Effects of \textit{n}-type modulation-doping barriers and a linear graded-composition GaInAsP intermediate layer on the 1.3 \textmu m AlGaInAs/AlGaInAs strain-compensated multiple-quantum-well laser diodes

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We report the fabrication, characterization, and comparison of four 1.3 \textmu m AlGaInAs/AlGaInAs strain-compensated multiple-quantum-well (SC-MQW) laser structures: (1) sample A—with only an undoped SC-MQW active region, (2) sample B—with an undoped SC-MQW active region and a linear graded-composition (LGC) GaInAsP intermediate layer, (3) sample C—with an \textit{n}-type modulation-doping (MD) SC-MQW active region, and (4) sample D—with an \textit{n}-type MD-SC-MQW active region combined with a LGC GaInAsP intermediate layer. The inclusion of either \textit{n}-type modulation-doping SC-MQW active region or LGC GaInAsP intermediate layer can improve the performance of a laser diode (LD). The LD sample D, which includes both an \textit{n}-type MD-SC-MQW active region and a LGC GaInAsP intermediate layer, exhibits the best overall performance including a threshold current of 12.5 mA, a characteristic temperature of 85 K in 20–80 °C temperature range, a lasing wavelength shift of 0.38 nm/K, and a relaxation frequency response of 9.9 GHz. © 2006 American Vacuum Society. [DOI: 10.1116/1.2172954]

I. INTRODUCTION

Semiconductor laser diodes (LDs) provide a higher power converting performance than the gas or solid-state lasers. The capability of integrating LDs with other semiconductor devices also makes them suitable for applications of subscriber loop networks and optical interconnection systems.\textsuperscript{1–4} The LD operating at 1.3 \textmu m wavelength can fully utilize the zero dispersion and low loss properties of a standard silica-based optical fiber system. However, the high-temperature performance of the 1.3 \textmu m LDs has been seriously degraded due to Auger recombination,\textsuperscript{5} phonon-assisted Auger recombination,\textsuperscript{6} intervalence band absorption,\textsuperscript{7,8} recombination in the separate confinement heterostructure region,\textsuperscript{9–12} and carrier leakage.\textsuperscript{13} In order to reduce these effects, the AlGaInAs/InP system, which has a larger conduction-band offset (\Delta E_c=0.5–0.7\Delta E_g), is suggested in place of the conventional InGaAsP/InP system (\Delta E_c=0.4\Delta E_g).\textsuperscript{2–5} The AlGaInAs/InP system confines carriers more tightly in the multiple quantum wells (MQWs) and reduces the thermal emission of carriers. It reduces these problems so that the LDs can operate at higher light output powers and higher temperatures. The AlGaInAs-based material also has a higher refractive index and larger band gap energy than that of GaInAsP. By adjusting Al/Ga ratio over a wide wavelength range, while maintaining the lattice constant match to InP, the AlGaInAs provides better electrical and optical confinements. Incorporation of a linearly graded-index separate confinement heterostructure (GRINSCH) and strain-compensated (SC) active region using the AlGaInAs/InP system would offer good carrier and photon confinements. However, these modifications are not sufficient for modern optical interconnection systems that require lower threshold current, higher output power, higher characteristic temperature, and faster speed. More recently, reduction of series resistance and introduction of \textit{n}- and \textit{p}-type modulation-doping barriers in the AlGaInAs/InP LDs have been proposed to increase the optical gain and decrease the device

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heating. These effects can effectively increase the light output power at higher operation temperatures, reduce the transparency carrier density to lower the threshold current density, and enhance differential gain to improve the relaxation oscillation, modulation frequency, and linewidth enhancement factor.14–20 Kazarinov and Belenky14 proposed that with the introduction of an AlInAs electron-stopping layer to the LDs, the thermal leakage could be reduced. Subsequently, Take-masa et al.15 verified this theory experimentally. Irikawa et al.16 and subsequent investigations17,18 analyzed the effect of AlInAs/AlGaInAs multiple quantum barriers and showed that these LDs have superior electrical characteristics of lower threshold current density $J_{th}$ and higher characteristic temperature $T_{ch}$ than those without multiple quantum barriers. Nevertheless, the Al composition and thickness of multiple quantum barriers should be accurately controlled.

For LDs with $p$-type modulation-doping barriers, the quasi-Fermi level of holes in the quantum well moves toward the valence-band edge. The change of hole quasi-Fermi level would reduce the effective hole mass and then lower the threshold current density. In addition, the differential gain can be enhanced by more symmetric quasi-Fermi level of electron and hole in the conduction band and valence band, respectively. However, the $p$-type dopants such as Zn and Be have higher diffusion coefficients which would degrade the optical gain because of the scattering caused by photons and dopants. In order to eliminate this problem, the low diffusion-coefficient $n$-type dopant Si is used in modulation-doping barriers, which can effectively reduce the transparency carrier density due to the small density of states in the conduction band as compared to that in the valence band. Although Uomi et al.19 inferred that the differential gain would degrade and broaden the gain spectra because of the small density of states, Sweetser et al.20 demonstrated that the $n$-type modulation-doping multiple-quantum-well (MD-MQW) structure still has a large population of free electrons near the band edge of the active region before any carriers are injected. It might be expected that the turn-on time for electron-hole recombination in an $n$-type modulation-doping structure will be shorter, provided that the relaxation rate of the injected holes to the top of the valence band in the well is sufficiently rapid.21 Our previous work22 reported that an introduction of $n$-type modulation-doping barriers to AlGaInAs/AlGaInAs SC-MQW LDs exhibits better electrical and optical characteristics than laser diodes without $n$-type modulation-doping barriers. Takemasa et al.15 reported that the 3-$\mu$m ridge-waveguide LDs with an electron stop layer have a threshold current and a characteristic temperature of 21 mA and 79 K, respectively. Camargo et al.23 reported that the AlGaInAs/AlGaInAs MQW LDs with the same structure have a threshold current and characteristic temperature of 16.6 mA and 102 K, respectively. However, the problem of reduced differential gain caused by asymmetric conduction and valence bands is still remained and leads to a low 3 dB bandwidth. More recently, we have reported the fabrication and characterization of LDs with undoped MQW active region and incorporated them with a linear graded-composition (LGC) $p$-GaInAsP intermediate layer between the $p$-GaInAs cap layer and $p$-InP cladding layer. The LGC layer was used to tailor the electric field distribution, which helps the injecting the holes into the MQW region.24

In this article, we report the improved characteristics of an improved LD structure which has an $n$-type MD-SC-MQW active region coupled with a LGC GaInAsP intermediate layer (sample D). Its properties are compared with three types of LDs that utilize either an undoped SC-MQW active region (sample A), or with an undoped SC-MQW active region combined with a LGC GaInAsP layer (sample B), or with an $n$-type MD-SC-MQW active region (sample C). This LD structure (sample D) exhibits superior device characteristics, temperature dependence, and higher relaxation oscillation frequency response.

II. DEVICE FABRICATION

The 1.3 $\mu$m AlGaInAs/AlGaInAs SC-MQW structures were grown by low-pressure metal organic chemical vapor deposition (MOCVD) on Si-doped (100) InP substrates. Ar-sine (AsH$_3$) and phosphine (PH$_3$) were used as group-V sources, and trimethylindium (TMI), trimethylgallium (TMGa), and trimethylaluminum (TMAI) were used as group-III sources. Silane (SiH$_4$) and dimethylzinc (DMZn) were used as the $n$- and $p$-type dopants, respectively. Growth was carried out at a pressure of 50 torr and a growth temperature of 700 °C. The use of AlGaInAs as the active region instead of GaInAsP would improve the high phosphorus vapor pressure related surface degradation problems during material growth. Figure 1(a) shows the schematic device structure of the 1.3 $\mu$m MD-SC-MQW AlGaInAs/AlGaInAs LDs with a LGC GaInAsP intermediate layer. The layers consist of (i) a 0.2 $\mu$m $n$-InP buffer layer; (ii) a 50 nm $n$-AlInAs cladding layer; (iii) an 80 nm GRINSCH AlGaInAs confinement layer with the Al composition decreasing from 0.44 to 0.30; (iv) the SC-MQW active region which consists of five 4.8 nm compressive-strained $A_{0.20}Ga_{0.11}In_{0.69}As$ quantum wells separated by six 8.6 nm tensile-strained $A_{0.20}Ga_{0.19}In_{0.81}As$ barriers, with about +1.15% and −0.6% strain and $\lambda_s=1.3$ and 0.86 $\mu$m in the well and barrier, respectively; (v) an 80 nm GRINSCH AlGaInAs confinement layer; (vi) a 50 nm undoped AlInAs cladding layer; (vii) a 1.6 $\mu$m $p$-InP cladding layer; (viii) a 50 nm $p^*$-LGC GaInAsP intermediate layer changing from $Ga_{0.42}In_{0.58}As_{0.9}$P$_{0.1}$ ($\lambda_s=1.05$ $\mu$m) to $Ga_{0.11}In_{0.89}As_{0.23}$P$_{0.77}$ ($\lambda_s=1.6$ $\mu$m); (ix) a 0.2 $\mu$m $p^*$-InGaAs Ohmic layer. The barriers of the SC-MQW active region contain a $\sim$28 Å Si-modulation-doped region surrounded by two $\sim$29 Å undoped regions to prevent the incorporation of Si dopants into the wells. The uniformity of the LD structure in term of photoluminescence (PL) intensity and full width at half maximum (FWHM) and thickness are controlled within 5% across the 2 in. epiwafer. The undoped AlInAs cladding layer serves as an electron-stopping layer due to its large band gap. It has also been used to prevent Zn diffusion from the $p$-InP cladding layer into the wells.
intermediate layer serves two functions. First, GaInAsP can be doped more heavily than the InP cladding layer. This higher doping concentration would reduce the series resistance and device heating and thus increase the maximum light output power. Second, the linear graded-composition profile of the energy band structure of the p'-GaInAsP LGC layer modifies the electric field intensity distribution near the InGaAs/InP discontinuous heterointerface, thereby enhances the threshold condition. Figure 1(b) shows the zinc doping profile measured by chemical etching capacitance-voltage measurements. The Si-doping profile in MQW, shown in Fig. 1(c), is measured by the secondary ion mass spectroscopy (SIMS, CAMEA-IMS-4f System). The measured Si-doping profile shows a FWHM of around 8.4 nm. To minimize material variation induced errors, the four LD structures were grown consecutively by MOCVD and the same portion of the wafers was used to fabricate LDs. All the LDs were fabricated into a ridge-stripe structure by using standard photolithographic, metallization, and bonding techniques. The Ohmic metals of Ti/Pt/Au with 500, 750, and 4000 Å were coated on both the heavily doped p'-InGaAs cap layer and the n-InP substrate side. The ridge structure was defined with a 3 μm wide stripe by reactive ion etching and refilled by silicon dioxide (SiO2). The finished samples with a total thickness of 90 μm were scribed and cleaved into laser bars with a 300 μm cavity length. The threshold current, lasing spectrum, relative intensity noise (RIN), and relaxation oscillation frequency of the ridge-stripe LDs were measured under cw operations.

III. RESULTS AND DISCUSSION

The optical gain coefficient can be described by the following equation:19

$$g = f_c - f_v = f_c(1 - f_v) - f_v(1 - f_c),$$

where $f_c(f_v)$ is the Fermi-Dirac distribution function for electrons (holes) in the conduction (valence) band. The optical gain increases with the shifting of the quasi-Fermi levels closer to the band edge of conduction and valence bands. The MQW barriers doped with n-type dopant would shift the quasi-Fermi levels closer to the conduction band edge. This could provide additional advantages: First, the transparent carrier density would be reduced, which lowers the threshold current density. Second, the optical gain would increase, which increases the light output power and differential quantum efficiency and enhances the linewidth enhancement factor and differential gain. Besides, the electric field profile of the LGC GaInAsP intermediate layer can help injecting the heavy holes into the MQW. This enhancement can shift the quasi-Fermi level even closer to the valence-band edge.

A semilogarithmic approximation for threshold current density is given by

$$J_{th} = \frac{N_w J_w}{\eta_i} \exp \left[ \frac{1}{N_w \Gamma_v G_0} (\alpha_i + \alpha_m) \right],$$

where $\Gamma_v$ is the optical confinement factor per well, $\alpha_m$ is the mirror loss, $\alpha_i$ is the internal optical loss, $\eta_i$ is the internal quantum efficiency, $N_w$ is the number of well, $J_w$ is the transparent current density, and $G_0$ is the gain coefficient. Increasing the doping concentration in the MQW region will reduce the transparent current density and the internal optical loss, as well as increasing the gain coefficient. These improvements can reduce the threshold current density. As a consequence, a proper selection of the doping concentration in the barriers of MQW can improve the internal parameters including internal quantum efficiency, internal optical loss and LD performance. Figure 2 shows the room-temperature cw light output power as a function of injection current for the four 300-μm-long as-cleaved LD structures. Sample D has the lowest threshold current of 12.5 mA and the highest slope efficiency of 0.259 as compared to others. These improvements are attributed to the higher optical gain and the lower series resistance for the MD-SC-MQW LDs with a LGC layer. The inset of Fig. 2 shows the dependence of current as a function of temperature for the four LDs. In the inset of Fig. 2, the LDs (sample D) again show the lower series resistance of 5.4 Ω than others because of their doped MQW barriers and the heavily doped LGC layer. Figure 3 shows the dependence of threshold current as a function of operation temperature for the four LD structures. The characteristic temperature for the four structures is 75, 80, 82, and 85 K in the temperature range from 20 to 80 °C, and 40.8, 42, 41, and 35 K in the temperature range from 80 to

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**Fig. 1.** (a) Schematic device structure of the 1.3 μm n-type MD-SC-MQW AlGaInAs/AlGaInAs LDs with a LGC GaInAsP intermediate layer. (b) the zinc doping profiles measured by chemical etching capacitance-voltage measurements. (c) the Si-doping profile in MQW determined by SIMS.
100 °C, for samples A, B, C, and D, respectively. The introduction of the LGC GaInAsP intermediate layer reduces the series resistance and, thus, device heating, which increases the characteristic temperature and light output power for the increased operation temperatures. Besides, in the temperature range between 20 and 80 °C, sample D has a higher optical gain and a lower transparent injection carrier density, which will reduce the threshold current and enhance the slope efficiency as compared to those of other three LD structures. With increasing the temperature from 80 to 100 °C, the higher optical gain and the lower transparent injection carrier density still improve the threshold condition. However, at higher operation temperatures, the dopants will have a high probability of diffusion into the quantum wells. In this case, the band-tail recombination effect would degrade the LD optical gain and thus lower the characteristic temperature for sample D. Furthermore, the carrier lifetime decreases with temperature, which would also increase the threshold current, as described in Eq. (2). Figure 4 shows the wavelength dependence of heat sink temperature at a driving current of 60 mA for the four LD structures, better than that of others. The lasing wavelength shifts for the four LD structures between 20 and 70 °C are from 1313 to 1335, 1320 to 1338, 1319 to 1340, and 1318 to 1337 nm, respectively. It is obvious that sample D has the lowest linear redshift rate of 0.38 nm/K. This illustrates that the MD-SC-MQW LDs with a LGC layer have a temperature insensitivity comparable to other three LD structures. Furthermore, the lasing wavelength for MD-SC-MQW LDs (sample C) is shorter than that for the undoped SC-MQW LDs (sample A). It is attributed to the conduction-band filling effect in the MD-SC-MQW LDs. Table I lists a summary of the static characteristics for the four LD structures. It is clear that the structure with an n-type MD-SC-MQW active region and a LGC layer (sample D) has the best static characteristics as compared to others.

![Fig. 2. cw light output power at 300 K as a function of injection current for the 300-μm-long as-cleaved LD structures for samples A, B, C, and D. The inset shows the dependence of current as a function of voltage for four LD structures.](image1)

![Fig. 3. Dependence of threshold current as a function of operation temperature for the four LD structures for samples A, B, C, and D.](image2)

![Fig. 4. Lasing wavelength dependence at a driving current of 60 mA as a function of operation temperature for samples A, B, C, and D.](image3)

![Table I. Summary of the static characteristics for samples A, B, C, and D.](table1)
The photon number varies with the instantaneous time due to random carrier recombination and generation even without an applied current modulation. Thus, there can be variations in the magnitude of light output power, which provides a noise floor. For this, it is important to consider the implications of intensity and frequency noise in practical laser applications. RIN can be defined as\(^{25,26}\)

\[
\text{RIN} = \frac{\langle \delta P(t)^2 \rangle}{P_0^2},
\]

where \(\langle \delta P(t)^2 \rangle\) is the mean square of the assumed Gaussian noise distribution, and \(P_0\) is the light output power. By correlation computing and Langevin approach, we obtain the RIN as follows:

\[
\frac{\text{RIN}}{\Delta f} = \frac{2h\nu}{P_0} \left[ \frac{a_1 + a_2 \omega^2}{\omega_R^2} |H(\omega)|^2 + 1 \right],
\]

where \(H(\omega)\) is the modulation transfer function; \(a_1\) and \(a_2\) are frequency coefficients, which are independent of power; \(\omega_R\) is a relaxation oscillation frequency. \(\omega_R\) can be expressed as

\[
\omega_R^2 = \frac{v_g a \eta}{q V_p} (I - I_{th}),
\]

where \(\eta\) is the internal quantum efficiency, \(v_g\) is the group velocity, \(V_p\) is the cavity volume occupied by photons, \(I_{th}\) is the threshold current, and \(a\) is a constant related to the photon density.

Figure 5 shows the frequency response as a function of injection current for the three LD structures (samples B, C, and D). The LD sample D exhibits the highest relaxation oscillation frequency of 9.9 GHz at 20 °C and 80 mA. This is because the MD-SC-MQW active region has a large population of free electrons near the band edge of the active region available for recombination with injected carriers. Thus, it might be expected that the turn-on time for electron and hole recombinations in an \(n\)-type modulation-doped barriers will be shorter than that of the undoped SC-MQW LD, provided that the relaxation rate of injection holes to the edge of the valence band in the well is sufficiently rapid. The 3 dB bandwidth for the MD-SC-MQW LD is as high as 15.34 GHz without considering the damping factor and coupling loss.

Figure 6 shows the threshold current and light output power at a 20 mA drive current against the chips. All of the chips were measured in the same time and conditions. It is found that the threshold current and light output power for each chip are almost the same. In addition, the four LD structures did show consistent improvements of light output power between 10% and 40%.

IV. CONCLUSIONS

We have investigated the performance of 1.3 μm AlGaInAs/AlGaInAs strain-compensated multiple-quantum-well laser diodes using three improved device designs including \(n\)-type modulation doping in the MQW barriers (MD-SC-MQW, sample B), a linear graded-composition GaInAsP intermediate layer (sample C), and the combination of both \(n\)-type MD-SC-MQW and LGC layer (sample D). As compared to LDs with an undoped SC-MQW active region, all three LD structures showed improved performance. The use of a MD-SC-MQW structure can improve the threshold current and power output level through the modification of positions of the quasi-Fermi levels. The device performance is also improved by adding a LGC intermediate layer to the LD. The linearly graded energy band structure created by the LGC layer modifies the electric field distribution near the...
active region and thus improves the LD performance. The LD with a combined $n$-type MD-SC-MQW active region and a LGC layer structure exhibits the best performance including the threshold current, characteristic temperature, lasing wavelength shift, and relaxation frequency response of 12.5 mA, 85 K in the temperature range between 20 and $80 \, ^\circ\text{C}$, $0.38 \, \text{nm}/\, ^\circ\text{C}$, and 9.9 GHz, respectively. Neglecting the damping factor and coupling loss, the calculated 3 dB bandwidth is around 14.26 GHz.

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