Extremely low threshold-current-density InGaAs quantum-well lasers with emission wavelength of 1215–1233 nm

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Extremely low threshold-current-density $In_{0.4}Ga_{0.6}As$ quantum-well (QW) lasers have been realized in the 1215–1233 nm wavelength regime. The measured room-temperature threshold current density of the InGaAs QW lasers with a cavity length of 1000 μm is only 90 A/cm^2 at an emission wavelength of 1233 nm. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1581978]

Conventional 1300 nm lasers are based on the InGaAsP or InGaAlAs quantum-well (QW) active material system on an InP substrate.[1] Unfortunately, these 1300 nm InP-based diode lasers suffer poor lasing performance at high-temperature operation.[1] Kondow and co-workers[2] of Hitachi Corporation introduced the InGaAsN material system as a material system with enormous potential for realizing light emitters on GaAs in the wavelength regime of interest for optical communications, namely 1300–1550 nm. The poor temperature characteristics of InP-based semiconductor lasers have led to enormous efforts in exploring the InGaAsN QW lasers,[2–11] as well as other types of 1300 nm active regions on GaAs, as alternatives to realize high-performance QW lasers for high-temperature operation.

Unfortunately, early InGaAsN QW lasers suffer from poor lasing performance due to the utilization of nearly lattice-matched InGaAsN.[2,3] The nearly lattice-matched or lattice-matched InGaAsN QW lasers require a relatively large N content of approximately 3% with an In content of 9%–12% to adjust the lattice constant back to that of an unstrained material system. Sato and co-workers[4] of Ricoh Corporation in Japan, proposed the approach of utilizing a *high* In-content InGaAsN QW active region. The concept proposed was to utilize as high an In content as possible in the InGaAsN QW, such that a minimum amount of N content is required to push the peak emission wavelength to 1300 nm. By utilizing this approach, Sato and co-workers[4] were able to realize 1300 nm InGaAsN QW lasers with reasonable threshold current densities, on the order of 0.92–1.0 kA/cm^2 for devices with a cavity length of approximately 1000 μm.[4] Recently, various groups utilizing an In content as high as 30%–40% have been able to realize high-performance InGaAsN QW lasers in the wavelength regime of 1280–1310 nm.[4–11]

In our previous work, InGaAsN QW lasers with an In content of 40% and N content of only 0.5% have been realized with threshold current densities of only 210 A/cm^2 at an emission wavelength of 1295 nm.[7] From studies on InGaAsN QW lasers with an In content of 35%–43%,[12] we also observe a trend toward a reduction in the threshold current densities for 1300 nm InGaAsN QW lasers with increasing In content. Therefore, it is extremely important to realize high-performance InGaAs QW lasers with a very long emission wavelength, such that it requires a minimal amount of N in the QW to push the emission wavelength to 1300 nm.

In this work, we present high-performance InGaAs QW lasers with an emission wavelength beyond 1230 nm, utilizing GaAsP tensile-strained buffer and barrier layers. The high Al-content AlGaAs lower cladding layer introduces a slight compressively strained template prior to the growth of the highly strained active region. The tensile-strained GaAsP buffer layer (Fig. 1) acts to partially strain compensate for the QW growth template leading to an improved optical quality for the highly strained InGaAs(N) QW. High optical luminescence intensity from the highly strained InGaAs(N) QW is only obtained with the utilization of the tensile buffer layer.[6,7] Further studies are required to fully understand the role of the buffer layer in the observed improvement of the optical luminescence for the $In_{0.4}Ga_{0.6}As$(N) QW.

All of the laser structures reported here are realized by low-pressure metalorganic chemical vapor deposition. Trimethylgallium, trimethylaluminium, and trimethylindium are used as the group-III sources. The group-V precursors used here are AsH_3 and PH_3. The dopant sources are SiH_4 and dielthylzinc for the *n* and *p* dopants, respectively. The composition of the QW is characterized by high-resolution x-ray diffraction experiments, and has been elaborated in our earlier work.[14]

The schematic band diagram of the 1200 nm laser structure is shown in Fig. 1, which is identical with that of the laser structure previously studied for 1300 nm InGaAsN QW lasers[7] except for the active region. The active region is based on the 60 Å $In_{0.4}Ga_{0.6}As$ QW, sandwiched by barrier

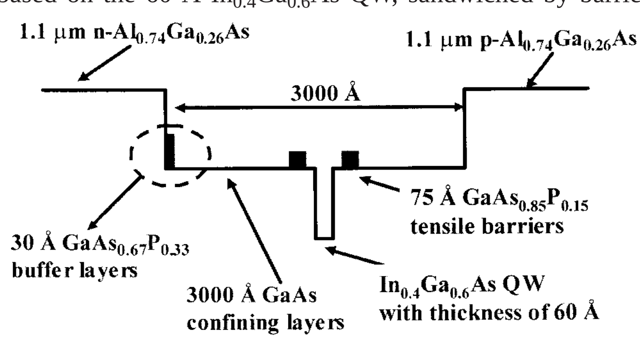

FIG. 1. Cross-sectional schematic conduction band diagram of the $In_{0.4}Ga_{0.6}As$ QW laser with tensile-strained $GaAs_{0.67}P_{0.33}$ buffer and $GaAs_{0.85}P_{0.15}$ barrier layers.

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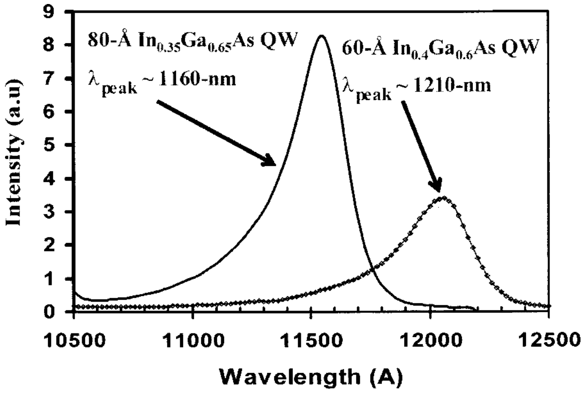

FIG. 2. Photoluminescence spectra comparison of 1170 nm $In_{0.35}Ga_{0.65}As$ QW and 1210 nm $In_{0.4}Ga_{0.6}As$ QW active region.

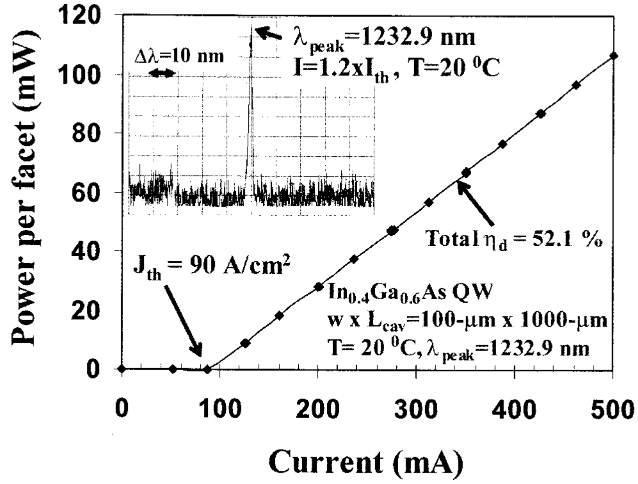

FIG. 3. The relation of output power per facet (P) and the total injected current (I) for $In_{0.4}Ga_{0.6}As$ QW lasers with a cavity length of 1000 μm at a temperature of 20 °C. The inset shows the lasing spectrum at 20 °C.

regions of 100 Å GaAs on each side. The strain compensation of the active region is provided by the 75 Å $GaAs_{0.85}P_{0.15}$ tensile barriers, which are grown before and after the GaAs barrier regions. The optical confinement factor for the InGaAs QW is calculated as approximately 1.7%. The growth of the active region and the optical confinement regions utilize an $[AsH_3]$/III ratio in excess of 100, at a reactor temperature of approximately 530 °C. The n- and p-cladding layers are based on an $Al_{0.74}Ga_{0.26}As$ material system, grown at 775 °C and 640 °C, respectively. Both cladding layers are designed with a doping level of approximately 1×10^{18} cm^{-3}. The tensile buffer layer consists of a 30 Å $GaAs_{0.67}P_{0.33}$, which we found to be crucial for the growth of the highly strained InGaAs(N) QW material system on top of a high Al-content lower cladding layer.[6,7]

The room-temperature photoluminescence of the 60 Å $In_{0.4}Ga_{0.6}As$ QW active material is presented in Fig. 2, along with that of an 80 Å $In_{0.35}Ga_{0.65}As$ QW for comparison. The peak emission wavelength of the $In_{0.4}Ga_{0.6}As$ QW is measured at approximately 1210–1215 nm, which is 50–60 nm longer than that of the $In_{0.35}Ga_{0.65}As$ QW. The reduction in the optical luminescence intensity of the $In_{0.4}Ga_{0.6}As$ QW ($\Delta a/a=2.78\%$), in comparison to that of $In_{0.35}Ga_{0.65}As$ QW ($\Delta a/a=2.45\%$), is presumably a result of a slight degradation in the crystal quality due to the higher strain of the 1210 nm InGaAs QW.

The lasing characteristics are measured under a pulsed condition with a pulse width of 5 μs and duty cycle of 1%. The measurements are performed on as-cleaved broad area laser devices, with an oxide-defined stripe width of 100 μm. The metal contacts are realized with 250 Å Ti/500 Å Pt/1500 Å Au and 200 Å Ge/1000 Å GeAu/500 Å Ni/3000 Å Au for p and n contacts, respectively. The contact annealing of the devices is accomplished under forming gas (10% H_2 +90% N_2) at a temperature of 370 °C for duration of 30 s.

The room-temperature ($T=20$ °C) lasing spectrum for the 60 Å $In_{0.4}Ga_{0.6}As$ QW devices with a cavity length of 1000 μm is measured as long as 1233 nm, as shown in Fig. 3. The lasing emission wavelengths range from 1216 nm to 1233 nm, with little variation in threshold current densities. As shown in Fig. 3, the threshold current density of these $In_{0.4}Ga_{0.6}As$ QW laser devices is found to be 90–92 A/cm^2 for measurements at a heat-sink temperature of 20 °C. The total external differential quantum efficiency (η_d) of the devices is measured as approximately 52.1%.

The temperature characteristics of the threshold current densities (T_0 values, with $1/T_0=(1/J_{th})\cdot dJ_{th}/dT$) and the external differential quantum efficiencies (T_1 values, with $1/T_1=(-1/\eta_d)\cdot d\eta_d/dT$) of the 1233 nm $In_{0.4}Ga_{0.6}As$ QW lasers are shown in Fig. 4. The temperature characterization is conducted from a temperature of 10 °C up to a temperature of 100 °C, with temperature steps of 5 °C. In the temperature range of 10 °C to 50 °C, the slope efficiency (η_d) hardly decreases with temperature, resulting in a T_1 value of approximately 1250 K based on our best fit. For the temperature range of 50 °C to 100 °C, we observe a significant drop of the T_1 value from 1250 K to approximately 480 K. It is important to note that T_1 values of 1250 K and 480 K are significantly larger than those of 1300 nm InGaAsN QW lasers. For 1300 nm InGaAsN QW lasers with the same separate confinement heterostucture as the InGaAs active lasers and cavity length of 1000 μm, we previously reported T_1 value of 255 K for measurements in the temperature range of 20 °C to 60 °C. The T_0 values are measured as 140 K and 105 K for measurements in the temperature ranges of 10–50 °C and 50–100 °C, respectively. The lowering of T_0 and T_1 values at elevated temperatures are presumably driven by the thermionic carrier leakage processes. Neverthe-

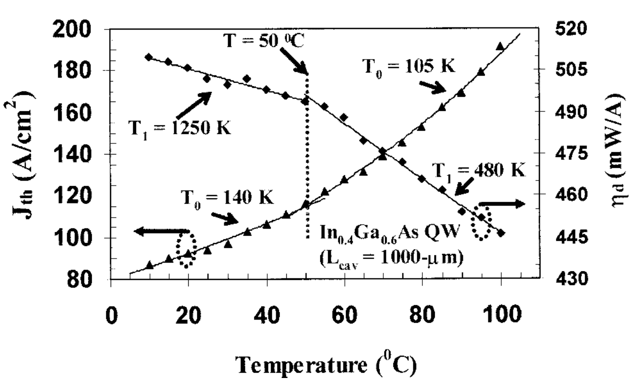

FIG. 4. Threshold current density (J_{th}) and external differential quantum efficiency (η_d) of 1233 nm $In_{0.4}Ga_{0.6}As$ QW lasers ($L_{cav}=1000$ μm) as a function of temperature in the range of 10 °C to 100 °C.

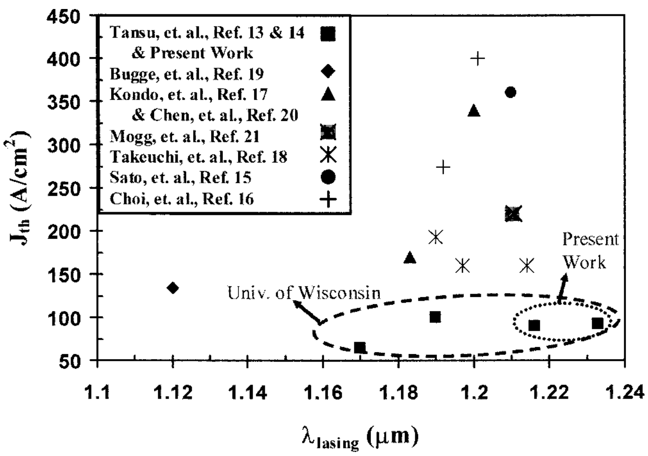

FIG. 5. Comparison of threshold current densities of InGaAs QW lasers in the 1100–1250 nm wavelength regime.

less, very-low threshold-current-densities of only 160 A/cm^2 and 190 A/cm^2 are achieved for $In_{0.4}Ga_{0.6}As$ QW lasers (L_{cav}=1000 μm) at temperatures of 85 °C and 100 °C, respectively.

Comparison of the lasing characteristics of the 1215–1233 nm InGaAs QW lasers with reported results in literature[13–21] is shown in Fig. 5. As the emission wavelength of the InGaAs QW lasers is extended, typically, their threshold current densities increase rapidly. Previously, very low reported threshold current densities for InGaAs QW lasers on GaAs beyond emission wavelength of 1210 nm were realized by Takeuchi and co-workers[18] with room-temperature threshold current densities of 160 A/cm^2 for devices with cavity length of 1000 μm. In our present work, we recorded threshold current densities of only 90–92 A/cm^2 for strain-compensated InGaAs QW lasers up to emission wavelength of 1233 nm. It is also important to note that we observe only a very slight dependence of the threshold current densities on emission wavelengths from 1170 nm to 1233 nm, which may be a result of the utilization of the GaAsP tensile-strained barriers.

In summary, high-performance InGaAs QW lasers have been realized with lasing performance up to an emission wavelength of 1233 nm. The realization of diode lasers with a room-temperature emission wavelength of 1233 nm, represents the longest emission wavelength realized with only an InGaAs QW active region on a GaAs substrate. The threshold current densities of only 90 A/cm^2 and 190 A/cm^2 are measured for laser devices with a cavity length of 1000 μm at temperatures of 20 °C and 100 °C, respectively. These reported threshold current densities represent among the lowest values for InGaAs QW diode lasers on GaAs in the wavelength regime beyond 1200 nm. No evidence of a significant increase in the threshold current of the InGaAs QW lasers, with increasing wavelength beyond 1200 nm, indicates the potential for achieving high-performance diode lasers on GaAs substrates with emission wavelength even beyond 1233 nm utilizing only an InGaAs QW active material.

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