HIGH TEMPERATURE OPERATION (185°C) OF InGaAs/GaAs/InGaP QUANTUM WELL LASERS

Y. K. Chen, M. C. Wu, J. M. Kuo, M. A. Chin, and A. M. Sergent

AT&T Bell Laboratories, 600 Mountain Ave, Murray Hill, NJ 07974

ABSTRACT

Aluminum-free InGaAs/GaAs/InGaP strained-layer quantum-well lasers are grown on GaAs substrates by gas-source MBE for the first time. High temperature cw operation of these ridge waveguide lasers has been demonstrated up to 185°C, which is comparable to the best high temperature laser performance in the strained-layer InGaAs/GaAs/AlGaAs quantum well lasers. Self-align index-guided lasers are also fabricated with gas-source molecular beam epitaxy in two growth sequences. Threshold current of 12 mA is obtained from a 2.5 μm-wide and 508 μm-long self-aligned laser at room temperature under cw operation.

INTRODUCTION

Quantum well lasers using InGaP cladding layers have attracted a great deal of attentions as an alternative for the conventional GaAs/AlGaAs lasers. The use of aluminum-free InGaP layers lattice-matched to GaAs promises multiple epitaxial growth processes without removing the stable aluminum oxide at the regrowth interface. The $In_{0.49}Ga_{0.51}P$ has a bandgap energy of 1.91 eV which is equivalent to that of $Al_{0.4}Ga_{0.6}As$. However, most of the bandgap difference of the GaAs/InGaP hetero-interface falls in the valence band. The conduction band discontinuity ΔE_c at the $GaAs/In_{0.49}Ga_{0.51}P$ hetero-interface is 198 meV[1]. This is much smaller than the 299 meV obtained from the conventional $GaAs/Al_{0.4}Ga_{0.6}As$ system with similar bandgap energy difference[2]. Because of the small effective mass of electrons, large ΔE_c is needed to efficiently confine the electrons at high temperature and under high current injection. Previously, low threshold current density was reported in InGaAs/GaAs/InGaP lasers grown by MOCVD.[3] However, the efficiency of carrier confinement with the $GaAs/In_{0.49}Ga_{0.51}P$ heterobarriers has not been proven under high injection level or under high temperature operation. In this paper, we demonstrate the cw laser operation of strained $In_{0.2}Ga_{0.8}As/GaAs/In_{0.49}Ga_{0.51}P$ quantum well lasers at temperatures as high as 185°C, which is comparable to the best reported high temperature performance (200°C) of strained $In_{0.2}Ga_{0.8}As/GaAs/Al_{0.6}Ga_{0.4}As$ lasers.[4]

RIDGE WAVEGUIDE LASERS

A separate confinement heterostructure (SCH) strained quantum well laser structure is used in our experiments. The schematic diagram of the device structure is shown in Fig. 1. The layers are prepared by gas-source molecular beam epitaxy in one growth sequence. The undoped active region consists of three 70 Å $In_{0.2}Ga_{0.8}As$ strained quantum wells and two 200 Å GaAs barriers. There are two undoped 800 Å GaAs wave guide layers outside the active region. The p-doped and n-doped InGaP cladding layers are 1.5 μm thick and lattice-matched to the GaAs substrate. A thin (70Å) GaAs stop-etch layer is placed in the upper InGaP cladding layer to control the etch depth of the ridge waveguide laser. The mismatch between

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GaAs and InGaP is less than 5×10^{-4} from x-ray diffraction measurements. Ridge waveguide lasers with 3 μm strip width are fabricated by wet chemical etching.

Figure 2 shows the L-I characteristics of an AR/HR-coated 3 μm x 508 μm laser for temperatures varying from 30 to 185°C. The facet reflectivity is ~0.1 for the AR-side and ~0.9 for the HR-coated facet. The lasing wavelength is ~1.0μm at room temperature. The characteristic temperature, T_o, is 180 K between 30° and 60°C. This T_o is higher than the previously reported value (140 K) of a InGaAs/GaAs/AlGaAs single quantum well laser grown by MOCVD.[4] The use of multiple quantum wells effectively lowers the threshold gain per well, reduces the threshold carrier density, and permits high temperature operation as well as higher T_o.

Figure 3 shows the L-I curve of the same laser operated with a peak output power of 160mW. Fundamental mode operation is obtained up to 90 mW with $\theta_{\perp}=48^{\circ}$ and $\theta_{||}=13^{\circ}$. Figure 4 shows the dependence of the threshold current density on the cavity length of 50μm-wide broad-area lasers. The lowest threshold current density is 177A/cm^2. High intrinsic quantum efficiency of 91% is obtained with an internal loss of 9.1cm^{-1}.

SELF-ALIGNED LASERS WITH TWO GROWTH SEQUENCES

Because of the difficulty of removing the stable oxide associated with aluminum alloys at the regrowth interface, the MBE growth of high performance laser structures such as buried heterostructure was not widely exploited yet. Previously, in-situ thermal selective etching of a GaAs oxidation-prevention layer before the MBE regrowth was used to fabricate self-aligned AlGaAs double heterostructure lasers with narrow bandgap GaAs confining layer.[5] Here, by replacing the aluminum alloys with InGaP, we have successfully demonstrated the first index-guided self-aligned InGaAs/GaAs/$In_{0.49}Ga_{0.51}P$ quantum well lasers grown by gas-source MBE in two growth sequences.

The layer structure of the self-aligned $In_{0.2}Ga_{0.8}As$/GaAs/$In_{0.49}Ga_{0.51}P$ quantum well laser is shown in Figure 5. The first growth sequence consisted of ten pairs of n^+-doped InGaP/GaAs superlattice as the buffer layer, a 1.5μm-thick n^+-InGaP cladding layer, a 1000Å-thick GaAs separate confinement heterostructure (SCH) layer, three $In_{0.2}Ga_{0.8}As$/GaAs (70 Å/200Å) strained quantum wells as the active medium, a 1000Å-thick GaAs SCH layer, a 1000Å-thick p^+-InGaP barrier layer, a 100Å-thick p^+-GaAs stop-etch layer, and a 2000Å-thick n^+-InGaP blocking layer. After the first growth, the wafer was patterned with SiO_2 window stripes of various widths. The stripes were aligned along the <110> crystal orientation to provide etching profiles with positive slopes. Channels of 2.5 μm, 4.5 μm, and 12 μm width were delineated by removing the exposed n^+-InGaP blocking layer with selective wet chemical etching. After removing the SiO_2 etch mask and the exposed thin p^+-GaAs stop-etch layer, the wafer was re-loaded into the chamber for the second growth sequence. During the second growth, the following layers were grown: a 1000 Å-thick p^+-GaAs waveguide layer, a 1.0 μm-thick p^+-InGaP cladding layer, and a 2000 Å-thick p^+-GaAs cap layer.

Previously, most of the self-aligned laser structures utilized a patterned low bandgap (or high refractive index) GaAs layer for current blocking and guiding of the lateral mode.[5,6] The lateral mode in these structures is stablized by the loss as well as the refractive index difference from the embedded anti-guiding *small* bandgap confining layer. In our structure, the patterned *wide* bandgap n^+-InGaP layer is reverse-biased as the current confinement layers. It also provides lateral optical confinement to the first regrown GaAs waveguide layer. To guide the lateral mode, the regrown high-index p^+-GaAs waveguide layer, which fills in the opening of the low-index n^+-InGaP blocking layer, couples the optical field from the active medium to constitute a large optical cavity and provides the necessary index-guiding.

Figure 6 shows the continuous wave (cw) light-current (L-I) characteristics of as-cleaved self-aligned lasers of various channel widths at room temperature. Threshold currents of 12 mA and 14 mA are achieved for the 508 μm-long lasers with 2.5 μm- and 4.5 μm- wide openings, respectively. In the absence of the lateral carrier confinements in the active region, the current spreading is high in these lasers (~8 mA), as estimated from the dependence of threshold current on channel width from 2.5 to 12 μm. The external differential quantum efficiency from both facets is 0.68 mW/mA at room temperature from a 2.5 μm-wide and 508 μm-long laser. The peak power emitted into free space from these AR/HR-coated lasers is 61 mW for the 2.5 μm-wide laser and 83 mW for the 4.5μm-wide laser. From the 2.5 μm-wide laser, a full-width-at-half-maximum (FWHM) angle of 54^o is obtained in the transverse direction ($\theta_\perp$, perpendicular to the junction plane) and 19^o in the lateral direction ($\theta_{||}$). The peak power is limited by the tightly confined optical modes in the cavity and can be increased significantly by using the much expanded cavity design such as the periodic index separate confinement heterostructure (PINSCH) lasers[7]. The characteristic temperature (T_o) for a 2.5 μm-wide 508 μm-long laser is 130 K. From 2.5 μm-wide lasers of various cavity lengths, the room-temperature cw internal differential quantum efficiency (η_i) is estimated to be 82% with a waveguide loss (α_i) of 11.9 cm^{-1}.

SUMMARY

In summary, aluminum-free lattice-strained InGaAs/GaAs/InGaP multiple quantum well lasers are grown by GSMBE for the first time. The ridge waveguide lasers demonstrate high operation temperature of 185^oC, which is the hottest for this material system and is comparable to the 200^oC from the best reported strained InGaAs/GaAs/AlGaAs lasers. Also, for the first time, the aluminum-free InGaP layers are successfully utilized to fabricate self-aligned index-guided InGaAs/GaAs/InGaP lasers by gas source molecular beam epitaxy (GSMBE) in two growth sequences. Very low threshold current (12 mA), high temperature operation (up to 145^oC), and fundamental mode radiation pattern have been demonstrated. This work demonstrates the regrowth capability of the gas source MBE technique to fabricate high performance optoelectronic circuits (OEIC's) and devices on the patterned aluminum-free InGaP layers.

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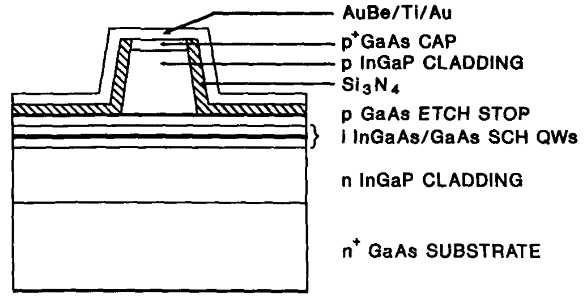

Fig. 1 Schematic diagram shows the layer structure of a ridge waveguide $In_{0.2}Ga_{0.8}As/GaAs/In_{0.49}Ga_{0.51}P$ multiple quantum well structure. The width of the ridge is 3 μm.

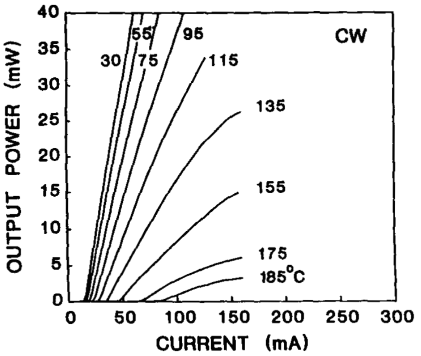

Fig. 2 The cw L-I characteristics of a 3 μm x 508 μm AR/HR-coated $In_{0.2}Ga_{0.8}As/GaAs/In_{0.49}Ga_{0.51}P$ ridge waveguide MQW laser for temperatures from 30 to 185°C.

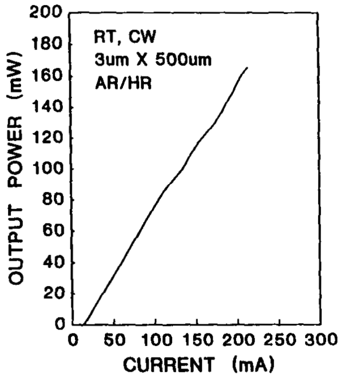

Fig. 3 The room-temperature cw L-I characteristics shows a peak output power of 160 mW from the 3 μm-wide ridge waveguide laser.

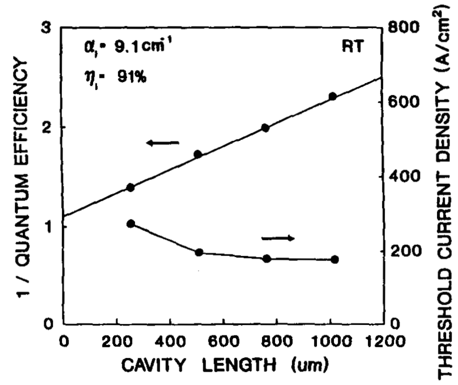

Fig. 4 The inverse external differential quantum efficiency and the threshold current density of 50 μm-wide broad-area lasers with various cavity lengths.

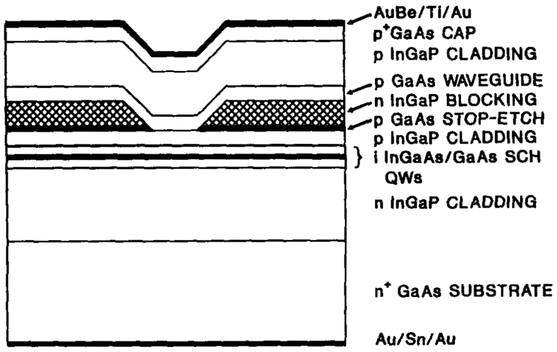

Fig. 5 Schematic diagram shows the layer structure of a self-aligned $In_{0.2}Ga_{0.8}As/GaAs$ $/In_{0.49}Ga_{0.51}P$ multiple quantum well structure using two-step growth with the gas source molecular beam epitaxy (GSMBE).

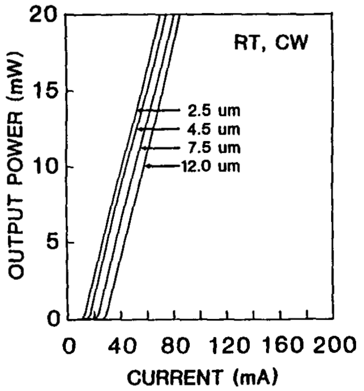

Fig. 6 The continuous wave (cw) light-current characteristics of as-cleaved 508 μm-long self-aligned lasers with various channel width at room-temperature.