Low-Temperature Sensitive, Compressively Strained InGaAsP Active (λ = 0.78–0.85 μm) Region Diode Lasers

N. Tansu, D. Zhou, and L. J. Mawst

***Abstract*—This letter reports comparative studies between (Al)GaAs versus InGaAsP active region edge-emitting semiconductor lasers for emission wavelength in the IR regime ($\lambda = 0.78$–0.85 μm). High characteristic temperature T_o(200 K) and T_1(450 K) edge-emitting diode lasers have been demonstrated by using the compressively strained ($\Delta a/a = 0.6\%$) Al-free (InGaAsP) active region with an emission wavelength of 0.85 μm. The high T_o and T_1, a result of low active-layer carrier leakage, will be beneficial for high-temperature and high-power operation. Implementation for InGaAsP-active VCSEL's with compressively strained InGaAsP-active layers and conventional DBR's is also discussed.**

***Index Terms*—Diode lasers, epitaxial growth, quantum-well lasers, semiconductor lasers, surface-emitting lasers.**

I. Introduction

FIBER optics is a popular choice for data link applications due to the higher bit rate and lower cost compared to the conventional copper-based data link systems. VCSEL's at $\lambda = 0.85$ μm are becoming the industry standard for short-distance optical data link applications. At shorter wavelengths, VCSEL's ($\lambda = 0.76$–0.78 μm) are needed for applications such as laser printing, optical data storage, and gas spectroscopy. To access this wavelength region, conventional VCSEL's utilize GaAs- or AlGaAs-based active layers. The use of an Al-free InGaAsP-based active region is an attractive alternative to the conventional (Al)GaAs active region for IR VCSEL's. While edge-emitting diode lasers with Al-free active regions have demonstrated performance and reliability surpassing AlGaAs-active devices [1], few studies have been reported on Al-free active VCSEL's in the 0.78–0.85-μm wavelength region [2]. Here, we will investigate the properties of compressively strained InGaAsP active-region edge-emitting lasers and the implementation of Al-free active regions into VCSEL's.

To access the $0.7 < \lambda < 0.80$-μm wavelength region, conventional diode lasers utilize AlGaAs quantum-well active regions. However, the high reactivity of aluminum compounds to oxygen leads to bulk degradation, which becomes aggravated as the wavelength becomes shorter (i.e., higher aluminum concentration) [1], [3]. The use of an Al-free InGaAsP active region avoids the bulk degradation associated with a large incorporation of oxygen impurities found in AlGaAs-active devices [1], [3]. In addition, the presence of indium in the active region is beneficial in that it inhibits the propagation of dark-line defects [4]. Higher performance is also expected by incorporating compressively strained (CS) quantum-well active regions. Theoretical calculations at $\lambda = 850$ nm have predicted a lower transparency current density in CS-InGaAsP-active VCSEL's compared to lattice-matched GaAs quantum-well active devices [5]. Furthermore, the use of tensile-strained barriers (InGaP) can provide strain compensation and reduce active region carrier leakage [1]. The fact that Al-free materials are significantly less reactive to O_2, compared to AlGaAs materials, also makes them ideal for the fabrication of regrown structures. Index-guided VCSEL's can then be easily fabricated using an etch and regrowth process [6].

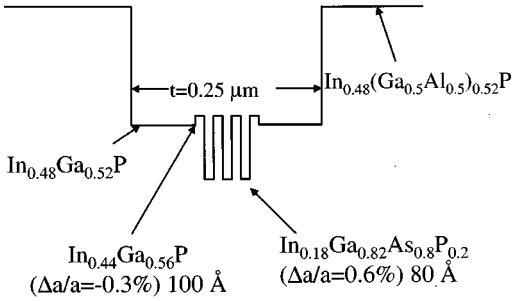

Fig. 1. Schematic energy bandgap diagram for CS-InGaAsP-active region, 0.85-μm emitting laser structure.

II. Edge-Emitting Device Structures

All the laser structures studied here were grown by low-pressure (50 mbar) metalorganic chemical vapor deposition (LP-MOCVD). TMGa, TMAl, and TMIn are used as the group III sources and AsH_3 and PH_3 are used as the group V sources. The Al-free active regions were grown at a temperature of 700 °C, and the GaAs–AlGaAs structures are grown at 800 °C.

The separate confinement heterostructure (SCH), 0.85-μm emitting Al-free active laser, is shown schematically in Fig. 1. In order to compare device performance between InGaAsP-active and GaAs-active layers, edge emitting lasers were designed and fabricated with identical optical confinement factors (Γ) and active volumes (d). The optical thickness of the InGaP-confinement layers, for the structure shown in Fig. 1, is designed to correspond to the λ-cavity for a VCSEL. However, since the SCH structure is taken directly from the

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TABLE I
PERFORMANCE OF InGaAsP-ACTIVE, GaAs-ACTIVE, AND BROAD-WAVEGUIDE InGaAsP-ACTIVE LASERS FOR 100-μm-WIDE × 1-mm-LONG DEVICES

	InGaAsP	GaAs	BW-InGaAsP
λ(nm)	860	850	845
J_{th} (A/cm^2)	420	350	350
η_d(%)	26	26	66
T_0 (K)	160	100	212
T_1 (K)	410	220	449

VCSEL design (i.e., λ-cavity), this Al-free laser is not intended to be an optimized edge-emitting laser structure. Tensile ($\Delta a/a = -0.3\%$) strained $In_{0.44}Ga_{0.56}P$ was used for the barrier layers in order to achieve a higher energy band offset between the barriers and quantum wells [1]. The active region is composed of 3–8-nm-wide QW's of $In_{0.18}Ga_{0.82}As_{0.8}P_{0.2}$ with ($\Delta a/a = 0.6\%$) compressive strain. This composition falls outside the miscibility gap for InGaAsP compounds grown at 700 °C [7]. For this structure the optical confinement factor is calculated to be 8.3%.

A comparison structure, consisting of three 8-nm GaAs QW's, was also grown. The GaAs-active structure consists of $Al_{0.25}Ga_{0.75}As$ and $Al_{0.85}Ga_{0.15}As$ as confinement/barrier and cladding layers. The thicknesses are chosen to give the same optical confinement factor and active volume as the InGaAsP-active structure.

Broad-area lasers ($w = 100\,\mu$m) are fabricated and compared for performance. The results for as-cleaved devices with cavity lengths of $L = 1$ mm are shown in Table I. For this value of active layer strain ($\Delta a/a = 0.6\%$), we do not observe a reduction in threshold current density for the Al-free active laser compared with the GaAs-active lasers. This may be a result of poor interface quality between the InGaP and InGaAsP in the active region, or an insufficiently high value of strain. Indium segregation from the InGaP to the InGaAsP is expected to lead to a strained interface [8]. The low value for the external quantum differential efficiency in both structures is simply a result of the large overlap of the optical field with the highly doped cladding layers ($n, p = 1 \times 10^{18}$ cm^{-3}), which leads to high internal loss α_i.

The characteristic temperature coefficients of the threshold current density T_o and external differential quantum efficiency T_1 were measured between 20 °C–60 °C under low duty cycle (1%) pulsed operation. The larger energy bandgap difference between the quantum well active and the cladding layer ($\Delta E_g = 757$ meV for Al-free active and $\Delta E_g = 620$ meV for GaAs-active) in the Al-free active structure results in reduced carrier leakage. Thus, the values of T_o and T_1 for the Al-free active structure are significantly higher compared to the GaAs–AlGaAs laser structure (see Table I). Typical values for T_o for as-cleaved GaAs single-quantum-well (SQW) lasers are about 100–120 K [9]. The values of T_o obtained here are comparable with the previously reported T_o values of GaAs-active [9] and InGaAsP-active ($T_o = 160$ K) diode lasers ($\lambda = 830$ nm) [10].

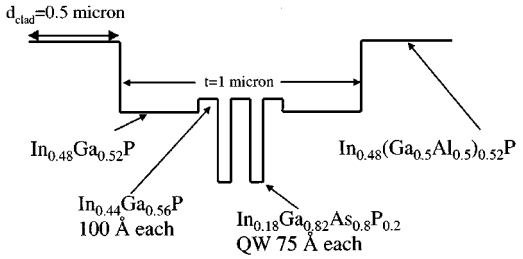

Fig. 2. Schematic energy bandgap diagram of the InGaAsP-active BW laser structure.

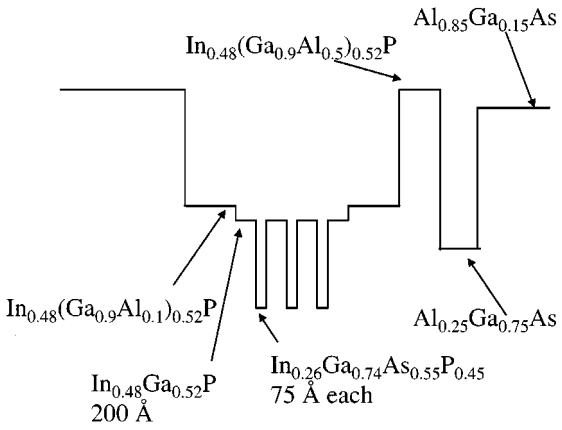

Fig. 3. Schematic energy bandgap diagram of the Al-free active ($\lambda = 0.78\,\mu$m) laser structure with an InGaAlP–AlGaAs interface.

In order to assess the Al-free 0.85-μm-emitting active region for high-power applications, an optimized edge-emitting laser structure was fabricated by using the broad-waveguide (BW) design [8]. The characteristic of BW lasers is that the fundamental transverse mode is designed to have very low loss (<1 cm^{-1}), while the second-order transverse mode is suppressed by large radiation losses [10]. For the BW structure shown in Fig. 2, the fundamental mode optical confinement $\Gamma_o = 2.8\%$ and the effective transverse spot size $d/\Gamma_o = 0.8\,\mu$m. The modal radiation loss is calculated to be $\alpha_o = 0.3$ cm^{-1} and $\alpha_2 = 112$ cm^{-1} for the fundamental and second-order transverse modes, respectively ($\Gamma_1 = 0$ for the first-order mode).

Since the InGaP–InGaAsP quantum-well interface is a concern, due to indium segregation from InGaP to InGaAsP, we reduce the number of wells to two. The performance characteristics from the InGaAsP active BW lasers for $L = 1$ mm and $w = 100$-μm devices are shown also in Table I. Although a low internal loss is observed (α_i = 1 cm^{-1}), the relatively low internal quantum efficiency (η_i = 0.72) is believed to reflect the interfacial quality of the InGaP/InGaAsP active region. Previously reported threshold current density ($J_{\rm th}$) and external differential efficiency (η_d) for ($\lambda = 830$ nm) InGaAsP lattice matched-active diode lasers with a BW structure are about 365 A/cm^2 and 77%, respectively [10]. The threshold current density of our GaAs-active lasers is comparable with the previously published results [9]. The high values of T_o and T_1, together with the large transverse spot size, is beneficial for high-temperature/high-output power edge-emitter operation. The reduced carrier leakage (high T_o and T_1) is also beneficial for realizing high-temperature and high-power VCSEL operation [11].

III. Implementation of the InGaAsP-Active into VCSEL's

Al-free active region VCSEL's with conventional AlGaAs–AlAs distributed Bragg reflectors (DBR's) contain an (Al)InGaP–AlGaAs interface between the cavity region and the top p-type DBR, which is susceptible to In segregation [12], [13]. Studies on the InGaAlP–AlGaAs interface have been done extensively for visible VCSEL's [13]. The use of an AlAsP transitional layer to continuously grade the group V composition was found to improve the AlGaInP–AlGaAs interface [13].

To study this interface, edge-emitting ($\lambda = 0.78\ \mu$m) Al-free active laser structures were fabricated, as shown in Fig. 3, which contain the AlGaInP–AlGaAs interface representing the top DBR of the VCSEL. A growth pause ($\sim$1 min) and temperature ramp ($T = 700$ °C–750 °C) between the AlGaInP and the AlGaAs (top DBR) resulted in significant indium carryover and subsequent high-threshold current densities (> 1 kA/cm^2). Highest performance was achieved by performing the growth of the Al-free cavity and AlGaAs-based p-DBR at the same temperature ($T_g = 700$ °C), with minimal growth pause and without the use of an interface transitional layer.

For this case, the threshold current density of the lasers is comparable to that of similar laser structures without the AlInGaP–AlGaAs interface ($J_{\rm th} = 470$ A/cm^2, $L = 1$ mm).

IV. Conclusion

Compressively strained InGaAsP active ($\lambda = 850$ nm) edge-emitting lasers, with tensile-strained InGaP as barriers, exhibit high T_o (200 K) and T_1 (450 K), which is beneficial for high-power and high-temperature operation. The high value of T_o and T_1 can be attributed to the larger bandgap difference between the quantum well and the cladding layers for InGaAsP-active lasers compared the the GaAs-active lasers. Further optimization is required to improve the InGaP–InGaAsP quantum well interface to fully utilize the benefits of compressive strain. To implement the InGaAsP-active into VCSEL's, Al-free active cavity and AlGaAs-based p-DBR should be grown at the same growth temperature (to minimize the pause time). By minimizing the growth pause for the InGa(Al)P–AlGaAs interface, indium carryover is minimized.

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