# Continuous-wave operation of AlGaInP/GaInP quantum-well lasers grown by metalorganic chemical vapor deposition using tertiarybutylphosphine

Jian-Rong Dong, Jing-Hua Teng, Soo-Jin Chua,[a] Boon-Chin Foo, Yan-Jun Wang, Lian-Wen Zhang, and Hai-Rong Yuan
*Institute of Materials Research and Engineering, 3 Research Link, Singapore 117602, Singapore*

Shu Yuan
*School of Materials Engineering, Nanyang Technological University, Singapore 639798, Singapore*

(Received 27 August 2003; accepted 11 February 2004)

Strained AlGaInP/GaInP multiple-quantum-well laser structures have been grown by metalorganic chemical vapor deposition using teriarybutylphosphine as the phosphorus precursor and ridge waveguide lasers of 4 $\mu$m wide have been fabricated. Room temperature continuous-wave lasing has been obtained with an emission wavelength of about 670 nm. A single-facet output power of more than 18 mW has been achieved for an as-cleaved laser chip. It can be concluded that it is feasible to fabricate AlGaInP red lasers using less toxic metalorganic source tertiarybutylphosphine in parallel with conventionally used highly toxic $PH_3$.  [DOI: 10.1063/1.1695591]

In 1985, several research groups demonstrated room temperature cw red lasers based on the AlGaInP material,[1–3] and since then, AlGaInP semiconductor red lasers have attracted a lot of research attention due to the wide applications, such as in color printer, barcode scanner, digital versatile disk read/write head, and so on. Most of the AlGaInP lasers are grown using $PH_3$ as a phosphorus source by either metalorganic chemical vapor deposition (MOCVD) or gas source molecular beam epitaxy. Because of the high toxicity of $PH_3$, researchers have been seeking after a less toxic and environment friendly alternative to $PH_3$. Tertiarybutylphosphine (TBP) has been considered a promising P precursor for material growth due to the lower vapor pressure, several orders of magnitude lower toxicity,[4] and lower decomposition temperature[5] which is useful for suppressing the diffusion of dopants in device structures where an abrupt doping profile is critical to the performance of the devices. High quality InGaAsP quantum well long wavelength lasers grown by TBP and tertiarybutylarsine (TBAs) were demonstrated in early 1990s.[6,7] However, compared with InGaAsP, AlGaInP is more sensitive to the impurity oxygen in the TBP and the growth of high quality AlGaInP epilayers and related devices using TBP is a more challenging topic, and only AlGaInP red light emitting diodes and pulsed operation of AlGaInP red lasers grown using TBP have been demonstrated in recent years.[8–11] For practical applications, room temperature cw lasers are desired. However, so far, cw AlGaInP red lasers grown by TBP have not been reported mainly due to the problem with the optical quality of AlGaInP material grown using TBP.

In this article, high quality AlGaInP/GaInP strained multiple-quantum-well (MQW) laser structures have been grown by MOCVD utilizing TBP and 4 $\mu$m wide ridge waveguide lasers have been fabricated. Room temperature cw lasing has been demonstrated with an emission wavelength around 670 nm and a single-facet output power of more than 18 mW at 15 °C and 3.7 mW at 70 °C for an uncoated laser diode with about 1000 $\mu$m cavity length. These results indicate that the growth of high quality AlGaInP and related devices using TBP is viable.

The material growths were performed employing a low-pressure horizontal MOCVD system with planetary rotation to ensure the uniformity of the grown materials in composition, thickness, and doping. AlGaInP epilayers were grown on $n^+$-GaAs substrates with the orientation of (100) 7° off towards (111)A to suppress the spontaneous ordering in the (Al)GaInP epilayers.[12] Trimethylgallium, trimethylindium, and trimethylaluminum were used as group III sources, and TBAs and TBP were utilized as the group V sources, $SiH_4$ and diethylzinc were used for the *n*- and *p*-type doping, respectively. The growth temperature was set at 675 °C and the growth chamber pressure was kept at 100 mbar. The V/III ratio was 75 and the growth rate was about 1 $\mu$m/h. All the compositions and growth rates were calibrated by high-resolution x-ray diffraction and photoluminescence (PL). Room temperature PL measurements were performed on an Accent RPM 2000 system in which the 532 nm line of a Kr laser at the power of about 11 mW was utilized as the excitation source and a charge coupled device for detection of the PL emissions.

Incorporating compressive strain into the well layers of a QW structure has proven to be an effective way to reduce the threshold current density and to improve the temperature characteristics of a semiconductor laser both theoretically and experimentally.[13,14] Before the growth of an AlGaInP/GaInP MQW laser structure, several compressively strained AlGaInP/GaInP QW structures were grown to identify the effect of compressive strain on the optical properties. The quantum well structures under investigation consist of three wells separated by 8 nm $(Al_{0.4}Ga_{0.6})_{0.52}In_{0.48}P$ barrier layers,

[a]Electronic mail: elecsj@nus.edu.sg

 

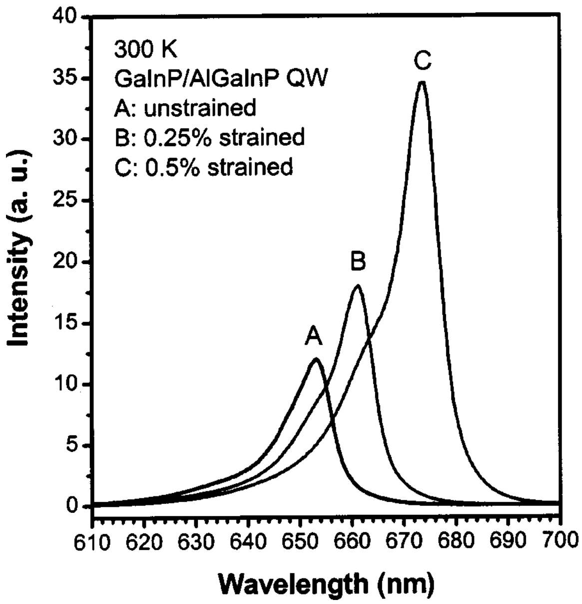


FIG. 1. RT PL spectra of AlGaInP/GaInP QW structures with differently strained well layers.

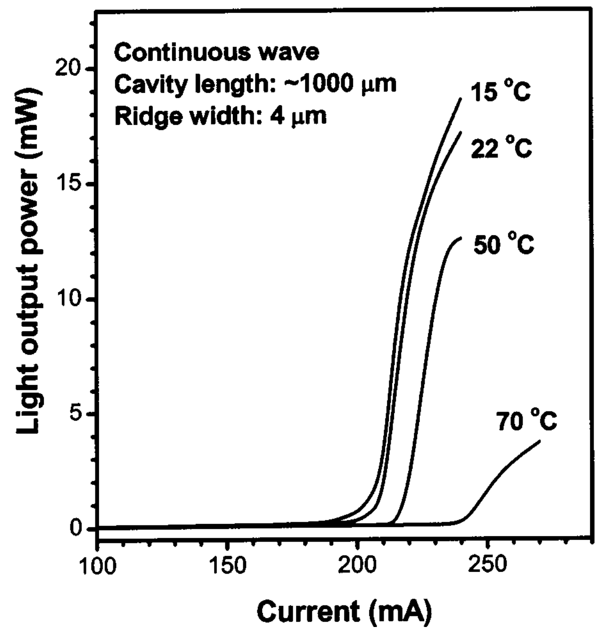


FIG. 2. $L-I$ curves of an AlGaInP/GaInP MQW laser at different heat sink temperatures.

which are sandwiched between two 100 nm $(Al_{0.4}Ga_{0.6})_{0.52}In_{0.48}P$ confinement layers. In the three samples A, B, and C, the well layers are 10 nm $Ga_{0.52}In_{0.48}P$, 8 nm $Ga_{0.48}In_{0.52}P$, and 8 nm $Ga_{0.44}In_{0.56}P$, respectively, and the corresponding strain in the well layer is 0%, 0.25%, and 0.5%, respectively. The RT PL spectra of samples A, B, and C are given in Fig. 1. The difference in the emission wavelength results from the different combinations of the composition and thickness of the well layer and, hence, different quantized energies. As can be seen, the full width at half maximum is about 31 meV for all the three samples, indicating good optical quality of the structures. The PL peak intensity of sample C is about three times stronger than that of sample A. This improvement in PL efficiency is mainly attributed to the higher indium composition in the well layer, required by the larger compressive strain, which results in a deeper well and stronger carrier confinement in the wells. Besides the earlier mentioned effects, due to the elimination of the degeneracy of light hole subband and heavy hole subband at the top of the valence band induced by the compressive strain,[13] the density of states at top of the valence band is reduced, and the carrier density needed to reach the population inversion is decreased. Therefore, the introduction of compressive strain into a laser structure can improve the laser performance.

Based on the PL results of differently strained QW structures, the strained MQW laser structure was grown with the well layers of 0.5% compressively strained. The laser structure consists of the following layers: starting from $n^+$-GaAs substrate, 200 nm Si-doped GaAs buffer layer ($n \cong 2\times10^{18}\,cm^{-3}$), 80 nm Si-doped GaInP transition layer ($n \cong 2\times10^{18}\,cm^{-3}$), 1000 nm Si-doped $n$-$(Al_{0.7}Ga_{0.3})_{0.52}In_{0.48}P$ cladding layer ($n \cong 2\times10^{18}\,cm^{-3}$), 30 nm undoped $(Al_{0.7}Ga_{0.3})_{0.52}In_{0.48}P$ cladding layer, 80 nm undoped $(Al_{0.4}Ga_{0.6})_{0.52}In_{0.48}P$ layer, three period $Ga_{0.44}In_{0.56}P$ (8 nm)/$(Al_{0.4}Ga_{0.6})_{0.52}In_{0.48}P$ (8 nm) quantum well active layers, 80 nm undoped $(Al_{0.4}Ga_{0.6})_{0.52}In_{0.48}P$ layer, 50 nm undoped $(Al_{0.7}Ga_{0.3})_{0.52}In_{0.48}P$ layer, 1200 nm Zn-doped $p$-$(Al_{0.7}Ga_{0.3})_{0.52}In_{0.48}P$ cladding layer ($n \cong 1\times10^{18}\,cm^{-3}$), 100 nm Zn-doped GaInP transition layer ($p \cong 2\times10^{18}\,cm^{-3}$), and 200 nm Zn-doped GaAs contact layer ($p \cong 1\times10^{19}\,cm^{-3}$). For the fabrication of ridge waveguide lasers, first, a dielectric film $SiO_2$ 200 nm thick was deposited on the wafer by plasma-enhanced chemical vapor deposition, then a ridge of 4 $\mu$m wide was formed by standard photolithography and wet etching with an etching depth about 1 $\mu$m using $SiO_2$ as the mask. Then the $SiO_2$ was removed and another $SiO_2$ film was deposited and a 2 $\mu$m wide window was opened up for the $p$-type ohmic contact using the Pd/Ti/Pd/Au metal layers electron-beam evaporated. Subsequently, the wafer was thinned to some 100 $\mu$m by mechanical polishing followed by the evaporation of AuGe/Ni/Au for $n$-type ohmic contact. Annealing at 450 °C was performed to form ohmic contacts. Finally, the wafer was cleaved, and the laser chips without facet coatings were mounted on a small copper plate with $p$-side up and tested at different temperatures on a stage with temperature controller. Under continuous current injection, the output power was measured with a calibrated detector and the laser emission spectra were recorded utilizing an ANDO 3615B optical spectrum analyzer. The wavelength resolution of the system is 0.05 nm.

Figure 2 shows the light output power versus current ($L-I$) curves of a laser with a cavity length of about 1000 $\mu$m at different temperatures. As can be seen, the threshold current $I_{th}$ is about 200 mA at 22 °C. Taking into account the shape of the wet-etched ridge with two (111)A sidewalls, the actual width at the bottom of the ridge is about 5 $\mu$m, and we can obtain the corresponding threshold current density of 4 $kA/cm^2$. As the temperature is increased from 15 to 70 °C, the threshold current increases from 190 to 240 mA mainly

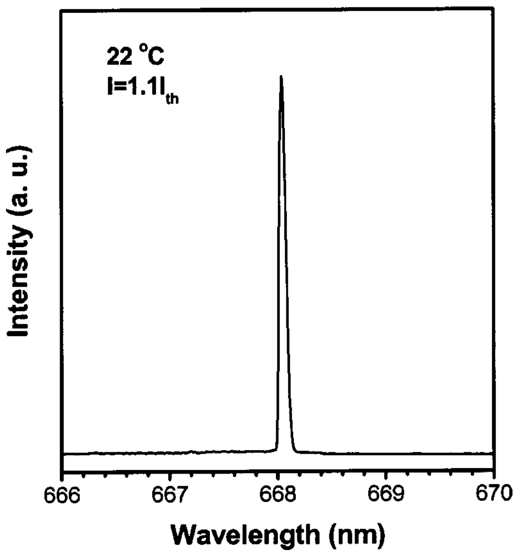


FIG. 3. Laser emission spectrum of an AlGaInP/GaInP MQW laser at 22 °C and an injection current of 1.1 $I_{th}$.

due to an increase in electron overflow current from active region to the *p*-type cladding layer and a decrease in internal quantum efficiency with increasing temperature.[15] At 15 °C, the single facet light output power of more than 18 mW is achieved before the roll over due to the thermal effect. The differential quantum efficiency is about 60% taking into account the symmetric light output on two facets. Figure 3 shows the laser emission spectrum at 22 °C and 1.1 $I_{th}$. One mode at 668 nm is dominant although the mutiple-mode characteristics of a Fabry–Pérot laser are expected. The line width is about 0.1 nm. The characteristics of this laser are significantly improved compared with those of the unstrained one reported previously,[10] which is attributed to the compressive strain in the well layers.

These preliminary results are comparable to those of the first reported AlGaInP/GaInP MQW laser grown using $PH_3$.[16] Considering that we have not optimized the device structure design and the processing parameters, with further improvement of the material quality and the device processing, lasers with a low threshold current density and a high power are expected.

In summary, AlGaInP/GaInP multiple-quantum-well laser structures with strained well layers have been grown by MOCVD using TBP and ridge waveguide lasers of 4 $\mu$m wide have been fabricated. Room temperature cw AlGaInP/GaInP MQW lasers grown using TBP have been demonstrated with an emission wavelength of about 670 nm, a threshold current density of 4 kA/cm$^2$, and an output power of more than 18 mW at 15 °C. With further optimization of material growth conditions, device structure design and processing parameters, it is feasible to fabricate high performance AlGaInP red lasers grown by TBP.

The authors would like to thank Rui Yin for his effort in the laser spectrum and $L-I$ measurements.

[1] M. Ikeda, Y. Mori, H. Sato, K. Kaneko, and N. Watanabe, Appl. Phys. Lett. **47**, 1027 (1985).
[2] M. Ishikawa, Y. Ohba, H. Sugawara, M. Yamamoto, and T. Nakanisi, Appl. Phys. Lett. **48**, 207 (1986).
[3] K. Kobayashi, S. Kawata, A. Gomyo, I. Hino, and T. Suzuki, Electron. Lett. **21**, 931 (1985).
[4] G. B. Stringfellow, *Organometallic Vapor-Phase Epitaxy* (Academic Press, San Diego, 1989), p. 29.
[5] S. H. Li, C. A. Larsen, N. I. Buchan, G. B. Stringfellow, W. P. Kosar, and D. W. Brown, J. Appl. Phys. **65**, 5161 (1989).
[6] A. Ougazzaden, A. Mircea, R. Mellet, G. Primot, and C. Kazmierski, Electron. Lett. **28**, 1078 (1992).
[7] M. E. Heimbuch, A. L. Holmes, Jr., M. P. Mack, S. P. DenBaars, L. A. Coldren, and J. E. Bowers, Electron. Lett. **29**, 340 (1993).
[8] M. Mashita, H. Ishikawa, T. Izumiya, and Y. Someya Hiraoka, Jpn. J. Appl. Phys., Part 1 **36**, 4230 (1997).
[9] K. Itaya, A. L. Holmes, Jr., S. Keller, S. G. Hummel, L. A. Coldren, and S. P. DenBaars, Jpn. J. Appl. Phys., Part 2 **34**, L1540 (1995).
[10] J. R. Dong, J. H. Teng, S. J. Chua, B. C. Foo, Y. J. Wang, H. R. Yuan, and S. Yuan, Appl. Phys. Lett. **83**, 596 (2003).
[11] C. Y. Liu, S. Yuan, J. R. Dong, S. J. Chua, M. C. Y. Chan, and S. Z. Wang, J. Appl. Phys. **94**, 2962 (2003).
[12] S. Minagawa and M. Kondow, Electron. Lett. **25**, 758 (1989).
[13] S. Kamiyama, T. Uenoyama, M. Mannoh, Y. Ban, and K. Ohnaka, IEEE J. Quantum Electron. **30**, 1363 (1994).
[14] M. Ohya, H. Fujii, K. Doi, and K. Endo, Electron. Lett. **35**, 46 (1999).
[15] M. Ishikawa, H. Shiozawa, K. Itaya, G. Hatakoshi, and Y. Uematsu, IEEE J. Quantum Electron. **27**, 23 (1991).
[16] M. Ikeda, A. Toda, K. Nakano, Y. Mori, and N. Watanabe, Appl. Phys. Lett. **50**, 1033 (1987).