize three quantum wells to compensate for the smaller Γ resulting from the expanded optical mode size. At high temperature, the gain is degraded by the loss of the carrier confinement. With the inherently narrow SCH layers in the PINSCH laser, the nonradiative recombination current outside the active region can be reduced. The layer structure of the PINSCH laser is shown in Fig. 1(a) and is prepared on n^+-GaAs substrates by organometallic vapor phase epitaxy (OMVPE) in an atmospheric-pressure vertical reactor.[7] The PINSCH structure is composed of three parts: a multiple-quantum-well (MQW) active region in the center, a *p*-doped periodic index (PIN) confinement layer, and an *n*-doped PIN confinement layer. Each periodic index confinement layer consists of eight pairs of $Al_{0.4}Ga_{0.6}As$/GaAs (1450 Å/1450 Å) heterostructures. The active region consists of three 70-Å-thick $In_{0.2}Ga_{0.8}As$ wells and two 200-Å-thick GaAs barriers. Two 840-Å-thick GaAs spacer layers are placed between the active region and the PIN layers. Electrons and holes are injected through the doped PIN layers into the undoped MQW active region. The carrier confinement in the active region is achieved by the first pair of $Al_{0.4}Ga_{0.6}As$ heterobarriers of the PIN layers next to the active region. The transverse optical confinement is provided by the Bragg reflection of the PIN layers, as proposed in Ref. 8. The transverse propagation constant is designed to be located in the forbidden bands, which is complex to make the optical field decaying evanescently in the transverse direction. Therefore, the transverse optical mode field can be synthesized with the PIN layers and the active quantum well medium. A de-

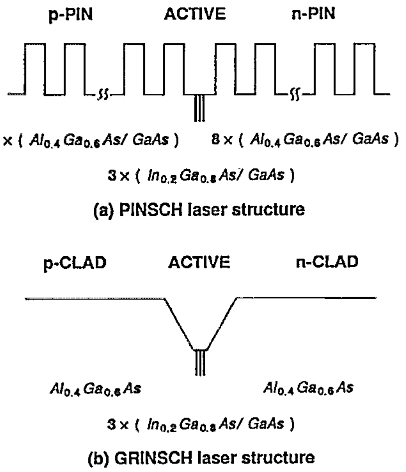

FIG. 1. Conduction-band energy diagrams of the laser structures used in the experiments (a) Periodic index separate confinement heterostructure (PINSCH) laser. (b) Graded index separate confinement heterostructure (GRINSCH) laser.

tailed description on the operation of the PINSCH laser structure can be found in Ref. 9.

For comparison, a conventional GRINSCH laser structure was also prepared by OMVPE and fabricated at the same time. As shown in Fig. 1(b), this GRINSCH laser has the same MQW active region. Instead of the two doped PIN layers in the PINSCH structure, a pair of 1850 Å graded $Al_xGa_{1-x}As$ (x from 0 to 0.4) layers and doped $Al_{0.4}Ga_{0.6}As$ cladding layers are used to obtain the carrier confinement as well as optical confinement. The doping concentrations in the optical confinement layers of both structures are more than 5×10^{18} cm^{-3} to alleviate the possible leakage current caused by the drift fields in the confinement layers and to reduce the series resistance from the heterointerfaces in the PIN layers. Compared to other waveguide designs, the PINSCH structure provides equally efficient carrier confinement as that of the GRINSCH structure.[10] At the same time, the optical mode field can be optimized separately without any compromise in the carrier confinement.

Three-micrometer-wide ridge waveguide lasers are fabricated by combining the reactive ion etching (RIE) technique[11] with follow-on wet chemical etching. The RIE is done with 10 sccm of $SiCl_4$ at a pressure of 5×10^{-3} Torr and a rf (13.56 MHz) power density of 0.16 W/cm^2. The wet chemical etching is done to remove the damage caused by the RIE process as well as to fine tune the depth of the ridge waveguide structure. Typical thickness removed by wet etching is 2500 Å. The etched ridge laser stripes are metallized using a self-aligned process.[7] The front and rear facets of the PINSCH laser are coated with SiO_2 and SiO_2/Si dielectric layers for AR and HR, respectively. Typical facet reflectivity after applying the coatings is ~0.1 for the AR side, and is ~0.9 for the HR side.

The high-temperature light versus current (L-I) characteristics of a AR/HR-coated 3-μm-wide, 508-μm-long PINSCH laser are shown in Fig. 2 from 30 to 145 °C. The temperature dependence (up to 195 °C) of an uncoated

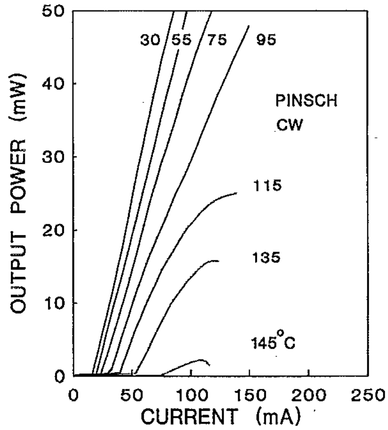

FIG. 2. Light-current (L-I) characteristics of a PINSCH laser at various temperatures up to 145 °C. The 3 μm×508 μm ridge waveguide laser is coated with AR and HR dielectric layers.

GRINSCH laser with the same dimensions is shown in Fig. 3 for comparison. At 30 °C, the threshold current of the PINSCH laser is 19 mA before coating, compared to the 10 mA of the uncoated GRINSCH laser. The higher threshold current in the PINSCH laser structure is the result of the reduced optical confinement factor associated with the expanded optical field. From the calculated near field, Γ is 0.025 for the PINSCH structure and ~0.05 for the GRINSCH structure. The expanded optical field in the PINSCH lasers also reduces the transverse beam divergence $\theta_\perp$, as shown in Fig. 4. We find $\theta_\perp=23°$ (full width at half maximum) for the PINSCH laser and $\theta_\perp=46°$ for the GRINSCH laser.

The temperature dependence of the threshold currents for the AR/HR-coated PINSCH laser and the uncoated GRINSCH laser are plotted in Fig. 5. The characteristic temperature of the threshold current T_0 is obtained by fitting the experimental temperature dependence of the threshold current to $I_{th}(T)=I_0\exp(T/T_0)$, where I_0 is the extrapolated I_{th} at low temperature ($T=0$ °C). From 30 to 75 °C, T_0 is 170 K for the PINSCH laser, and is 163

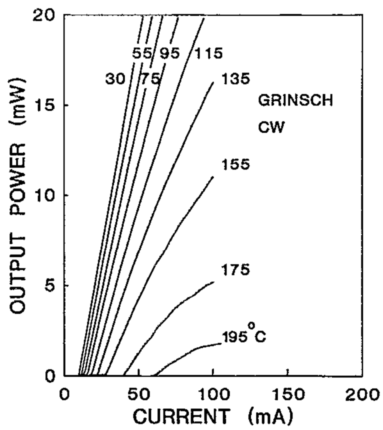

FIG. 3. Light current (L-I) characteristics of a GRINSCH laser at various temperatures up to 195 °C. The facets of this 3 μm×508 μm ridge waveguide laser is uncoated.

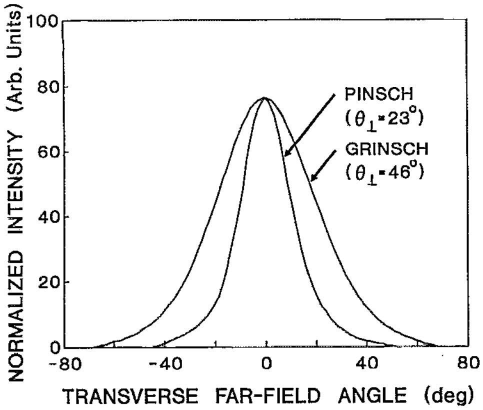

FIG. 4. Normalized far-field patterns of the PINSCH laser and the GRINSCH laser perpendicular to the *p-n* junction. The full width at half maximum (FWHM) transverse beam divergence ($\theta_\perp$) is 23° for the PINSCH laser and 46° for the GRINSCH laser.

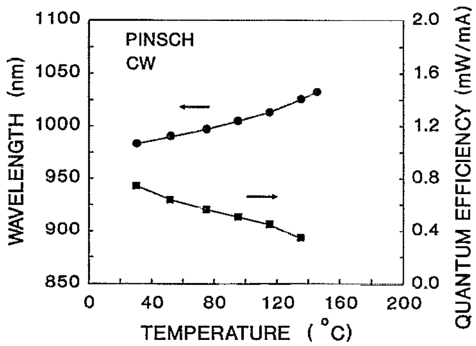

FIG. 6. Temperature dependence of the emission wavelength and the external differential quantum efficiency of the AR/HR-coated PINSCH laser. The wavelength is 980 nm at 30 °C and is shifted to longer wavelength with increasing temperature at a rate of 3.6 Å/°C.

K for the GRINSCH laser. Because of the similarity in the design of the active regions and the SCH layers between the PINSCH laser and the GRINSCH laser, T_0 is similar for both structures near room temperature. The stronger temperature dependence of the PINSCH laser at high temperature comes from its higher threshold current. Because of the smaller optical confinement factor, the PINSCH laser operates at a higher injection level than the GRINSCH laser. Consequently, the effective barrier height of the injected carriers is reduced slightly in the PINSCH structure with the same $Al_{0.4}Ga_{0.6}As$ barrier. For other narrow-beam laser designs, such as large optical cavities and coupled active waveguides, the carrier confinement is a trade-off with the optical confinement. Their temperature sensitivity remains to be determined.

Figure 6 shows the temperature dependence of the emission wavelength and the external differential quantum efficiency of the coated PINSCH laser. The external differential quantum efficiency is $\approx$0.75 mW/mA at 30 °C, and is decreasing with increasing temperature. The emission wavelength is 980 nm at room temperature. The emission wavelength is shifted to longer wavelength at higher temperature with a temperature coefficient of + 3.6 Å/°C. The cavity loss α_i is 9.1 cm^{-1} for PINSCH lasers and is 14.2 cm^{-1} for GRINSCH lasers.

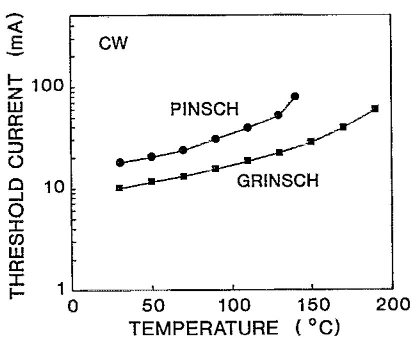

FIG. 5. Temperature dependence of the threshold currents of the PINSCH laser and the GRINSCH laser. The characteristic temperature (T_0) is 170 K from 30 to 75 °C for the PINSCH laser near room temperature. For the GRINSCH laser, T_0 is 163 K.

In summary, we have demonstrated the high-temperature operation, up to 145 °C, of the semiconductor lasers with narrow transverse beam divergence. The separate optimization of carrier confinement and optical confinement is achieved by using a periodic index separate confinement (PINSCH) quantum well laser structure. The expanded optical mode field inside the laser cavity effectively reduces the transverse beam divergence to 23° from 46° of a GRINSCH laser. The expanded optical mode in the PINSCH laser maintains the high differential quantum efficiency with only moderate increase in the threshold current and the temperature sensitivity.

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